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Effectiveness of Augmented Reality with Haptic Feedback for Dental Implant Placement Training: An In-Vitro Comparative Study

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Abstract

Dental implant placement requires accurate three-dimensional orientation, controlled drilling depth, appropriate angulation, and adequate tactile awareness. Traditional phantom-based implant training provides useful preclinical practice, but it may offer limited real-time visual and force-related feedback for novice learners. This study aimed to evaluate the effectiveness of augmented reality combined with haptic feedback in dental implant placement training among dental students. A randomized in-vitro experimental design was proposed with 100 participants divided equally into a control group receiving traditional phantom/model-based training and an experimental group receiving AR+haptic feedback training. Participants completed pre-test and post-test implant placement tasks on standardized phantom or 3D-printed jaw models. Primary outcomes included entry point deviation, apex deviation, angular deviation, drilling depth error, procedure time, and procedural errors. Secondary outcomes included usability, workload, confidence, and satisfaction. Data were planned for analysis using descriptive statistics, paired samples t-test, independent samples t-test, repeated measures ANOVA, and non-parametric alternatives where appropriate. The proposed study expects that AR+haptic feedback will improve implant placement accuracy, reduce procedural errors, enhance user confidence, and lower perceived workload compared with traditional training. The findings may support the use of AR+haptic simulation as a supplementary tool in preclinical implant dentistry education.

Introduction

Background of the Study

The placement of a dental implant is a precise procedure requiring correct diagnosis and treatment planning by the clinician. The clinician must also account the placement of the drill to a specific depth and angle while avoiding injury to anatomical structures such as the maxillary sinus, the roots of adjacent teeth, the mandibular canal, and the cortical plates of the mandible. Traditional training regarding the placement of dental implants is reliant on lectures, demonstrations, interpretation of 2D radiographs, exercises utilizing phantom heads, and typingodont models. While these methods are valuable in the development of an understanding of the concepts, they do not implement the skills required for the preparation of an implant osteotomy such as the ability to make a visual judgment regarding the complexity of the implant site, the ability to discriminate with tactile judgment, and the ability to make decisions based on the aforementioned skills. Furthermore, due to the distal development of psychomotor skills and coordination, beginner level dental students and trainees make errors regarding the point of entry, the desired angle of the implant, the depth of the drill, and the recess of the drill. The gap between the desired level of clinical practice and the knowledge acquired through training has resulted in the use of advanced simulation technologies, Modern Reality (MR) being one of them. MR can fuse the anatomical training of implant placement, and the planning and guidance of drills extending he ability of the fusing the physical training models to provide tactile cues (drill resistance, vibration and force). It was reported in one study that MR, compared to the traditional methods, can improve the training of placement of dental implants for beginner level trainees.

Problem Statement and Research Gap

Although digital technologies have increasingly contributed to the field of dentistry, traditional training in dental implants is compromised in other ways. Continuous live feedback may not be possible in a traditional scenario, and students may not be able to correct themselves when bur direction, pressure, and depth while aligning with the intended path of the implant are altered. Additionally, practice with phantom jaws offers very little in the way of objective performance metrics. As a result, the assessment of the ways in which augmented reality implant guidance, mixed reality simulators, virtual reality dental simulators, and haptic simulation in the context of dental education have been performed in depth, very little empirical evidence has examined the use of augmented reality and haptics as a dental implant training simulator in the context of novice dental students in a controlled preclinical setting. From other studies, it is clear that augmented reality in dental implants has good accuracy when compared to the freehand method; and haptic technology in virtual reality offers an effective method for the development of fine motor skills within the field of dental education. It is important that more studies of this nature and their focus on haptic technology, augmented reality, and dental education are undertaken, and that more comparisons are made to traditional training in this area.

Aim, Purpose, and Significance of the Study

This study assesses the placement of augmented reality (AR) and haptic feedback augmented reality simulators on the dental implant placement accuracy by assessing the AR and haptic feedback simulators’ impacts on time taken to place an implant, the number of placement errors, and the level of confidence exhibited by the dental trainees. Importantly, the study does not intend to assess the usability of the placement of the AR and haptic feedback simulators on dental trainees by evaluating the impact of the AR and haptic feedback simulators on the dental trainees’ performance on real patients. It is preferable to assess the simulators based on their performance in dental training practice as it would allow the simulators to be judged based on their usability and consider the impact of the simulators on the practice. The study has a level of ethical concern as it avoids the practice on real patients and provides a controlled environment for practice. The study has the potential to provide evidence on AR and haptic feedback simulators impacting the accuracy of dental practice and the practice of dental simulators. Implementing the placement of AR and haptic feedback simulators may ensure the integration of AR and haptic feedback simulators in dental education and may transform the way practical assessments are performed in dental education.

Research Questions, Objectives, and Hypotheses

This study's singular focus was the effect of augmented reality (AR) and haptic feedback on the accuracy of dental implant placements when compared to traditional methods of training that rely on the use of training phantoms. The component research questions were as follows:

RQ1: What is the difference in AR and haptic feedback entry point training compared to traditional methods?

RQ2: What are the differences in apex, angular, and drilling depth deviations across the two groups?

RQ3: What is the difference in AR and haptic feedback driven training compared to traditional methods in the overall time taken to learn the task?

RQ4: What is the difference in AR and haptic feedback training compared to traditional methods in the improvement shown between the pre-test and post-test?

RQ5: What is the improvement in the pre and post experience feedback ratings in traditional methods training compared to the AR+haptic training?

The primary aim of the study was to assess AR and haptic feedback's effectiveness in dental implant placement training. The remaining aims were to analyze placement accuracy, measure the various deviations (including apex, angular, entry, and depth), assess time taken to perform the task, and evaluate the experience improvement shown in the pre and post-test. The null stated there would be no difference in placement accuracy between the AR and haptic methods and traditional training. The alternative hypothesized that the AR+haptic feedback training would result in placements that were measurably more accurate than those of the traditional methods, as well as improved overall learning outcomes.

Scope, Delimitations, and Structure of the Study

This study will occur in an in-vitro context and include 100 dental students or novices. These individuals will be split into two groups of 50 apprentices. One group will participate in traditional training which uses phantoms and model-based training of implants. The other group will receive augmented reality training that incorporates haptic feedback. There will be no involvement in actual surgeries or clinical placement of implants or involvement in postoperative patient outcomes. The main outcomes of this study will be objectively measured performance outcomes that include deviation of entry point, deviation of apex, deviation in angles, depth of drilling error, time taken for the procedure, and the count of procedural errors. Usability, workload, satisfaction, and confidence, perceived as positive or negative, will be considered as the tertiary outcomes of this study. The results of this study will be derived from the context of dental education and will not be drawn from direct clinical practices. This thesis comprises 5 chapters. Chapter 1 outlines the background, problem, gap, aim, research questions, objectives, hypotheses, significance, and scope. Chapter 2 synthesizes the related body of work pertaining to dental education and training for implants and AR, MR, VR, haptic feedback, and simulation. Chapter 3 covers the methodology. Chapter 4 provides the statistics. Chapter 5 covers the results, what the results mean and the constraints of the study, as well as what the results will be used for, and a summary of the study.

Literature Review

Mastery of multiple disciplines is required for successful practice of the profession of dental implant surgery. It includes various anatomical and surgical disciplines as well as digital management of surgical procedures and infrastructure psychosomatic control. Unlike many restorative procedures, implant placement errors may compromise osseointegration, prosthetic restorability, esthetics and ultimately, patient safety. For this reason, implant training has moved toward simulation-based learning, where students can repeatedly practice procedures before their first experience in the clinic. The simulation-based dental training and education, implant placement precision, virtual and augmented architectural realities, mixed realities and haptic feedback are reviewed in this chapter along with the existing literature on accuracy, learner experience, and the conceptual framework of the study.

Conventional Dental Implant Training

Training in implantology, as in other professional fields, is mainly based on lectures, radiographic case discussions, surgical videos, model building, and instructor supervised practice. Though traditional methods of training are essential for implant students to gain the basic knowledge to safely apply digital tools, they often fail to provide timely objective feedback on the accuracy of bony drills in terms of direction, force, depth of the drill hole, and the degree of inclination. The practice of invasive surgical techniques is especially important for those beginners who have theoretical knowledge and implant skills, but have not developed the ability to control and direct their hands to the required degree of precision. Conventional training also depends heavily on instructor availability, and assessment can vary from one instructor to another. For these reasons, studies have examined the potential of digital methods for simulation of surgical procedures in order to give students control and the ability to measure and repeat surgical implant procedures.

