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Impact of Virtual Reality and Haptic Simulators in Dental Education and Training Among Dental Students: An Umbrella Review

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ABSTRACT

Objectives: To synthesise and critically appraise systematic reviews evaluating the impact of virtual reality (VR) and haptic simulators on dental students' learning outcomes in preclinical and clinical education.

Methods: Three databases were searched from January 2011 to June 2025. Eligible evidence comprised only systematic reviews (with/without meta-analysis) published in English which focused on undergraduate or postgraduate dental students using VR, haptic, or integrated VR–haptic simulation for skills training. Two reviewers independently screened records, extracted data, appraised methodological quality using A MeaSurement Tool to Assess systematic Reviews 2 (AMSTAR 2), and calculated the Corrected Covered Area (CCA) to assess citation overlap.

Results: Six systematic reviews met the inclusion criteria; one included a meta-analysis reporting a significant performance advantage after haptic-simulator training, albeit with very high heterogeneity ($I^2 = 92\%$). Across reviews, VR–haptic training was consistently associated with improved preclinical performance (accuracy, error reduction, efficiency) and greater learner confidence, with the strongest evidence in restorative dentistry and supportive signals in endodontics, implantology, periodontics, paediatric dentistry, radiology and oral & maxillofacial surgery. Methodological confidence was limited: AMSTAR 2 ratings were low to critically low. Overlap analysis indicated moderate redundancy (CCA = 6.05%), suggesting some recirculation of primary trials across reviews.

Conclusions: VR and haptic simulators confer meaningful advantages for preclinical acquisition and learner confidence in dental education, but certainty is tempered by methodological weaknesses and substantial heterogeneity. Their optimal role is as high-fidelity adjuncts within blended curricula.

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1 | Introduction

Dental education has consistently embraced technological innovation to meet evolving pedagogical needs, professional standards and competency frameworks [1, 2]. The early years of training demand mastery of fine psychomotor skills, tactile sensitivity and spatial reasoning in simulated environments, which are subsequently refined in clinical settings [3–5]. This preclinical–clinical transition is pivotal for building student confidence, sustaining motivation and preparing for safe patient care. Traditionally, preclinical instruction has relied on manikin-based exercises [6, 7], which provide structured opportunities for practice but lack the adaptability, real-time feedback and fidelity to clinical reality necessary to optimise skill transfer [7–10].

Advances in immersive technologies, most notably virtual reality (VR), haptic simulation, the metaverse, and augmented reality (AR), have introduced new pedagogical opportunities across the fields of medicine and dentistry [11–17]. VR technologies have long roots in aviation and military training, but only in the past two decades have they been more widely adopted in education, driven by improvements in computational power, graphics processing and display fidelity [18, 19]. Within dentistry, the integration of VR with haptic feedback represents a significant evolution in simulation. By combining three-dimensional visualisation with tactile sensation, VR-haptic platforms enable students to experience enamel cutting, dentine resistance and force modulation with a degree of realism unattainable in conventional methods. Since their introduction in the early 2010s, haptic-enabled trainers such as the Simodont Dental Trainer have expanded in reach, with adoption accelerating after 2020 as the COVID-19 pandemic catalysed global acceptance of digital and virtual learning technologies [20, 21].

The educational value of VR-haptic systems is increasingly documented. Evidence indicates that these simulators enhance psychomotor performance, procedural accuracy, ergonomic posture and learner confidence, while simultaneously reducing stress and anxiety in preclinical environments [11, 22–24]. These technologies further offer the advantage of integrated analytics, capturing performance metrics such as convergence angles, preparation depths and error counts, thereby enabling objective, data-driven feedback and longitudinal monitoring of progress.

Despite these advances, the global uptake and effectiveness of VR-haptic technologies remain inconsistent. High acquisition and maintenance costs, technical infrastructure requirements and the need for faculty training continue to present barriers [23, 25]. Faculty knowledge and perceptions are particularly influential in determining adoption. Generally, while students and educators frequently report positive attitudes towards VR-haptic tools, relatively few institutions have fully integrated them into their teaching programmes [12, 26, 27]. Even when systems such as Simodont are incorporated, their effectiveness is moderated by contextual factors including staff readiness, teaching styles and curricular alignment. Furthermore, although studies consistently demonstrate improvements in motivation, engagement and early psychomotor skills, questions remain regarding cost-effectiveness, sustainability of outcomes and transferability to real patient care.

In this context, an umbrella review provides a timely and rigorous means of consolidating the evidence base. By synthesising and critically appraising multiple systematic reviews, this method offers a higher-order perspective on the consistency, strength and limitations of current findings. For dental educators, curriculum committees and policymakers, such synthesis is essential for making informed decisions about the integration of VR and haptic simulators into training programmes. Hence, the present umbrella review aimed to evaluate and critically appraise systematic reviews examining the impact of VR and haptic simulators on dental students' learning outcomes in preclinical and clinical education. By providing the most comprehensive synthesis to date, this work seeks to clarify the role of immersive simulation technologies in competency development and inform both educational practice and future research in dental training.

