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Is virtual reality enhancing dental anatomy education? A systematic review and meta-analysis

Katarina Bevizova¹, Hisham El Falougy¹, Andrej Thurzo² and Stefan Harsanyi^{3*}

Abstract

Background Traditional dental anatomy education, reliant on cadaver dissections and lectures, faces challenges such as high costs, ethical concerns, and difficulty conveying complex 3D dental structures. Virtual reality (VR) offers a solution by providing immersive, interactive learning environments that can enhance students' understanding. This study systematically reviews the effectiveness of VR in dental anatomy education compared to traditional methods, focusing on its potential to improve learning outcomes.

Methods A comprehensive search was conducted across Web of Science (WoS), PubMed, and Scopus databases until May 2024. Data were extracted, summarized, and analyzed for qualitative synthesis. The following keywords and their combinations were used: "dental OR dentistry", "education OR teaching", "virtual AND reality OR VR", and "anatomy OR dental AND anatomy". Studies were included if they met the following criteria: Investigated the use of VR in anatomy education. Compared VR-based learning to other methods such as lecture-based teaching, 3D printed or natural models, or non-interactive 3D models. Quantitative synthesis was performed using standardized mean differences (SMD) with Hedges'd and 95% confidence intervals (CI).

Results Out of 178 records screened, seven studies were included in the meta-analysis and eight in the personal evaluation analysis. The analysis indicates a moderately positive effect of VR on dental anatomy education (SMD = 0.74, $p = 0.05$) compared to lecture-based education using X-ray, CBCT, or 3D models. However, at the same time, VR falls short compared to clinical experience, training with physical teeth, or quality printed models. Studies reported rare cases of discomfort, disorientation, diplopic image, and VR sickness.

Conclusions The use of VR-based learning moderately positively affects educational outcomes, and enhances knowledge retention, especially before clinical experience. The personal evaluation of students showed a strong interest in VR, with positive feedback on its ease of use, accuracy, and educational value.

Keywords Dental education, Dentistry, Virtual reality, VR, Systematic review, Meta-analysis

*Correspondence:

Stefan Harsanyi
stefan.harsanyi@fmed.uniba.sk

¹Institute of Anatomy, Faculty of Medicine, Comenius University in Bratislava, Sasinkova 2, Bratislava 811 08, Slovakia

²Department of Orthodontics, Regenerative and Forensic Dentistry, Faculty of Medicine, Comenius University in Bratislava, Dvořákovo nábrežie 4, Bratislava 811 02, Slovakia

³Institute of Biology, Genetics, and Clinical Genetics, Faculty of Medicine, Comenius University in Bratislava, Sasinkova 4, Bratislava 811 08, Slovakia



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Introduction

For centuries, the cornerstone of anatomy education has been a solemn ritual—the study of cadavers. With its meticulous precision and raw exposure to the human form, dissection has provided an invaluable hands-on experience that has shaped generations of medical professionals [1]. However, this traditional method is not without its limitations. Access to cadavers can be severely restricted by cost, ethical considerations surrounding body donation, and regional variations in availability [2]. Even when available, traditional methods often struggle to effectively convey the body's intricate three-dimensionality [3]. Static images in textbooks and even physical models fail to capture the dynamic relationships between muscles, organs, and bones. This is where virtual reality (VR) is poised to revolutionize how we learn about the human body [4, 5]. While foundational in imparting theoretical knowledge, traditional lecture-based teaching often falls short in delivering the spatial and interactive understanding necessary for mastery of complex anatomical structures. Lectures rely heavily on static images and diagrams, which can be abstract and difficult for students to translate into a three-dimensional understanding of the human body, and students allowed to experience the VR report positive feedback [6]. Moreover, the passive nature of lectures can limit student engagement and retention of information. This approach contrasts sharply with VR's immersive, interactive experience, which can transform anatomy education from a passive memorization experience to an active exploration and discovery journey [7, 8]. Similarly, three-dimensional (3D) printed models are beneficial for providing tactile learning aids and improving practical learning outcomes [9, 10]. Although these models offer a tangible representation of anatomical structures, they are static and cannot demonstrate physiological processes or allow for the dynamic manipulation of parts [11]. These models can also be expensive and may not capture the fine details necessary for a comprehensive understanding of complex anatomy. Non-interactive 3D models, whether digital or physical, similarly fail to provide the interactive experience that VR can offer.