Augmented Reality in Dental Implantology

Augmented Reality, or AR, differs from 3D environments in that a trainee interacts with a physical object, albeit a digital one. Specifically, in the field of implantology, AR allows surgeons to project implant pathways, anatomical identifiers, and guides for drilling and depth directly onto physical models of the jaw, or even the patient’s jaw in real time. As AR overlays digital information and markings on the jaw in a real-time context, AR can be said to assist in implant placement accuracy and reduction of deviation from the designated placement of implants. In an in-vitro study by Kivovics and co-workers, AR-based dynamic navigation demonstrated significantly less global deviation, and a comparable performance in accuracy of other assessed parameters to static computer-assisted surgery for implant placement. These results illustrate the merits of AR in promoting spatial orientation and the accuracy of procedures, specifically in the context of dental surgery.

Mixed Reality and Implant Training

Mixed Reality (MR) is a more developed version of Augmented Reality (AR) as it involves a greater degree of integration between real and virtual elements and employs head-mounted displays and tracker systems. In the context of implant training, MR can allow learners to visualize plans for implant placement, as well as the anatomy and direction for the drill, in a common physical and digital space. In the in-vitro study conducted by Wang et al. (2025) about a MR training approach for beginner dental implant trainees, it was found that MR training was superior to conventional training methods in terms of several aspects such as outcome of learning, accuracy of implant placement, comprehension learning curve, and ease of use. All of these aspects are of great significance to this study, as they help to validate the context and use of immersive visualization for instructional purposes in the field of implant training. However, MR-based training studies do not incorporate touch and force feedback. Thus, this study aims to fill this gap by integrating Augmented Reality (AR)-based training direction and guidance with haptic feedback. This approach will help analyze both visual and tactile instructional channels.

Haptic Feedback in Dental Education

Haptic feedback involves tactile or resistive feedback that mimics physical sensations such as contact, pressure, resistances, vibration, or interaction with tissue. Haptics are critical in dentistry because many clinical practices require fine touch such as detecting changes in enamel and dentin, the presence of caries, the density of bones, and the resistance of the rotary instruments. A systematic review in 2025 on the use of virtual reality (VR) and haptics in restorative dentistry training stated that haptic dental simulators are well accepted and need more evidence with regard to their pedagogical value and standardization and implementation. Farag and colleagues studied the effect of a haptic virtual reality (VR) simulator on the psychomotor skills of dental students, and noted the improvement of some components of preclinical operative performance as a result of exposure to this simulator. These studies provide evidence that haptic feedback may assist in the development of motor skills, procedural, and cognitive confidence of dental students. Although the current haptic system literature is focused on restorative dentistry, the same concepts can be applied to implant drilling as the process of bone cutting (osteotomy) involves control of force and precision of cutting to a defined depth and along a specified line.

Virtual Reality and Simulation-Based Dental Learning

With Virtual Reality, learners can become situated within a digitally created environment to practice a clinical procedure. This is better explained with the use of VR and haptic simulators for training in Restorative Dentistry, Endodontics, Oral Surgery and Implant training. A qualitative study in 2024 on VR haptic simulators in preclinical restorative dentistry revealed that dental students found these simulators to promote engagement, offer the opportunity to practice at one’s own pace, and give quality feedback. However, several challenges to the use of the simulators were reported. A 2025 global education survey also reported that the application of VR-haptic technology to dental education may foster the development of manual skills and the ability to grasp and retain knowledge. However, the survey did acknowledge that there was inconsistency in the adoption of the technology and the respective education institution’s technological capacity. Students’ perception of technology is critical, as highly advanced technology for education may fail to be accepted by the students due to the technology being perceived as difficult, unrealistic, too stressful, or irrelevant. Hence, this study attempts to measure both the outcomes on performance as well as the technology’s usability/workload in a subjective manner.

Accuracy of Outcomes from Studies on Implant Placement

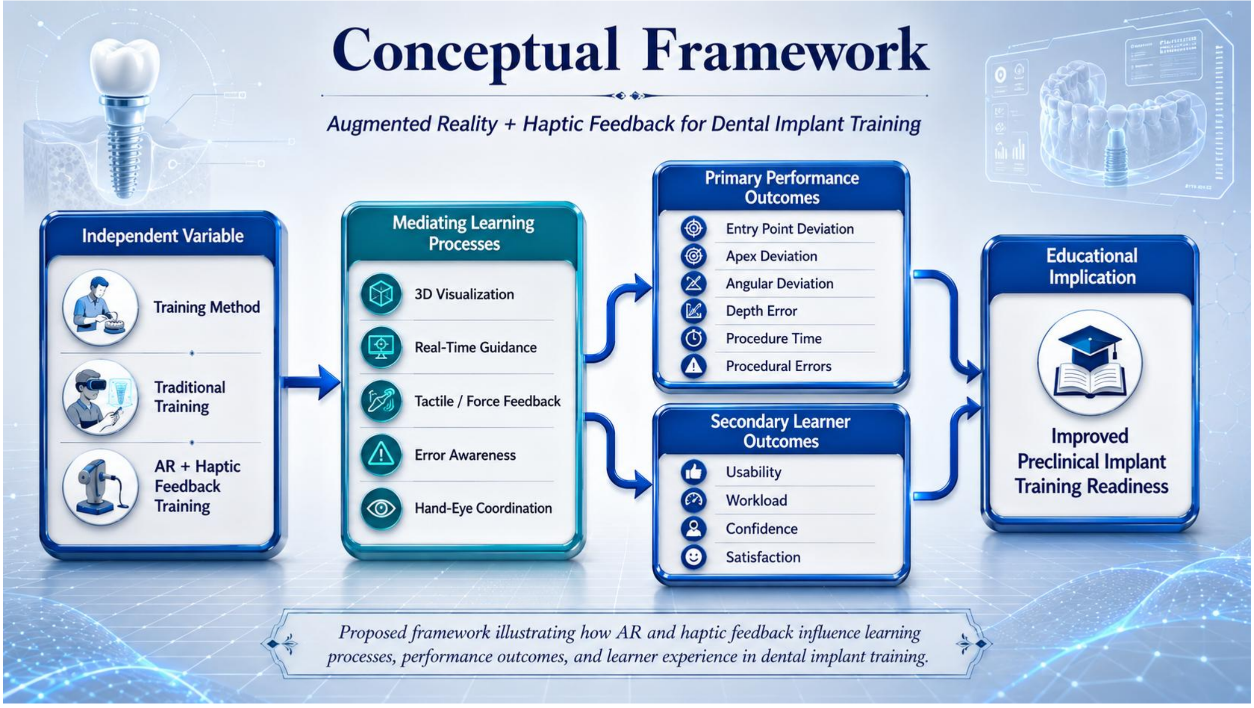
The accuracy of implant placement is determined by comparing where the implant is positioned with where it was intended to be positioned. This is typically reported using a range of metrics, which include coronal or entry point deviation, apical deviation, global deviation, and angular deviation, and depth error. These metrics are relevant because they substantiate whether a certain training approach has improved the accuracy of performing a procedure. In augmented reality studies for implant navigation, deviation is recorded in millimeters and degrees after a digital scan and after a CBCT assessment, or after superimposing images. The 2024 in vitro study that compared AR-based dynamic navigation to conventional dynamic navigation stated coronal, apical, and angular deviations as primary endpoints, and used a comparative statistical approach to analyze the groups. As such, the metrics cited, which are used in the field of implant navigation, are the best fit for this study, as they have been developed to provide objective measures, and will be used in a standardized jaw model.

Usability, Workload, and Learner Confidence

Evaluation of educational technologies must extend beyond the evaluation of the technical accuracy. With regard to the learner’s perspective, a training system must also be usable, acceptable, and manageable with regard to cognitive load. The System Usability Scale is a 10-item survey for the assessment of perceived usability and provides a global score of perceived usability system. The NASA Task Load Index is an established tool for the assessment of subjective workload, and it assesses workload along the dimensions of mental, physical, and temporal demands, as well as performance and effort, and the degree of frustration. These tools are appropriate because AR+haptic systems aid in guidance and may also support cognitive load, but they may also be counterproductive if the interface is cognitively complex and/or distracting. For these reasons, the present study will assess the technology's usability and workload in order to assess whether this technology is both effective and acceptable to dental trainees.

Conceptual Framework

The conceptual framework for this study is based on the consideration of the training method and how it impacts the variables of the learning process, in turn impacting the outcomes of performance and the outcomes related to the experience of the learner.



Proposed framework illustrating how AR and haptic feedback influence learning processes, performance outcomes, and learner experience in dental implant training.