2 | Materials and Methods

2.1 | Protocol and Registration

This umbrella review was prospectively designed in accordance with the Preferred Reporting Items for Systematic Review and Meta-analyses (PRISMA) 2020 guidelines [28]. The protocol was registered on the International Prospective Register of Systematic Reviews (PROSPERO) [29], University of York (CRD420251123272), to enhance methodological transparency and reduce the potential for selective reporting. The PICO framework was defined as follows: (1) Population: undergraduate or postgraduate dental students enrolled in recognised programmes and undertaking preclinical or clinical skills training; (2) Intervention: virtual reality (VR) simulators, haptic-enabled simulators, or integrated VR–haptic systems used for teaching and assessment across any dental discipline; (3) Comparison: conventional instruction or alternative simulation modalities where available, with no comparator required for eligibility at the review level; (4) Outcomes: educational and skill-based measures including psychomotor accuracy, procedural quality, efficiency and time-on-task, error reduction, ergonomic posture, knowledge acquisition, confidence and stress or anxiety. Hence, the review question was: 'What is the effectiveness and current practice of utilising VR and haptic simulators in dental education for improving learning and competency outcomes among dental students?'

2.2 | Search Strategy

A comprehensive search was independently conducted by two reviewers (AFL and NDAZ) across three databases: PubMed, Scopus, and Web of Science, for records published from January 2011 to June 2025. Search strings combined controlled vocabulary and free-text synonyms for immersive technologies. Database-specific strategies combined controlled vocabulary and free-text terms for dental education and learners (e.g., MeSH terms 'Education, Dental' and 'Students, Dental'; free-text 'preclinical dental education', 'clinical dental education', 'dental

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students'), immersive and simulation technologies (e.g., MeSH 'Virtual Reality', 'Computer Simulation', 'Simulation Training'; free-text 'virtual reality', 'VR', 'dental simulators') and haptics (e.g., MeSH 'haptic interfaces', 'haptic technology'; free-text 'haptic*'). Review filters were applied using publication types and title/abstract terms ('Systematic Review', 'Meta-Analysis', 'umbrella review', 'review of reviews'). Equivalent logic was implemented in Scopus with TITLE-ABS-KEY constructs (e.g., haptic AND (dental OR dentistry) AND training AND ('systematic review' OR 'umbrella review')) and in Web of Science with All Fields combinations (e.g., haptic AND dental students AND systematic review). No language limits were applied at the search stage. All records were exported to EndNote 20 for de-duplication and imported into Covidence for independent title/abstract and full-text screening. Reference lists of included articles were hand-searched to identify additional studies. Discrepancies between reviewers were resolved through discussion and consensus. No language restrictions were applied at the search stage.

2.3 | Inclusion and Exclusion Criteria and Study Selection

After de-duplication, two investigators (AFL and NDAZ) independently screened titles and abstracts, followed by full-text assessment against pre-specified criteria. Eligible evidence consisted of systematic reviews, with or without meta-analysis, that examined immersive simulation in dental education. Interventions of interest were virtual reality platforms designed for dental training, haptic-enabled dental simulators such as Simodont and Virteasy that provide tactile feedback, and integrated VR–haptic systems. We included reviews in which the exposure comprised preclinical or clinical training activities aimed at skill acquisition in dentistry, used either as adjuncts or alternatives to conventional teaching, and applicable across any dental discipline, such as restorative dentistry, endodontics, prosthodontics, oral surgery, and orthodontics. We excluded reviews evaluating augmented reality in isolation without VR or haptic components, non-immersive computer-assisted learning such as 2D videos or static e-learning modules, conventional manikin-based simulation without haptic feedback, and interventions focused solely on non-dental clinical skills. Reviews in which VR or haptic technology was not the primary instructional or assessment modality were also excluded. Calibration exercises were undertaken between two raters (AFL and NDAZ) [11]. The decision reached a substantial agreement, with a Cohen's Kappa score of $\kappa = 0.82$ after two calibrations were undertaken to assess interrater reliability (IRR) [11, 30, 31]. Discrepancies at any stage were resolved through discussion with the third and fourth reviewers (GSSS and MN) until consensus was achieved.

2.4 | Data Extraction

Two investigators (AFL and NDAZ) independently retrieved data from the included systematic review into customised Microsoft Excel spreadsheet extraction forms. Data extracted includes the author's name, year of publication, title, study type, search period, number of studies included, study design included, study objective, population, intervention, comparator, outcome measured, discipline, sample size range, conclusion, risk of bias evaluation tools and presence of meta-analysis. Any discrepancies among the reviewers were resolved through discussion until a consensus was achieved.

2.5 | Risk of Bias Assessment

Two investigators (AFL and NDAZ) evaluated the risk of bias (RoB) of the included systematic reviews independently using the Assessment of Multiple Systematic Reviews (AMSTAR) 2 checklist. The 16 domains are each responded to with a 'yes', 'partial yes', or 'no' based on the given criteria [32]. The response 'no meta-analysis conducted' was given to systematic reviews that did not involve meta-analysis. The AMSTAR 2 paper by Shea et al. (2017) [32] was referred to for correct comprehension before the assessment. The overall quality of each systematic review was given a rating of either 'high', 'moderate', 'low' or 'critically low' based on the response to the domains. Seven domains, specifically domains 2, 4, 7, 9, 11, 13 and 15, were considered critical domains for a systematic review with meta-analysis. However, domain 11 was not considered a critical domain when no meta-analysis was done. The guide for evaluating the overall confidence is: (1) high: no or one non-critical weakness, (2) moderate: more than one non-critical weakness, (3) low: one critical flaw with or without non-critical weaknesses, and (4) critically low: more than one critical flaw with or without non-critical weaknesses [32]. The two investigators achieved consensus for the assessment of bias.

2.6 | Degree of Overlap Between Studies

Redundancy of primary evidence across reviews was assessed by constructing citation matrices and calculating the Corrected Covered Area (CCA) [33]. CCA quantifies the proportion of repeated citations after adjusting for the number of reviews and unique primary studies and was computed as $CCA = (N - r)/[r \times (c - 1)] \times 100$, where N is the total number of primary-study citations across reviews, r the number of unique primary studies and c the number of reviews. Overlap was interpreted using established thresholds: slight (0%–5%), moderate (6%–10%), high (11%–15%), and very high (>15%) [33, 34].

3 | Results

3.1 | Study Selection

The screening process is summarised in Figure 1. A total of 119 records were identified from three databases (Web of Science, $n = 100$; Scopus, $n = 14$; PubMed, $n = 5$). Two duplicate records were removed before screening, leaving 117 records for title and abstract review. Automation tools flagged 102 records as ineligible and removed a further six as duplicates; one additional record was excluded as irrelevant. Six reports were sought and successfully retrieved for full-text assessment, all of which met

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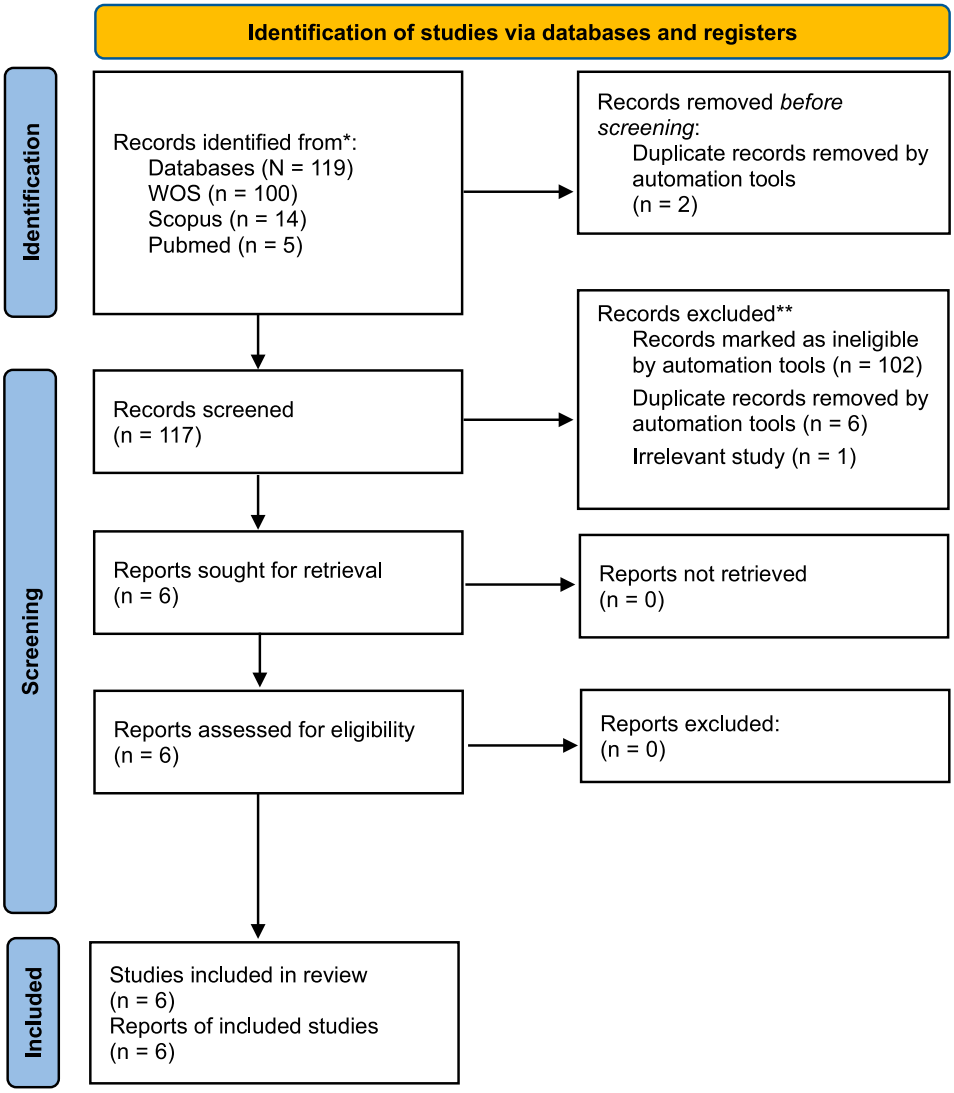


FIGURE 1 | PRISMA flow diagram summarising study selection: Records identified, screened, excluded (with reasons), and studies included in the umbrella review.

the inclusion criteria. Consequently, six systematic reviews were included in the umbrella synthesis.