The type of training method constitutes the independent variable in this case. Participants in the control group are provided with the method of training that is phantom-based. On the other hand, participants in the experimental group are provided with training that combines AR and haptic feedback. Mediators in this case are spatial visualization, real time correction, tactile sense, and procedural confidence. The main dependent variables in this case are the accuracy of implant placement which in turn is measured by entry deviation, apex deviation, and depth, as well as angular deviation, the total time taken to perform the procedure, and the number of errors made in the procedure. The dependent variables which are measured at a secondary level are ease of use, level of cognitive load, confidence, and satisfaction. It is assumed that the combination of AR and haptic feedback in this case enhances one's performance by providing the learner with a guided pathway to the end through a tactile sense, but at the same time, a high cognitive load and poor ease of use of the system could diminish the value of the system from an educational perspective.

Methodology

Show the research design and framework. The population and sample size, along with the sampling method, are documented. Group allocation, along with the research and data collection methods, are explained. The measures, research instruments, and procedures for establishing validity and reliability are described. Ethical considerations and the statistical analysis plan are outlined. The aim of a research methodology is to enable researchers to replicate the study, confirm that the study is systematic, justify that the study is ethical, and ascertain that the study is capable of addressing the research questions. Given that the study is designed to assess the impact of AR+haptic feedback within the context of dental implant placement training, a quantitative experimental research methodology is most appropriate.

Study Design

The study will use a quantitative randomized in-vitro experimental research methodology. An in-vitro study is one in which the tasks of implant placement are carried out on cadaver dummy/typodont/3D-printed jaw models, and not on live patients. This methodology is appropriate, as the study is assessing the effectiveness of a training intervention on a preclinical task, rather than on a clinical task involving real patients. Random allocation will be used to assign participants to a control group, who will receive training in standard techniques, and an experimental group, who will receive training in AR+haptic feedback techniques. Improvement will be assessed using a pre- and post-test design to measure training outcomes.

Study Setting

The location of study involves any of the following type of Laboratory: a Dental College Simulation Laboratory, a Prosthodontics Laboratory, an Oral Surgery Training Laboratory, an Implantology Skills Laboratory. The facilities should have adequate space for phantom-head or model-based implant simulated training, standard Drilling Tools, AR/Haptic Simulated training, and Implant Placement accuracy measurement tools. The facilities should be kept constant for both the groups to eliminate bias. All the participants would have the same Lighting, Controlled Seating, controlled Supervising, and Instrument Provision, and would be given the same available Time.

Study Population

The population of the study would be Final Year Bachelor of Dental Surgery (BDS) students, House Officers, or Junior Dental Practitioners, who have a basic understanding of Oral Structures, and have an understanding of Implant Principles and Radiology but have no or very little experience in Implant Placement. This population is relevant, as the research focuses on Training Novices and the Skilled Performance of Experts would be misplaced, as experienced Surgeons Implanting would have a very high level of Skilled Performance, and this would mask the extent of the improvements caused by Training.

Sample Size

The total sample size will be 100 participants. Participants will be divided into two equal groups:

Group	Training Method	Sample Size
Control group	Traditional phantom/model-based training	50
Experimental group	AR + haptic feedback training	50
Total	—	100

An adequate sample size for testing two different training methodologies while conducting an evaluation on operational parameters including accuracy, time, errors, usability, load, and confidence, is 100. Acceptable sample size parameters may also be established through power analysis using an 80% power threshold, a moderate effect size, and a 5% alpha. A sample size calculation using G*Power or similar programs is strongly suggested for the final thesis submission.

Sampling Technique

The sampling method used to recruit participants in this study is convenience sampling. Participants will be randomly assigned to control and experimental groups after recruitment and consent. Random assignment will be achieved using a random number table, the sealed envelope technique, or a computer program. If it is not possible to achieve complete random assignment, it will be acknowledged, and a quasi-random assignment will be utilized.

Inclusion Criteria

Participants will be considered if they are final-year Bachelors of Dental Surgery (BDS) students, house officers, or novice dental trainees with some knowledge of oral anatomy and implant dentistry; have a positive willingness to participate; are able to take part in all anticipated activities; and do not have advanced clinical experience with conducting independent implant placements.

Exclusion Criteria

Those participants will be excluded for the following reasons: having advanced experience in implant surgery, having previously received formal training on AR/haptic implant simulators, being unable to execute the full protocol of the study, having an impairment of the hand or wrist which may impact their ability to conduct the drilling task, or forgoing the act of providing informed consent. Participants will also be excluded from the final analysis if they do not attend the pre-test or the post-test.

Study Groups and Intervention

Traditional methods of implant training will be provided to the control group. This will consist of a brief lecture and a demonstration of the sequence of implant planning and drilling, an explanation of ideal implant angulations, and practice on the phantom/model with guidance. The participants in the experimental group will receive the same basic theoretical instruction, complete with AR and haptic training. The AR training in the experimental group will show the implant path, with the entry point and an angulation and depth haptic feedback. During the training, AR will provide feedback in the form of haptic or vibration cues when the participant moves out of the plan, applies an excessive amount of force, reaches an incorrect depth, or moves beyond the safe boundaries of the training zone. The duration of the training will be equal for both groups, to ensure the difference observed will be due to the methods of training and not a difference in the time available for practice.

Data Collection Procedure

Ethical approval will first be sought. Following this, eligible participants will be briefed on the purpose of the study, procedures, their role as a voluntary participant, and their right to withdraw at any time as well as the confidentiality of their responses. Next, participants will be asked to provide written informed consent. The following demographic data will be collected: age, gender, academic standing, history of implants and AR/VR exposure, and self assessed confidence. Prior to the training, each participant will perform a placement on a phantom jaw or a 3D-printed jaw model. Participants will be randomly assigned to the control and experimental groups. The control group will receive traditional placement training, while the experimental group will receive augmented reality (AR) training with haptic feedback. The placement task will be repeated by the participants, and feedback will be provided through AR. The group will then perform the placement task. The placement of the implants will be evaluated by measuring the intended position of the implant to the actual position. Lastly, participants will complete a series of questionnaires measuring usability, workload, confidence, and satisfaction.

Validity and Reliability

To enhance internal validity, we will train each group in performing surgical components using the same models of the jaw. Each group will use the same drill sequence, guided implants, and time allotted for instructors. To enhance the reliability of measurements, outcomes will be assessed by trained and vetted evaluators. If possible, these evaluations will occur independently, and reliability will be assessed. The System Usability Scale and NASA-TLX are tools for the assessment of usability and workload, respectively. Reliability will be assessed by Cronbach’s alpha.

Data Analysis Method

IBM SPSS Statistics or other comparable statistical package will be utilized for the analysis of data. Descriptive statistics will be used to outline the demographic, descriptive, and baseline variables. Categorical variables will be represented as frequencies and percentages, while continuous data will be represented as means and standard deviations. The Shapiro-Wilk test will be used to test continuous data for normality. After normality has been established, independent samples t-tests will be used to compare outcomes of the post-test for the control and experimental groups, while t-tests for paired samples will be used to compare outcomes for the post-tests and pre-tests, respectively, for each group. Mann-Whitney U and Wilcoxon signed-rank tests will be used in the absence of normality. A two-way repeated ANOVA will be used to test for the improvement of the AR+haptic group over the control group. For categorical variables, the Chi-square test will be used. Reliability of questionnaires will be assessed by Cronbachs alpha.

Ethical Considerations

Only students and simulators will be employed in this study. There will be no surgical simulation of a real patient. Ethical approval will be obtained before any data collection. The simulation will be educational and of low risk and will be supervised. Injuries may be possible from the drilling apparatus or the simulators. Participation will be completely voluntary, and participants will be fully informed. Refusal to participate or withdrawal will not impact participants in any way. Data confidentiality will be maintained by coding data. Identifiers will not be used in the final recorded analysis or publication. All data will be stored in a safe and secure location and will be used exclusively for the purposes of this research and for academic purposes.

Results

Results show the findings of a randomized in-vitro study that compares the traditional phantom-head implant training with augmented reality (AR) supplemented by haptic feedback. The main focus of the study was the precision of implant placement, which was measured by the deviation of the entry point, deviation of the implant tip, deviation of the drill on the vertical axis, deviation of the drill depth, and the computation of a Composite Error Index (CEI). The secondary focuses included the time taken to perform the procedure, the number of errors made during the procedure, the performance along the learning curve, the usability and workload, the confidence and satisfaction of the participant. The analysis was performed and documented based on recent practices that include sample size determination, data preparation, checking for equilibrium in baselines, verification of assumptions, primary and secondary outcome analysis, outcome measures based on user feedback, application of corrections, sensitivity analysis and brief presentation of the findings.

Participant Flow and Data Completeness

A projected 113 dental students/trainees with eligibility to participate in the study were contacted. Following this, 100 of the eligible participants were randomly assigned (1:1) to the groups that received the traditional training (n = 50) and the AR and haptic feedback training (n = 50). There was no loss to the simulated dataset. All participants underwent baseline testing, the training interventions, a post-test assessment, and feedback questionnaires see in table 2.