3.2 | Characteristics of the Included Studies

Six systematic reviews were chosen after the study selection process, and their characteristics are summarised in Table 1. All the articles were published within the last 5 years (2021–2025), with only one of them containing a meta-analysis. All reviews employed at least three search engines, and the search queries were reported. The reference lists were also considered during the literature search in four of the systematic reviews [35–38], while one review also searched for grey literature [39], and another review explored study registries [35]. Only one systematic review included fewer than 10 primary studies [38], whereas Moussa et al. (2021) [37], included 73 primary studies in their review. All systematic reviews included randomised clinical trials. Non-randomised clinical trials were included in three review papers [35, 37, 40], while cohort studies were found in three review articles [36, 38, 39]. No review had incorporated case reports or case series in its selected studies.

A total of 10 122 samples were included in the current umbrella review. All reviews included the components of PICO in their protocol, where the population was dental students, the intervention was virtual reality devices, and the comparator was conservative training or no comparator. The outcomes measured varied between psychomotor skills acquisitions, procedural competencies, theoretical test scores, perceptions, and ergonomic development. One systematic review focused solely on Simodont [38], while other reviews focused on various virtual reality tools, including haptic devices, navigation systems and visuo-tactile VR. Four systematic reviews incorporated several disciplines in dentistry in their studies [35–37, 40], like restorative dentistry, endodontics, oral and maxillofacial surgery and periodontics, while two reviews focused on restorative dentistry alone [38, 39].

Heterogeneity was reported in four systematic reviews [35–37, 40], due to different types of VR devices used, while Patil et al. (2023) [38] reported heterogeneity in results, as one of the included studies

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TABLE 1 | Characteristics of the included studies.

Author (Year)	Search period	Study design included	Objective	Discipline	No. of study	Sample size (range & participants No.)	Population (P); intervention (I); comparator (C)	Outcomes measured (O)	Risk of bias evaluation tools	Conclusion
Javed et al. (2025) [35]	2010 until 2024	RCTs, non-randomised studies, quasi-experimental studies, systematic reviews, observational studies	To systematically evaluate the effectiveness of VR simulation in endodontic education	Dental anatomy, Endodontic, Restorative	15	5–199 (total $n = 737$)	P: Undergraduate dental students (postgraduate and experts included in 1 study) I: VR, with or without Haptic Technology (HT) C: Phantom head, no control, or unclear control	Procedural accuracy, efficiency, confidence, error reduction, and satisfaction	RoB-2, Newcastle Ottawa Quality Assessment Scale, MINORS	There is a significant impact of VR simulation on improving procedural accuracy, student confidence, and error reduction in endodontic education. No meta-analysis conducted.
Bandiaky et al. (2024) [36]	Up to Feb 2023	RCT, CST, CT, CCO, RCS	(1) To evaluate the impact of haptic simulators in preclinical dentistry education in terms of motor skill acquisition (2) To determine the learners' perception of the use of those simulators (3) To determine their ability to discriminate users according to their initial level of manual dexterity.	Restorative, Implantology, Prosthodontic OMFS, Periodontics, Endodontics, Paediatric Dentistry	23 (only 22 listed)	20–163 (total $n = 1303$)	P: Dental students enrolled in a traditional program of motor skills teaching in preclinical dental training (volunteers, non-dentists, and experienced practitioners included in some studies) I: Haptic simulators (IDEA, VirTeaSy, Simodont, UniDental, HVRS) C: Conventional simulators	-Primary: Motor skill acquisition in preclinical dentistry. -Secondary: participants' perception of using the haptic simulators, the ability of haptic technologies to discern the users according to the initial level of their manual dexterity	Cochrane Handbook for RCT, Tsirogiannis et al.	Haptic simulators can significantly improve the acquisition, maintenance, and transfer of motor skills. The new digital technology is well perceived by participants and shows encouraging results regarding its ability to discriminate against users based on their initial level of manual dexterity. No meta-analysis conducted.

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TABLE 1 | (Continued)

Author (Year)	Search period	Study design included	Objective	Discipline	No. of study	Sample size (range & participants No.)	Population (P); intervention (I); comparator (C)	Outcomes measured (O)	Risk of bias evaluation tools	Conclusion
Moussa et al. (2021) [37]	Jan 2010–March 2021	RCT, CST, CT, CCO, Quasi-experiment	To evaluate the effectiveness of VR simulations on dental education outcomes	Restorative (23 studies) = 32–289; total $n = 2201$ Endodontic (6 studies) = 10–53; total $n = 189$ OMFS & oral pain (9 studies) = 11–221; total $n = 730$ Prosthodontics (13 studies) = 10–143; total $n = 815$ Implantology (5 studies) = 14–166; total $n = 351$ Radiology (2 studies) = 39–45; total $n = 84$ Periodontics (2 studies) = 19–26; total $n = 55$ Paediatric (4 studies) = 21–103; total $n = 295$ Orthodontic (1 study) = 9; total $n = 9$ Miscellaneous: oral health education, anatomy, diagnosis (8 studies) = 29–101; total $n = 543$ Total: 73 studies (total $n = 5272$)	P: Undergraduate and postgraduate dental students (clinical practitioners included in one study) I: VR and Interactive Simulators. C: Not a mandatory item to include	Primary: Clinical competency measured pre- or post-intervention represented in learners' knowledge and manual skills. Secondary: Students' and educators' perceptions of VR designs.	—	There is a significant quality improvement in dental educational outcomes, and virtual technologies were positively perceived by all the participants. Within the limitations of this review, virtual technology appears to improve education outcomes in dental students. No meta-analysis conducted.		

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TABLE 1 | (Continued)

Author (Year)	Search period	Study design included	Objective	Discipline	No. of study	Sample size (range & participants No.)	Population (P); intervention (I); comparator (C)	Outcomes measured (O)	Risk of bias evaluation tools	Conclusion
Patil et al. (2023) [38]	Search on March 2023	RCTs, controlled clinical trials, cohort studies	To investigate the impact of haptic feedback devices on the development and acquisition of psychomotor skills in dental students during preclinical training	Restorative	9	21–289 (total $n = 843$)	P: Dental students (clinicians included in 1 study) I: Haptic feedback device (Simodont) C: preclinical training without using haptic feedback devices (Phantom head or no control)	Development and acquisition of Psychomotor skills/ clinical skills/dexterity	RoB-2, ROBINS-I, GRADE	There is low-certainty evidence that Simodont is effective in improving the motor skills, manual dexterity, and clinical performance of dental students. No meta-analysis conducted.
Shetty et al. (2025) [39]	Up to Jan 2023	RCT, cross-sectional, cross-sectional cohort, prospective interventional study, retrospective study, descriptive/ survey study	(1) To identify the published studies related to the application of VR and haptic technology in the restorative dentistry training of dental students (2) To recognise the outcome criteria used (3) Subjective evaluation of VR and haptic technology in restorative dentistry	Restorative	22	2–207 (total $n = 1059$)	P: Undergraduate, postgraduate dental students and faculties of dental programs I: VR and haptic technology-based learning and assessment (VR haptic dental simulator, visuo-tactile VR, Haptic 3D VR, Visio-haptic integrated, DENTIFY, PerioSim, iDental, VirTeaSy) C: Conventional training methods	-Primary: Preclinical skills of students in restorative dentistry and their influence on clinical competencies measured pre-intervention and post- intervention. -Secondary: students' perceptions of VR and haptic technology	Cochrane Collaboration Risk of Bias Tools, Newcastle-Ottawa Scale	The use of VR and haptics plays a central role in improving dental students' confidence and preclinical skills. The outcomes of this study demonstrate the feasibility and acceptance of haptic VR technology among dental students mainly because of utility and usability. Meta-analysis indicates a significant improvement in performance post-training with the haptic simulator.

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TABLE 1 | (Continued)

Author (Year)	Search period	Study design included	Objective	Discipline	No. of study	Sample size (range & participants No.)	Population (P); intervention (I); comparator (C)	Outcomes measured (O)	Risk of bias evaluation tools	Conclusion
Koolivand et al. (2024) [40]	Up to Sept 2023	RCT, quasi-randomised trials	To compare the effectiveness of VR-based education and conventional teaching methods for dental sciences	Restorative, Prosthodontic OMFS, Implantology, Endodontics, Periodontics, Dental Anatomy	14	26–194 (total $n = 908$)	P: Undergraduate and postgraduate dental students I: VR: Moog Simodont, Omni haptic devices, Oculus Rift and Leap Motion, Haptic device and IDEA software, DentSim, Navigation system (Denex image-guided implantology; DenX advanced dental systems; Moshav ora), micro-CT tooth models, Oculus Quest 2 All-In-One, UniDental, VR headset, EKEN 4 KUHD 60 C: Conventional extracted tooth or traditional method (free hand implant placement, phantom head)	Satisfactory performance, confidence level, clinical skills indicators (film thickness, setting time, tooth preparation scores, completion time, error scores, completion percentage), ergonomic development, theoretical assessment scores, knowledge retention	Cochrane Collaboration Tool, GRADE	-VR technologies help dental education in various clinical procedures-Haptic technology adds a sense of touch to former visual-only interfaces. These systems can simulate tactile input and visual feedback to help the training of clinical psychomotor skills. -VR might serve as a complement to traditional learning methods. -The only ambiguity mentioned in the studies is related to the student evaluation methods and the hardware and software used.