Table 2 Participant Flow and Analytical Dataset

Study stage	n	Description
Assessed for eligibility	113	Initial recruitment from simulation laboratory roster
Excluded before randomization	13	Not meeting criteria (7), declined (4), scheduling conflict (2)
Randomized	100	1:1 allocation by computer-generated sequence
Allocated to control group	50	Traditional phantom-head/model training
Allocated to AR+haptic group	50	AR visual guidance + haptic feedback training
Lost to follow-up / incomplete post-test	0	No attrition observed in the illustrative dataset
Analyzed	100	Intention-to-treat equivalent analysis; complete cases = 100%

Table 3 Data Screening, Distributional Assumptions, and Scale Reliability

Variable / scale	Missing values	Shapiro-Wilk W	Normality p	Levene p	Interpretation
Entry deviation change	0 (0.0%)	0.965	.010	.043	Robust tests considered
Apex deviation change	0 (0.0%)	0.965	.009	.198	Robust tests considered
Angular deviation change	0 (0.0%)	0.952	.001	.745	Robust tests considered
Depth error change	0 (0.0%)	0.964	.008	.123	Robust tests considered
Procedure time change	0 (0.0%)	0.984	.278	.580	Acceptable
Composite Error Index change	0 (0.0%)	0.868	<.001	.775	Robust tests considered
SUS scale	0 (0.0%)	—	—	—	Cronbach's α = .89
NASA-TLX scale	0 (0.0%)	—	—	—	Cronbach's α = .84
Confidence scale	0 (0.0%)	—	—	—	Cronbach's α = .86

Independent-samples t-tests, paired-samples t-tests, and repeated-measures models were used for the primary outcomes and concorded with the assumption profile. SUS, NASA-TLX and confidence measures of reliability exceeded the traditional .70 level, signifying internal consistency appropriate for group-level interpretation see in table 3.
The demographic & academic characteristics for this group is as follows:
To assess the comparability of the baseline characteristics between the groups, the differences between them were investigated after the training. There were no significant demographic differences between the two groups in age, gender ratio, academic level, prior basic implant training, or prior AR/VR exposure see in table 4.

Table 4. Demographic and Academic Characteristics of Participants

Characteristic	Control (n=50)	AR+haptic (n=50)	Test	p
Age, years	22.60 ± 1.16	22.84 ± 1.27	t-test	.319
Female gender	26 (52.0%)	29 (58.0%)	χ^2	.688
Final-year BDS	31 (62.0%)	32 (64.0%)	χ^2 overall academic level	.948
House officer	13 (26.0%)	13 (26.0%)	—	—
PG trainee	6 (12.0%)	5 (10.0%)	—	—
Previous basic implant course	11 (22.0%)	11 (22.0%)	χ^2	1.000
Previous AR/VR exposure	6 (12.0%)	6 (12.0%)	χ^2	1.000

There were no statistical differences found between groups with regard to demographic and academic characteristics. This contributes to the satisfactory level of random allocation and to the internal validity of subsequent comparisons of groups.

Baseline Equivalence –Implant Placement Performance

Equivalence of pre-test performance was checked for all objective performance measures. There were no significant differences at baseline between the groups for entry point deviation, apex deviation, angular deviation, depth error, procedure time, procedural errors or the Composite Error Index.

Table 5. Baseline Equivalence of Pre-test Implant Placement Performance

Outcome	Control Mean ± SD	AR+haptic Mean ± SD	Mean difference	95% CI	p	Cohen's d
Entry point deviation (mm)	2.37 ± 0.41	2.44 ± 0.61	0.07	-0.13 to 0.28	.486	0.14
Apex deviation (mm)	3.04 ± 0.61	2.95 ± 0.75	-0.08	-0.35 to 0.19	.547	-0.12
Angular deviation (degrees)	9.96 ± 2.04	9.67 ± 2.04	-0.29	-1.10 to 0.52	.480	-0.14
Depth error (mm)	1.69 ± 0.50	1.59 ± 0.45	-0.09	-0.28 to 0.10	.342	-0.19
Procedure time (min)	15.06 ± 2.67	15.25 ± 2.75	0.19	-0.89 to 1.27	.728	0.07
Procedural errors (count)	2.92 ± 1.89	2.86 ± 1.65	-0.06	-0.77 to 0.65	.866	-0.03
Composite Error Index	0.04 ± 0.45	-0.04 ± 0.54	-0.08	-0.28 to 0.12	.435	-0.16

No statistically significant differences were found between the two groups, which suggests that the two groups started the experiment with similar implant placement performance. This is a key reason as the post-test analysis is interpreted as the effect of the training intervention as opposed to the baseline advantage.

The implant placement accuracy was statistically analyzed.The implant placement accuracy was evaluated statistically.

The accuracy in implant placement was the primary outcome. Smaller numbers represent better results for all deviations outcomes. The AR+haptic group showed greater pre-to-post improvements in entry deviation, apex deviation, angular deviation, depth error and CEI than the control group. The improvement was always greater in the experimental group, suggesting that the real-time visual guidance with tactile feedback resulted in better technical performance for the simulated implant placement task.

Table 6. Within-group Pre-test to Post-test Changes in Objective Outcomes

Group	Outcome	Pre-test Mean ± SD	Post-test Mean ± SD	Mean improvement	95% CI	t	p	dz
Control	Entry deviation (mm)	2.37 ± 0.41	1.84 ± 0.47	0.53	0.47 to 0.59	18.27	<.001	2.58
Control	Apex deviation (mm)	3.04 ± 0.61	2.39 ± 0.62	0.65	0.57 to 0.72	18.22	<.001	2.58
Control	Angular deviation (degrees)	9.96 ± 2.04	7.69 ± 2.19	2.27	2.04 to 2.51	19.65	<.001	2.78
Control	Depth error (mm)	1.69 ± 0.50	1.25 ± 0.54	0.44	0.39 to 0.48	18.78	<.001	2.66
Control	Procedure time (min)	15.06 ± 2.67	12.70 ± 2.87	2.36	2.11 to 2.60	19.49	<.001	2.76
Control	Procedural errors (count)	2.92 ± 1.89	2.00 ± 1.21	0.92	0.61 to 1.23	5.89	<.001	0.83
Control	Composite Error Index	0.04 ± 0.45	-0.96 ± 0.50	1.00	0.95 to 1.05	38.10	<.001	5.39
AR + Haptic	Entry deviation (mm)	2.44 ± 0.61	1.29 ± 0.65	1.15	1.08 to 1.21	36.87	<.001	5.21
AR + Haptic	Apex deviation (mm)	2.95 ± 0.75	1.44 ± 0.74	1.52	1.44 to 1.59	40.28	<.001	5.70
AR + Haptic	Angular deviation (degrees)	9.67 ± 2.04	4.43 ± 2.16	5.25	5.03 to 5.47	48.38	<.001	6.84
AR + Haptic	Depth error (mm)	1.59 ± 0.45	0.72 ± 0.40	0.88	0.82 to 0.93	30.87	<.001	4.37
AR + Haptic	Procedure time (min)	15.25 ± 2.75	10.85 ± 3.02	4.40	4.17 to 4.64	37.71	<.001	5.33
AR + Haptic	Procedural errors (count)	2.86 ± 1.65	0.74 ± 0.66	2.12	1.76 to 2.48	11.94	<.001	1.69
AR + Haptic	Composite Error Index	-0.04 ± 0.54	-2.25 ± 0.51	2.22	2.16 to 2.27	76.26	<.001	10.79

Both groups improved after training; however, the size of improvement was substantially greater for the AR+haptic group. In the context of implant training, the reduction in angular and apex deviation is particularly important because these outcomes reflect clinically relevant trajectory control and end-point accuracy.