Abbreviations: CCO: Comparative crossover; CST: Cross-sectional trial; CT: Comparative trial; GRADE: Grading of Recommendations, Assessment, Development and Evaluations; HT: Haptic technology; MINORS: Methodological Index for Non-Randomised Studies; NOS: Newcastle–Ottawa Scale; OMFS: Oral and maxillofacial surgery; RCS: Retrospective cohort study; RCT: Randomised controlled trial; RoB-2: Cochrane Risk of Bias 2 tool; ROBINS-I: Risk Of Bias In Non-randomised Studies of Interventions; VR: Virtual reality.

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indicated the performance of the intervention group (Simodont device) was lower than that of the control group. Only one systematic review, Shetty et al. (2025), conducted a meta-analysis and found a high heterogeneity of $I^2 = 92\%$ in their findings [39].

The risk of bias of selected studies was not evaluated in one of the systematic reviews [37]. The remaining five reviews used the Cochrane Collaboration Risk of Bias tool or its updated version, RoB-2 [35, 36, 38–40], to analyse randomised controlled trials. The Newcastle-Ottawa Scale was applied in two reviews [35, 39], while Risk of Bias in Non-randomised Studies—of Interventions (ROBINS-I) and Methodological Index for Non-Randomised Studies (MINORS) were each utilised in one review to evaluate the risk of bias of non-randomised studies [35, 38]. One review used methods proposed by Tsirogiannis et al. (2016) [41] to assess non-randomised studies [36].

Two systematic reviews [38, 40] examined the level of evidence of each included primary study using the Grading of Recommendations, Assessment, Development and Evaluations (GRADE) tool. The criteria for ranking the quality of evidence into one of four levels: very low, low, moderate and high are five domains which are risk of bias, inconsistency of results, indirectness of the evidence, imprecision of the results, and publication bias [38, 40]. Publication biases were assessed in the two systematic reviews [38, 40], while the other four reviews [35–37, 39] did not assess publication bias. Two reviews reported receiving funding [35, 36] while all six reviews declared no conflict of interest [35–40].

3.3 | Risk of Bias Assessment for Selected Systematic Reviews

The AMSTAR 2 checklist was used to evaluate the quality of the systematic reviews. As shown in Table 2, one of the included systematic reviews fulfilled all the AMSTAR 2 criteria [32]. Even one 'no' for one of the seven critical domains will downgrade the review to low quality, as in Javed et al. (2025) [35]. None of the reviews performed domain 10, which accounts for looking for sources of funding in the primary studies. Moussa et al. (2021) [37], received the most 'no' for the domains scoring. Two included systematic reviews were demonstrated to have an overall low quality [35, 36], whereas four other reviews had an overall critically low quality [37–40]. The major factors contributing to the quality are not mentioning the registered protocol prior to the commencement of review, the absence of a list of excluded articles after full text read, and no consideration of risk of bias during interpretation of results.

3.4 | Degree of Overlap Between Studies

Across six reviews ($c = 6$), 155 total citations to primary studies were identified ($N = 155$), representing 119 unique studies ($r = 119$) (File S1), yielding a CCA of 6.05%. According to the predefined thresholds, this indicates moderate overlap, suggesting some duplication of primary evidence across reviews without substantial redundancy.

4 | Discussion

This umbrella review synthesises six systematic reviews published between 2021 and 2025 and appraises the educational impact of virtual reality and haptic simulators in dental training. Although systematic reviews are often regarded as high-level evidence, uncritical reliance on a single review is hazardous because methodological shortcomings and analytic choices can distort conclusions [32, 34]. Accordingly, an umbrella review, which is positioned at the apex of evidence synthesis, was undertaken to provide a higher-order, methodologically explicit summary and to judge the consistency, magnitude and limits of effects across reviews.

TABLE 2 | AMSTAR checklist for the included studies.

Studies	Domains																Review, quality
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
Javed et al. (2025) [35]	Y	Y	Y	PY	Y	Y	Y	Y	Y	N	NMC	NMC	N	Y	NMC	Y	Low
Bandiaky et al. (2024) [36]	Y	Y	N	PY	Y	Y	N	Y	RCT: Yes NRSI: No	N	NMC	NMC	Y	Y	NMC	Y	Low
Moussa et al. (2021) [37]	Y	N	N	PY	Y	Y	Y	Y	N	N	NMC	NMC	N	N	NMC	Y	Critically low
Patil et al. (2023) [38]	Y	PY	N	PY	Y	Y	N	Y	Y	N	NMC	NMC	Y	Y	NMC	Y	Critically Low
Shetty et al. (2025) [39]	Y	PY	Y	PY	Y	Y	N	Y	Y	N	Y	N	N	Y	N	Y	Critically low
Koolivand et al. (2024) [40]	Y	PY	N	PY	Y	Y	N	Y	Y	N	NMC	NMC	Y	Y	NMC	Y	Critically low

Abbreviations: N, no; NMC, no meta-analysis conducted; PY, partial yes; Y, yes.