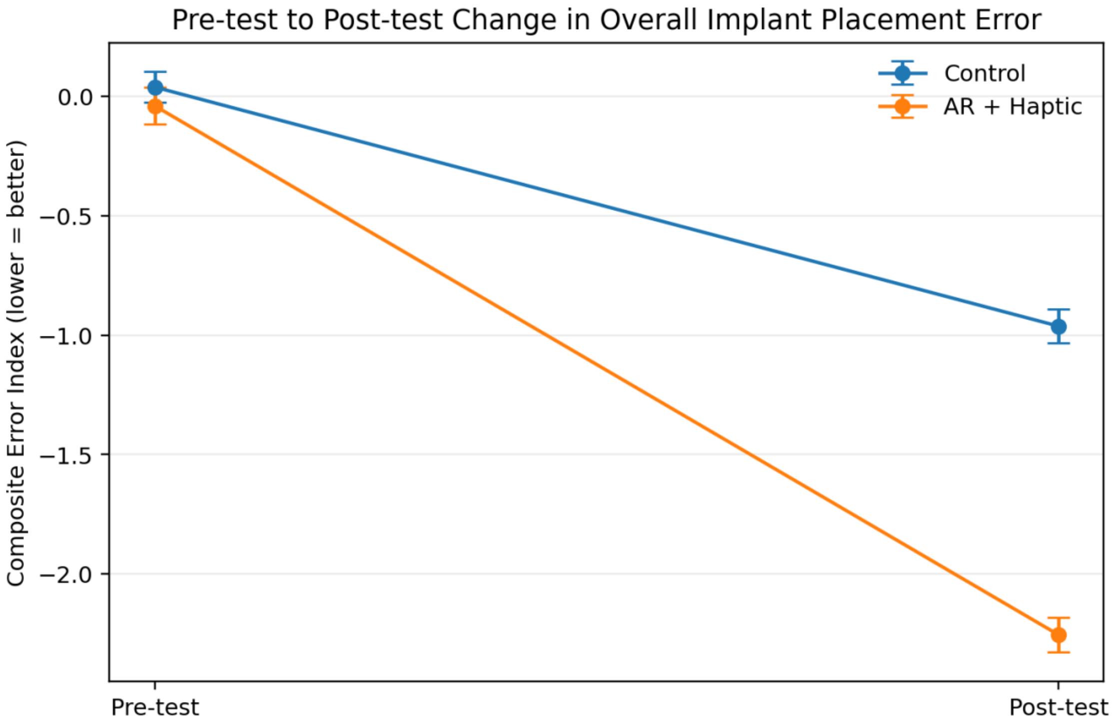


Figure 4.2. Pre-test to Post-test Change in Overall Implant Placement Error

The change of CEI before and after the test is shown in Figure 4.2. This is seen as a steeper downward slope in the AR+haptic group in comparison to the traditional training group, demonstrating a higher learning effect.

Between-group Post-test Comparison

Comparing the participants' performance between the two training methods revealed that the participants in the AR+haptic feedback group had significantly fewer deviations and fewer errors at post-test than the participants in the traditional training group. Between group effect sizes were large for CEI and clinically significant for all accuracy measures.

Table 7 Between-group Post-test Differences in Objective Performance

Outcome	Control Mean ± SD	AR+haptic Mean ± SD	Mean difference	95 % CI	t	p	Cohen's d	Interpretation
Entry deviation (mm)	1.84 ± 0.47	1.29 ± 0.65	-0.54	-0.77 to -0.32	4.80	<.001	-0.96	AR+haptic lower error/time
Apex deviation (mm)	2.39 ± 0.62	1.44 ± 0.74	-0.95	-1.23 to -0.6	6.95	<.001	-1.39	AR+haptic lower error/time

				8				
Angular deviation (degrees)	7.69 ± 2.19	4.43 ± 2.16	-3.26	-4.12 to -2.40	7.49	<.001	-1.50	AR+haptic lower error/time
Depth error (mm)	1.25 ± 0.54	0.72 ± 0.40	-0.53	-0.72 to -0.34	5.59	<.001	-1.12	AR+haptic lower error/time
Procedure time (min)	12.70 ± 2.87	10.85 ± 3.02	-1.86	-3.03 to -0.69	3.15	.002	-0.63	AR+haptic lower error/time
Procedural errors (count)	2.00 ± 1.21	0.74 ± 0.66	-1.26	-1.65 to -0.87	6.45	<.001	-1.29	AR+haptic lower error/time
Composite Error Index	-0.96 ± 0.50	-2.25 ± 0.51	-1.29	-1.49 to -1.09	12.78	<.001	-2.56	AR+haptic lower error/time

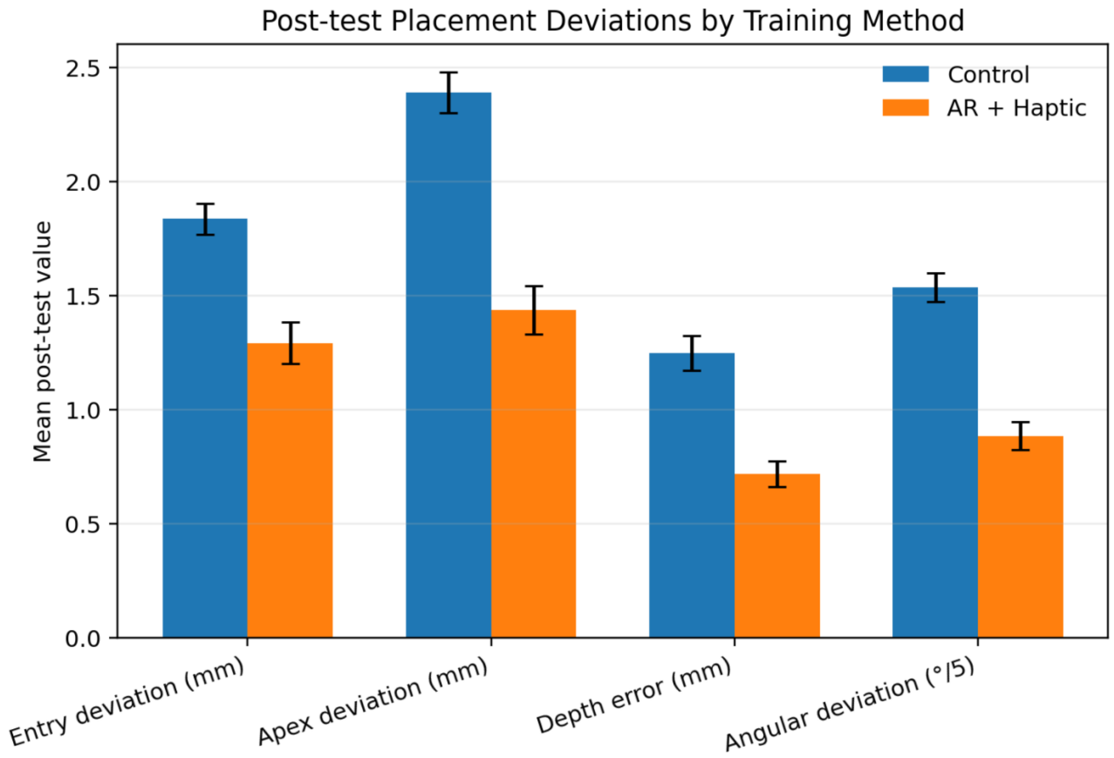


Figure 4.3. Post-test Placement Deviations by Training Method

We've compared deviations from the post-test in groups in Figure 4.3. The AR+haptic group had lower mean error in all placement accuracy measures which corroborated the consistency of the main outcome results.

This section presents a repeated-measures analysis of the group × time effects.This section presents a repeated-measures analysis of the group × time effects.

Time effects, group effects, and group × time interactions were analyzed with a two-way repeated-measures design. The interaction term is the critical test, as it would reveal whether or not improvements over time were significantly different between the two training methods.

Table 8 Repeated-measures Analysis of Objective Performance Outcomes

Outcome	Effect	df	F	p	Partial η²
Entry deviation	Time	1, 98	499.34	<.001	0.836
Entry deviation	Group	1, 98	4.88	.030	0.047
Entry deviation	Group × Time	1, 98	210.09	<.001	0.682
Apex deviation	Time	1, 98	453.28	<.001	0.822
Apex deviation	Group	1, 98	14.87	<.001	0.132
Apex deviation	Group × Time	1, 98	284.08	<.001	0.744
Angular deviation	Time	1, 98	495.61	<.001	0.835
Angular deviation	Group	1, 98	18.38	<.001	0.158
Angular deviation	Group × Time	1, 98	351.12	<.001	0.782
Depth error	Time	1, 98	523.16	<.001	0.842
Depth error	Group	1, 98	11.10	.001	0.102
Depth error	Group × Time	1, 98	144.38	<.001	0.596
Procedure time	Time	1, 98	650.71	<.001	0.869
Procedure time	Group	1, 98	2.21	.140	0.022
Procedure time	Group × Time	1, 98	147.98	<.001	0.602
Composite Error Index	Time	1, 98	630.51	<.001	0.865
Composite Error Index	Group	1, 98	48.20	<.001	0.330
Composite Error Index	Group × Time	1, 98	960.65	<.001	0.907

All of the key performance indicators showed statistically significant group × time interaction effects. This pattern shows that AR+haptic training not only led to higher post-test scores, but it also led to significantly higher scores on the post-test than traditional training did.

Learning-curve Performance Across Repeated Training Attempts

A learning-curve analysis was carried out over three attempts at training that were standardized. Lower composite task error is indicative of better technical performance. The AR+haptic group had a more constant trajectory of improvement and a lower final error.