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Across reviews, a consistent positive signal emerges for preclinical outcomes: learners trained with VR–haptic platforms generally demonstrate superior psychomotor accuracy, reduced errors, improved efficiency and increased confidence compared with traditional instruction. When the direction of evidence across the six systematic reviews is considered collectively, a consistent pattern emerges. All six reviews reported favourable educational effects of VR or haptic simulators on at least one learning outcome, including psychomotor accuracy, procedural efficiency, confidence or error reduction. Four reviews explicitly concluded that VR-haptic systems improved preclinical skill acquisition compared with conventional simulation methods, while the remaining two reported encouraging but cautious findings due to heterogeneity or methodological limitations. This convergence of positive signals across independent reviews strengthens confidence in the direction of effect, even though the magnitude of benefit remains uncertain due to variability in devices, instructional designs, and outcome measures. These gains are most reliably observed in foundational restorative tasks, with supportive, albeit less dense, evidence in endodontics, oral and maxillofacial surgery, implantology, periodontics, paediatric dentistry, radiology and dental anatomy. The single meta-analysis in the corpus reported a statistically significant performance benefit following haptic-simulator training [39], although the estimate was accompanied by very high heterogeneity ($I^2 = 92\%$), indicating that the magnitude of effect depends on the device characteristics, instructional design, learner level, and outcome choice. The evidence base suggests a consistent direction of educational benefit, particularly for early psychomotor skill acquisition in simulated environments. Therefore, the present umbrella review supports the interpretation that VR–haptic simulation provides promising adjunctive educational benefits, but the magnitude and durability of these effects remain uncertain. Future research should prioritise methodologically robust trials and standardised outcome frameworks to strengthen the certainty of conclusions.

The methodological substrate supporting these conclusions warrants careful interpretation. AMSTAR 2 assessments placed the overall confidence in included reviews in the low to critically low range, driven by absent preregistration in several cases, limited reporting of excluded studies, and incomplete integration of risk-of-bias judgements into result interpretation. None of the reviews examined funding sources of the primary studies, and only two reviews appraised the certainty of evidence with GRADE. These features collectively increase susceptibility to selective reporting and interpretive optimism [42]. Consequently, although the direction of findings across reviews was generally consistent, the overall certainty of evidence should be interpreted as moderate to low. The AMSTAR-2 appraisal indicates that methodological weaknesses at the review level, particularly absent protocol registration, incomplete reporting of excluded studies, and insufficient integration of risk-of-bias assessments, which limit the strength of causal inference that can be drawn from the current synthesis. While the direction of effect across reviews is convergent, the certainty remains attenuated by study-level imprecision, inconsistency across tasks and platforms, and occasional indirectness of outcomes. Heterogeneity has both technical and pedagogical roots. Platforms vary markedly in visual fidelity, haptic resolution, ergonomics and task libraries (e.g., Simodont, VirTeaSy, IDEA, UniDental, visuotactile VR and navigation systems), and these differences plausibly translate into distinct learning curves and effect sizes. Instructional design elements, such as dose and spacing of practice, the balance between automated analytics and tutor-mediated feedback, progression rules, and integration with conventional simulation were unevenly specified and seldom experimentally manipulated. Learner populations ranged from novices to mixed cohorts, creating additional variability in baseline competence and ceiling effects. Against this backdrop, it is instructive that at least one review noted instances in which simulator-trained learners underperformed controls for particular tasks [38]. Such counterexamples underscore that VR–haptic systems are not uniformly beneficial; their value depends on fit-for-purpose deployment, calibration, and informed supervision rather than device acquisition alone.

A central unanswered question concerns transfer to authentic clinical performance. Most outcomes are proximal and simulator-bound, including instrument control, convergence angles, preparation depths, error counts, completion time and ergonomics. Although these metrics have face validity and are objectively captured, their construct validity and external correlation with clinical endpoints, evidence for transfer to authentic clinical endpoints such as objective structured clinical examinations (OSCEs) performance, supervisor-rated procedural quality and safety, and patient-centred outcomes were inconsistently established, despite these measures traditionally demonstrating educational effectiveness in dental education [43, 44]. Longitudinal follow-up beyond preclinical settings was uncommon. Without stronger validity arguments and longitudinal evidence, it remains uncertain whether early simulator gains persist and translate into safer, more efficient care at chairside. This gap is particularly salient for curriculum committees and regulators who must justify capital investment on the basis of learner competence and patient safety.

Implementation realities shape both the evidence and its application. Reviews consistently report that learners perceive VR–haptic simulation positively, often describing increased engagement, motivation, and confidence when practising complex procedures in a safe environment. At the same time, several barriers to implementation remain prominent. These include high acquisition and maintenance costs, institutional IT infrastructure requirements, and the need for faculty development to effectively integrate simulation analytics into teaching. The coexistence of strong learner acceptance with persistent institutional barriers suggests that organisational readiness and curriculum integration, rather than user resistance, represent the principal obstacles to broader adoption. The juxtaposition of strong acceptability with uneven institutional adoption suggests that organisational readiness and curricular alignment, rather than learner resistance, limit uptake. Embedding simulators within structured deliberate-practice pathways with objective progression thresholds, targeted tutor feedback informed by analytics, and early placement in programmes where tactile calibration matters most offers a pragmatic route to maximising educational yield while safeguarding resource use.