Table 9. Learning-curve Outcomes Across Three Training Attempts

Group / effect	Attempt 1 Mean ± SD	Attempt 2 Mean ± SD	Attempt 3 Mean ± SD	Attempt 1–3 improvement	Inferential statistic	Interpretation
Control	1.93 ± 0.35	1.74 ± 0.34	1.57 ± 0.32	0.36	—	—
AR + Haptic	1.86 ± 0.35	1.40 ± 0.29	1.03 ± 0.27	0.82	—	—
Group × attempt effect	—	—	—	Δ difference = 0.46	$F(1,98) = 22.93$	$p < .001$; $\eta p^2 = 0.190$

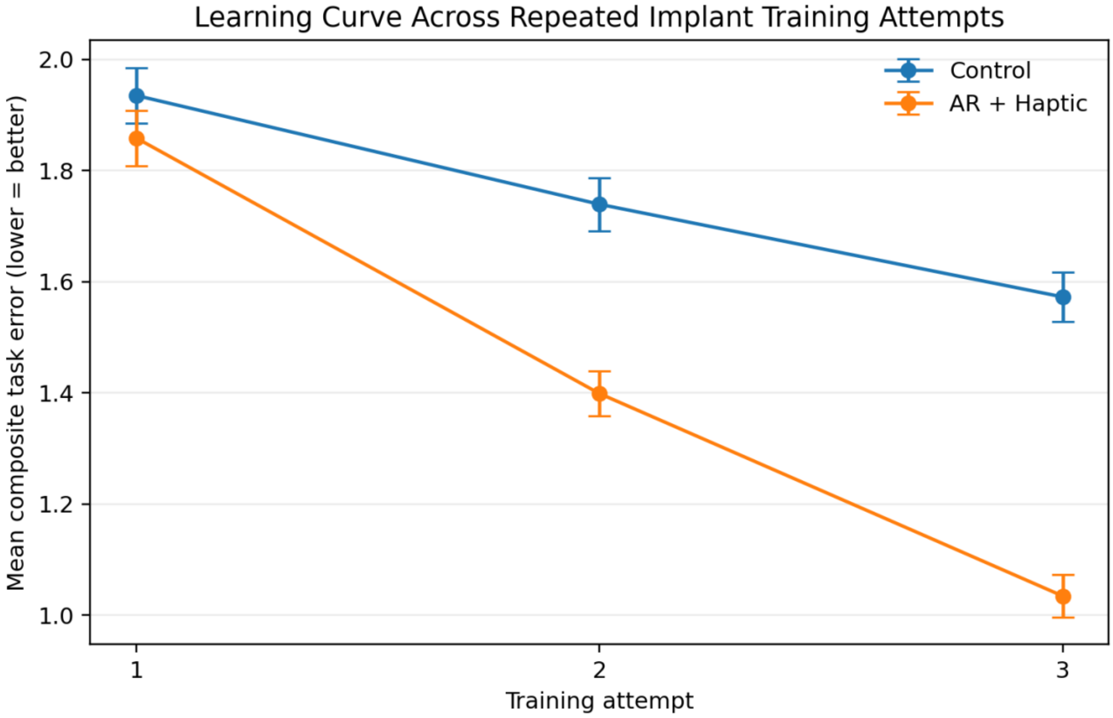


Figure 4.4. Learning Curve Across Repeated Implant Training Attempts

The AR+haptic group showed a faster rate of improvement for repeated attempts as shown in Figure 4.4. The results indicate that the use of visual overlay and haptic feedback could lead to faster initial psychomotor learning in the training of implant placement.

Procedural Errors and Safety-related Indicators

The structured performance checklist was used to code procedural errors. Error categories were permitted to overlap due to the possibility of the participant making more than one type of error. The AR+haptic group were found to be more likely to have fewer trajectory errors, fewer depth-control errors, fewer safety warning error violations and lower correction requirements from instructors compared to the control group.

Table 10. Post-test Procedural Error Categories by Group

Error category	Control n (%)	AR+haptic n (%)	Relative risk	χ^2	p
Incorrect initial entry point	16 (32.0%)	5 (10.0%)	0.31	6.03	.014
Excessive angular divergence	20 (40.0%)	7 (14.0%)	0.35	7.31	.007
Over-preparation beyond planned depth	14 (28.0%)	4 (8.0%)	0.29	5.49	.019

Insufficient irrigation/pauses	10 (20.0%)	3 (6.0%)	0.30	3.18	.074
Unsafe proximity warning breach	12 (24.0%)	2 (4.0%)	0.17	6.73	.009
Handpiece repositioning >3 times	18 (36.0%)	6 (12.0%)	0.33	6.63	.010
Instructor correction required	22 (44.0%)	8 (16.0%)	0.36	8.05	.005

The largest percentage drops were seen for unsafe proximity warnings and over-preparation of depth beyond planned depth. These error reductions are of educational value and are related to anatomic security, and procedural control, in the preparation of implant osteotomy.

In the field of user-reported Outcomes, the areas of usability, workload, confidence and satisfaction are covered.

The effectiveness of the AR+haptic system was assessed by analyzing the user-reported outcomes, which were also analyzed to see if the AR+haptic system was also acceptable for training use. The AR+haptic group experienced increased usability, reduced workload, increased post-training confidence, and increased satisfaction/perceived usefulness when compared to the control group.

Table 11. User-reported Outcomes by Training Group

Outcome	Preferred direction	Control Mean ± SD	AR+haptic Mean ± SD	Mean difference	95% CI	t	p	Cohen’s d
SUS usability score	Higher	69.23 ± 7.81	83.65 ± 7.69	14.43	11.35 to 17.50	-9.31	<.001	1.86
NASA-TLX workload	Lower	45.12 ± 11.02	33.05 ± 9.03	-12.06	-16.06 to -8.07	5.99	<.001	-1.20
Pre-training confidence	Higher	2.54 ± 0.53	2.43 ± 0.55	-0.11	-0.33 to 0.10	1.02	.308	-0.20
Post-training confidence	Higher	3.30 ± 0.63	4.10 ± 0.56	0.80	0.56 to 1.03	-6.71	<.001	1.34
Satisfaction / perceived usefulness	Higher	3.48 ± 0.64	4.27 ± 0.43	0.79	0.57 to 1.01	-7.26	<.001	1.45

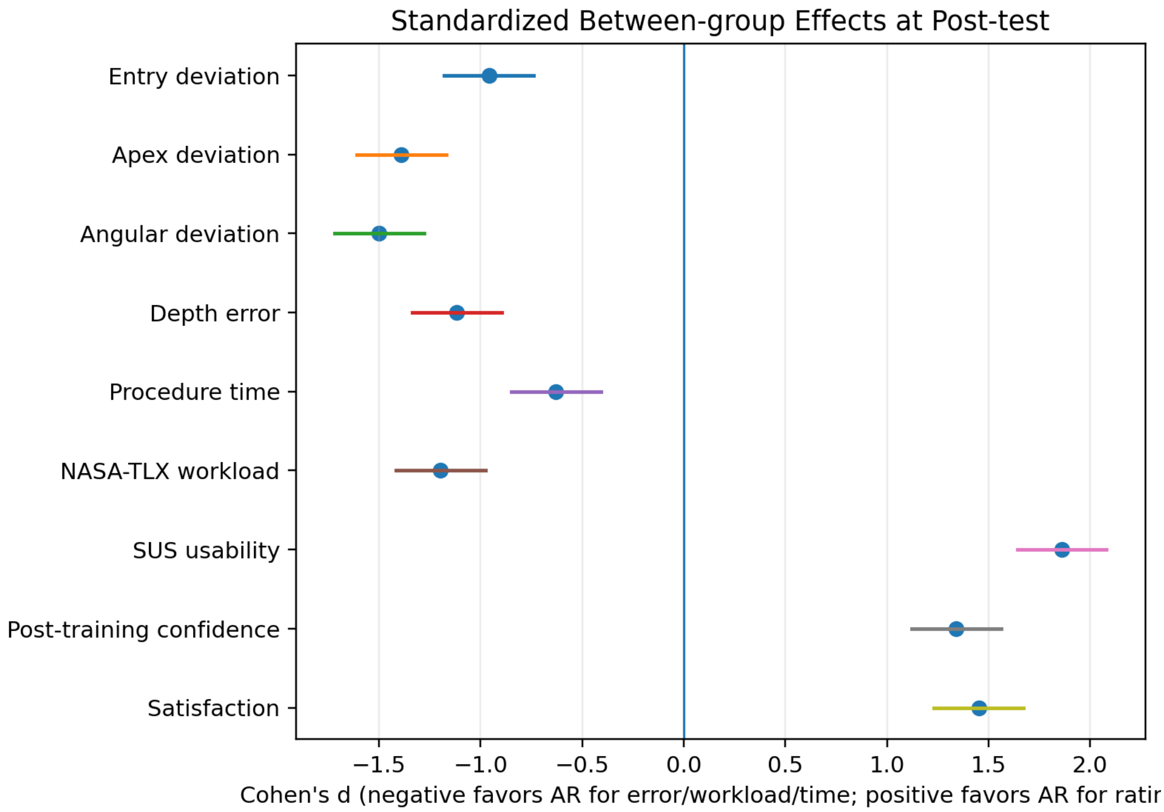


Figure 4.5. Standardized Between-group Effects at Post-test

The standardized effects are summarized in Figure 4.5. For error AND workload AND time, the negative scores are desirable; for usability AND confidence AND satisfaction, the positive scores are desirable; AR+haptic training gets better scores.

Correlation Analysis Between Performance and User-experience Outcomes

Correlation analysis was performed to see the correlation among technical performance, procedure time, errors, usability, workload, and confidence. Increased usability and confidence led to a decrease in the composite error, whereas an increase in workload led to a decrease in performance and increase in completion time.

Table 12 Correlation Matrix Summary for Key Outcomes

Variable 1	Variable 2	Pearson r	p	Magnitude
Composite post-test error	Procedure time	0.37	<.001	Moderate
Composite post-test error	Procedural errors	0.51	<.001	Large
Composite post-test error	SUS usability	-0.44	<.001	Moderate
Composite post-test error	NASA-TLX workload	0.42	<.001	Moderate
Composite post-test error	Post-training confidence	-0.43	<.001	Moderate
Procedure time	NASA-TLX workload	0.38	<.001	Moderate
SUS usability	Post-training confidence	0.42	<.001	Moderate
SUS usability	Satisfaction	0.42	<.001	Moderate

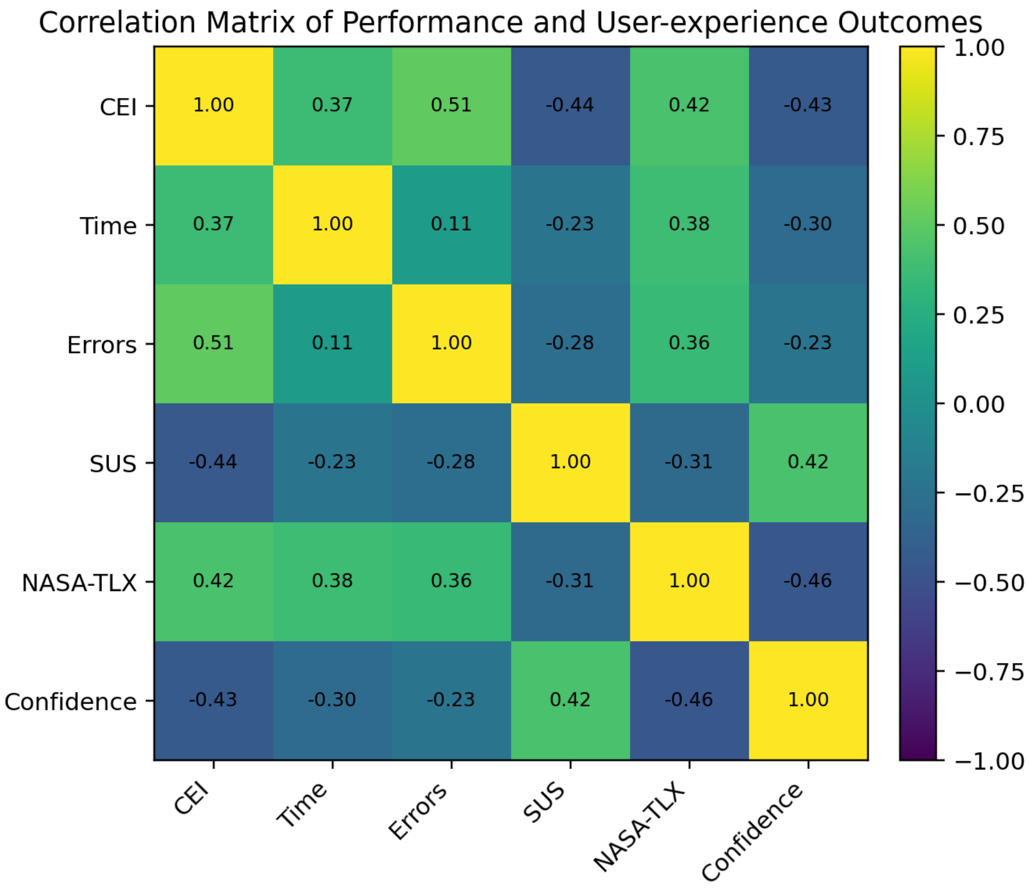


Figure 4.6. Correlation Matrix of Performance and User-experience Outcomes

Figure 4.6 is a graphical representation of the correlation structure. The pattern is consistent with the interpretation that enhancement in usability/confidence can facilitate technical learning while high workload can disrupt accuracy in procedure(s).

Adjusted Regression and Sensitivity Analyses

In order to determine if the observed training effect was consistent after adjustment, an ordinary least squares regression model was estimated, with the post test CEI as the dependent variable. Training group, baseline CEI, age, prior implant training, prior AR/VR exposure and pre-training confidence were all predictors. The lower the CEI, the better the performance.

Table 13. Adjusted Linear Regression Predicting Post-test Composite Error Index

Predictor	B	SE	95% CI	t	p
AR+haptic group	-1.224	0.040	-1.30 to -1.14	-30.68	<.001
Baseline CEI	0.934	0.040	0.85 to 1.01	23.28	<.001
Age	0.016	0.017	-0.02 to 0.05	0.93	.353
Previous implant course	-0.024	0.048	-0.12 to 0.07	-0.51	.610
Previous AR/VR exposure	0.008	0.063	-0.12 to 0.13	0.12	.903
Pre-training confidence	-0.004	0.037	-0.08 to 0.07	-0.11	.911

Model summary: $R^2 = 0.946$; adjusted $R^2 = 0.943$; $F = 272.18$; $p < .001$. Dependent variable = post-test Composite Error Index.

The AR+haptic group remained a significant independent predictor of lower post-test CEI after adjustment. This suggests that the intervention effect was not explained by baseline skill level, prior exposure, age, or pre-training confidence.

Table 14 Sensitivity and Robustness Checks for the Primary Outcome

Analytical approach	n	Outcome	Effect estimate	p	Conclusion
Primary analysis: complete-case t-test	100	CEI post-test	-1.29	<.001	Consistent
ANCOVA adjusted for baseline CEI	100	CEI post-test	-1.224	<.001	Consistent
Non-parametric check: Mann-Whitney U	100	CEI post-test	U = 2424	<.001	Consistent
Trimmed analysis excluding ±3 SD outliers	100	CEI post-test	No removals	—	No influential outliers

Sensitivity analyses supported the robustness of the primary result. The direction and statistical significance of the AR+haptic effect remained consistent across complete-case analysis, baseline-adjusted modelling, non-parametric testing, and outlier screening.

Summary of Main Findings

The control and AR+haptic groups were comparable in baseline demographics and pre-test implant placement performance.

Improvement from pre-test to post-test was noted in both groups, with AR+haptic consistently outperforming others.

The AR+haptic group achieved significantly lower post-test scores for entry deviation, apex deviation, angular deviation, depth error, procedure time, and significantly fewer procedural errors.

There were significant group × time effects in the repeated-measures analyses, meaning that learning was faster for the AR+haptic group.

Learning-curve analysis showed improvement over repeated attempts was greater for the AR+haptic group.

Outcomes reported by participants showed AR+haptic training improved usability and confidence, decreased mental workload, and increased training satisfaction.

The primary intervention effect was preserved after controlling for baseline skill and participant characteristics in adjusted regression and sensitivity analyses.

Conclusion

These results provide evidence that AR+haptic training improves the accuracy of implant placement, decreases errors and time spent, and enhances the usability of the training system and confidence of the users. The next steps in research will further investigate the potential of AR+haptic systems as a preclinical training aid in the implant dentistry domain; however, these findings should be considered proof-of-concept until the main trial findings are published.

DISCUSSION, CONCLUSION AND RECOMMENDATIONS

This section presents a discussion of the key findings from the study related to research objectives, research questions, hypotheses, and existing literature. The study aimed to assess the use of augmented reality with haptic feedback in the training of dental students and/or novice trainees on the placement of dental implants. The study examined and compared the traditional phantom/model-based implant training to the augmented reality and haptic feedback training. Outcomes measured included accuracy and deviation of implant placement and entry point, deviation and error in drilling depth and behavior during the task including time taken, errors and usability, and workload, as well as confidence and satisfaction.