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In the present study, the CCA was used as a descriptive metric to quantify the degree of overlap among primary studies included in the systematic reviews [45]. As CCA is calculated from a fixed dataset rather than sampling variability, confidence intervals are not typically reported for this measure. The calculated CCA indicated moderate overlap across the included reviews. Such overlap is commonly observed in emerging research fields [34, 46, 47], where a relatively limited pool of primary studies is repeatedly synthesised across multiple systematic reviews. Importantly, the observed level of overlap remains below thresholds typically associated with substantial redundancy and is therefore unlikely to meaningfully distort the overall conclusions of the umbrella synthesis. Nevertheless, the convergent findings should be interpreted with awareness that a proportion of the evidence base derives from overlapping primary studies.

Several priorities emerge for scholarship and policy. Future primary studies should be prospectively registered, adequately powered randomised comparisons with transparent, validated assessments, pre-specified exposure parameters, and longitudinal follow-up into clinical phases. A harmonised core outcome set spanning accuracy, error taxonomy, efficiency, ergonomics, stress and confidence, and clinically anchored transfer outcomes would reduce heterogeneity and enhance synthesis. Economic evaluation incorporating capital and maintenance costs, throughput, faculty time, and opportunity costs remains conspicuously absent and is essential for procurement and scaling decisions [48, 49]. Given the rich data streams from modern simulators, learning-analytics approaches, and AI-assisted feedback warrant rigorous testing against expert ratings for reliability, validity and fairness [50–52]. Finally, equity considerations should be integrated explicitly: access to high-fidelity simulation is uneven across institutions, and research should evaluate models that broaden access without compromising quality.

In aggregate, the evidence supports a balanced conclusion. VR and haptic simulators confer meaningful advantages for preclinical skill acquisition and learner confidence across multiple dental domains [35–40], but the certainty of effect is constrained by methodological limitations and substantial heterogeneity. Their optimal role is as high-fidelity adjuncts within a blended pedagogy, not wholesale replacements for conventional approaches. Realising their promise will require outcomes-driven curricular integration, robust faculty development and stronger science that links simulator metrics to durable, clinically relevant improvements.

5 | Limitations

The present umbrella review has several limitations. First, the synthesis included six systematic reviews published between 2021 and 2025, of which two were rated low quality and four critically low using AMSTAR-2, reflecting methodological weaknesses such as absent preregistration, incomplete exclusion lists and limited integration of risk-of-bias assessments. Only one review conducted a meta-analysis, which reported substantial heterogeneity, limiting precision. Second, moderate overlap of primary studies was observed (CCA = 6.05%), which may partially amplify recurring evidence signals. Third, substantial heterogeneity across simulator platforms, learner levels, dental disciplines and outcome measures limited the feasibility of quantitative synthesis. Most outcomes were simulator-based metrics, with limited evidence linking these to clinical performance. Furthermore, many primary studies included in the underlying systematic reviews were conducted with relatively small participant samples, which may reduce statistical power and increase uncertainty around the magnitude of reported educational effects. Finally, although the search followed a registered protocol and dual-reviewer process, it was limited to three databases (PubMed, Scopus and Web of Science) and excluded grey literature, which may introduce retrieval bias. Findings, therefore, primarily apply to dental students using immersive VR–haptic modalities (not AR-only or non-immersive tools), and despite dual independent screening and extraction, residual misclassification cannot be fully excluded.

Future research must pair rigorous trial design and validated measurement with longitudinal follow-up and economic analyses and should leverage simulator-generated analytics to refine adaptive feedback. Under these conditions, immersive simulation can accelerate competency development and contribute to safer, more efficient clinical training, aligning technological innovation with demonstrable educational and patient-centred outcomes.

6 | Conclusion

The current body of systematic reviews supports a cautious but coherent conclusion: VR and haptic simulation could enhance preclinical learning in dentistry, particularly in foundational restorative procedures, but the certainty of evidence is constrained by methodological shortcomings and substantial heterogeneity. Dental faculties should adopt VR–haptic technologies through targeted, blended integration that prioritises deliberate practice, objective performance thresholds and expert coaching, while committing to ongoing evaluation of clinical transfer and cost-effectiveness.

Author Contributions

Conceptualisation, methodology, data curation, formal analysis; interpretation and original draft: Amirul Faiz Luai, Nur Dini Ahmad Zawawi, Fadhli Rusli, Methodology, validation, visualisation, and writing, review and editing: Galvin Sim Siang Lin, Methodology, validation, and writing, review and editing: Masako Nagasawa, supervision and writing, review and editing: Haslina Rani, Young-Seok Park, Tuti Ningseh Mohd Dom, Rahimah Abdul Kadir.

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The authors have nothing to report.

Ethics Statement

This study was registered with the Prospective Register of Systematic Reviews (PROSPERO) with a registration number (CRD420251123272).

Conflicts of Interest

The authors declare no conflicts of interest.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Appendix 1.** Citation matrix showing overlapping of primary studies among included systematic reviews. **File S1:** CCA Matrix Study List.

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