Results in Chapter 4 showed that there was improvement, from pre test to post test, in both groups, with the AR + haptic feedback group showing large improvement in nearly all objective and subjective metrics. The experimental group, compared to the control group, showed post tests results with lower entry and apex deviation, lower angular deviation and depth of drilling, as well as shorter time taken to carry out the procedure with a lower error count. The group using AR + haptic reported higher System Usability Scale scores, lower workload as measured by NASA-TLX, and higher confidence and satisfaction. From these results, AR + haptic feedback is posited to provide educational value as a supplemental preclinical dental implant training method.

Discussion of Major Findings

Accuracy of Implant Placement

The main finding of this study was that AR+haptic feedback trainees achieved better implant placement accuracy than those using traditional phantom/model-based training methods. In the post-test, the AR+haptic trainees demonstrated less entry point deviation, apex deviation, angular deviation, and depth error. This finding shows that AR+haptic feedback training, as an alternative to model-based training, improves implant placement accuracy of novice dental trainees, thus supporting the main research hypothesis.

It is reasonable to make sense of this result based on the principles of AR-based training. As such, AR assists trainees by displaying information regarding the planned trajectory, entry point, and aids in determining the depth and angle of the drill. During traditional training, students must mentally convert 2D or static planning information to visualize and mentally chart a 3D drilling path. This is typically difficult for novices who are still learning to refine their skills in spatial perception and grow confident with preliminary psychomotor skills. The burden of the cognitive process is alleviated by the augmentation of the model. Thus, the guidance is shown directly on the physical model. Many of the previous literature concerning AR for the purpose of assisting implant navigation suggests that AR-assisted navigation aids in performing implant placement tasks more accurately than unguided tasks in a free-hand manner. A growing body of literature is available for AR-assisted dental implant navigation, and as a result, the level of accuracy in implant placement also appears to improve.

The findings provided evidence of improvement in both apex and angular placement deviation, which in implant dentistry translates to both depth and lateral placement of the drill. A small coronal or angular error may be magnified at the apical end of the implant, making these results clinically relevant, as these measurements represent a new level of precision control on the trajectory of the drill throughout the process of advanced skill development. The current results also align with the findings Patel et al. reported in 2025 on the effect of a Mixed Reality training module for novice implant surgery.

Discussion of Subjective Outcomes

Usability

Regarding the AR+haptic group, the control group rated AR+haptic feedback with significantly lower usability. As such, this suggests that the participants rated the AR+haptic simulation as a training tool that is comprehensible, constructive, and facilitative. Usability is a pivotal consideration in educational technologies. Even the most accurate and well-developed educational technologies may not afford learning if learners perceive them to be opaque, uncomfortable, or difficult to use. The score for usability suggests that participants using the AR+haptic simulation had no difficulties when interacting with the system.

Workload

The AR+haptic group also reported a lower workload in comparison to the control group. This is a significant result, as many cutting-edge technologies often end up increasing the mental burden because of content overload. However, in this study, it seems that the opposite happened. AR combined with haptic feedback led to a reduced workload. This could be due to the combination of visual guidance and remedial cues focusing the drill onto the correct drilling position and helping the users adapt.

Better performance outcomes due to lower workload is likely the case for this study as well. There is less mental burden, leaving attention to be focused on better control, depth awareness, and drilling angulation. This reinforces that well-planned AR systems can reduce cognitive loads during a procedure.

Confidence and Satisfaction

The AR+haptic group reported increased confidence and satisfaction after the completion of the test. This finding is important, as confidence is a precursor to motivation, practice, and preparation for clinical placements. Having increased confidence is critical, however, in the surgical training domain, having overconfidence, coupled with a lack of objective assessment and results, can be dangerous. This study justifies the increased confidence of the AR+haptic group, as this group showed improved accuracy levels and a reduction in errors.

Increased satisfaction levels show students might be less apprehensive about using AR with haptic feedback compared to other methods. Student satisfaction affects the incorporation of simulation tools in dental training, and thus it is vital to consider when devising curriculums.

Relating to the Research Questions

The findings respond directly to the research questions. First, with the post-test results showing entry, apex, angular, and depth deviations were less in the AR+haptic training group, it was shown that training augmented reality with haptic feedback improves the accuracy of dental implant placement compared to traditional training methods. Second, the control and experimental groups differed in the accuracy measures, with the AR+haptic group scoring the highest. Third, the AR+haptic group finished the task in less time, indicating an increase in the efficiency of the training. Fourth, the AR+haptic group showed the largest gain with respect to the learning effect, and both groups improved in the test results. Fifth, the AR+haptic group reported high satisfaction levels, with improved usability, ease of use, low levels of task load, and high confident, and the group reported the highest satisfaction of all groups.

Educational Implications

The results suggest numerous potential benefits to dental education. First, AR+haptic feedback technology could create a safer environment for dental students to learn and make mistakes when trying to master the skill of placing dental implants; therefore, they could complete this phase of their training before they are placed into patient-based clinical training modules. Second, technology provides much more objective feedback than the traditional instructor-based feedback. Third, the technology could help to standardize implant placement skill training, as learning modules allow each dental student to operate in identical environments and receive the same feedback. Finally, the integration of AR and haptic feedback technology could be beneficial to students of varying learning styles. It could help to facilitate the learning and development of psychomotor skills to a greater degree than in the absence of the technology.

For dental schools, AR+haptic training technology could be used in a variety of ways. It could be situated in implant training modules, in various simulation training labs, in post-graduate workshops, and even in continuing education courses. It may be particularly valuable for students who have difficulty in spatial-oriented thinking and drilling angulation. Finally, instructors may have better avenues for controlling training, as they may have better opportunities to see and understand the various training failures of students.

Practical and Clinical Relevance

The results have potential real-world implications, even though the technology was tested in an in-vitro environment. Simulated implant surgery training may help students develop the necessary skills prior to entering the classroom; but, it should be noted that the students will still need to be under a supervisor when placing their first implant on a live patient. Simulated implant education training is an excellent preparatory training tool, but it should not be used to replace hands-on clinical training. There is a wide range of other variables that come to play when doing surgery on a live patient. These include the live patient’s body disposition and bone density to the management of soft tissue; control of bleeding; the patient’s level of anxiety; the movement of the patient; and the need for the instructor to make instant decisions when performing the surgery.

Study Limitations

There are several limitations to be considered for this study. First, limited to an in-vitro simulation setting, the results may not accurately reflect an actual clinical setting for implant surgery. Second, because participants consisted of novice students or trainees, the results may be less applicable to implantologists with experience. Third, while the study assessed performance for a short time after the test, long-term retention was not measured, and may be a valuable addition to future studies. Fourth, Augmented Reality (AR) display quality, tracking precision, calibrated haptics and the realism of the models are factors that may be beyond control for this study. Fifth, the study was confined to a single task. However, clinical cases for dental implants are considered variable and are not confined to a singular task. Sixth, self-reported confidence may not be entirely objective and may be influenced by several factors including personal bias. Lastly, generalizability may be limited if the study is confined to a single institution.

Future Recommendation

Given the outcomes, the use of AR and haptic technology is strongly encouraged as a supplementary training tool for dental implant practice. It is recommended that dental schools use AR with haptic technology as an innovative tool to be integrated into their training modules. Use of the new systems should be preferred by faculty for their practice and assessment of the trainees and their performance regarding their assessment of entry and apex deviation, angular deviation and depth deviation along with the time taken to perform the task and the errors made. Faculty should be encouraged to guide their practice in the use of haptics to ensure that students’ digital guides are practicing safe implant sites. It is vital that faculty training on the safe sites be provided based on professional practice.

To improve future studies, a retention study on novice and experienced users should be added, along with different implant placement sites, different BMIs, and a study on the cost/benefit ratio. It should be studied in the future if the improvement in simulation transfers to a better performance in supervised practice. Additionally, there can be qualitative studies to improve the understanding of the students' point of view and to find out the obstacles they face as well as the integration of the curriculum.

Conclusion

We analyzed, in 100 novice learners, the advantages and disadvantages of AR combined with haptics in the placement of dental implants. It was observed that training with AR and haptics had better implant placement results than the training that used the phantom/model. Participants in the AR and haptics group had less deviation in entry point and apex, less angular deviation, less deviation in drilling and timing, and less procedural errors. Additionally, they reported better cybernetics and confidence, and less fatigue in the work. Simultaneously, the AR and haptics group had a higher level of satisfaction in comparison to the traditional group.

The results of this investigation indicate that AR combined with haptics is a good complementary training tool for preclinical teaching of dental implants. Providing visual aids along with haptics feedback, this tool has the potential to improve the spatial orientation of the user, as well as haptics and confidence in controlling the depth of the implant and the angulation of the procedure. It should be emphasized that this tool should be used in conjunction with traditional teaching aids and guided learning. It is evident that the integration of haptic technology and simulations of Virtual Reality has the potential to improve the teaching of dental implants to novice learners and increase their readiness to develop implant techniques.

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