In the field of microsurgery, the need for precise anatomical knowledge is paramount. This is true for example in neurosurgery, ophthalmic surgery, or dentistry, as professionals work in a limited workspace and manipulate small, delicate tissues. The understanding of oral and maxillofacial anatomy, including the relationships between teeth, bones, nerves, and blood vessels. Traditional methods of teaching anatomy, which often rely on cadavers, textbooks, and non-interactive models, can be insufficient for conveying the complexities of these structures. VR technology, however, offers a powerful tool to enhance dental education by providing a fully immersive,

interactive experience [12]. Dental students can use VR to explore detailed virtual models of the oral cavity, manipulate these models to observe structures from different angles, and even simulate dental procedures, gaining valuable hands-on experience in a risk-free environment [13]. VR technology creates a fully immersive, simulated environment that users can interact with in a seemingly real or physical way [14]. This potential transformation in anatomy education shifts the experience to an active journey of exploration and discovery, as shown in a recent study by Chen et al., where participants scored best post-intervention in VR and cadaver groups [8]. VR technology offers an immersive experience and the potential to enhance anatomy education in several ways [15–17]:

- **Enhanced Visualization:** VR allows students to explore a detailed virtual human body. They can rotate, zoom in, and dissect layers, gaining a superior understanding of spatial relationships between organs, muscles, and bones. This surpasses the limitations of static 2D images and even 3D models, offering a dynamic and interactive learning experience.
- **Overcoming Cadaver Limitations:** VR can alleviate the challenges associated with cadaver dissection. Access to cadavers can be limited due to ethical restrictions, costs, and regional variations. VR offers a readily available and standardized alternative, ensuring all students have equal access to a complete and realistic anatomical model.
- **Engaging Active Learning:** VR transforms anatomy learning from passive observation to active exploration. Students can virtually dissect a body, isolate specific structures, and even visualize physiological processes like blood flow or nerve impulses. This improves knowledge retention and promotes critical thinking skills.
- **Addressing Ethical Concerns:** The use of cadavers raises ethical considerations regarding body donation and respect for the deceased. VR offers an alternative that avoids these concerns while still providing a realistic and comprehensive learning experience.
- **Benefit for patients:** A study by Fahim et al. 2022 reports the potential of VR and AR in overcoming dental phobia especially in pediatric patients [18].

The primary aim of this systematic review and meta-analysis is to evaluate the effectiveness of VR technology in dental anatomy education compared to other teaching methods.

Practical applications of VR for anatomy education

The potential of VR in anatomy education is rapidly transforming classrooms and training labs. VR technology enables students to explore a meticulously detailed virtual human body with unprecedented realism and interactivity [19]. By providing a dynamic and interactive learning environment, VR enhances students' ability to comprehend complex anatomical structures and physiological processes, especially in times such as the COVID-19 pandemic, when personal interaction needs to be limited [20, 21]. Moreover, VR models can simulate various pathological conditions and surgical procedures, allowing students to practice critical thinking and decision-making in realistic clinical scenarios [8, 22]. In Table 1, specific applications that showcase its versatility, are presented [23–25].

By embracing these practical applications, VR technology has the potential to significantly enhance the quality and accessibility of all visually dependent education, not only dental, or anatomy, paving the way for more effective and inclusive training for future healthcare professionals.

Materials and methods

This systematic review and meta-analysis study was registered in OSF Registries, registration DOI: <https://doi.org/10.17605/OSF.IO/4HYQC>.

Search strategy

This systematic review and meta-analysis follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [26]. The

Population, Intervention, Comparison, and Outcomes (PICO) framework was used to develop the research eligibility criteria [27]: population (dentistry students, practitioners), intervention (education using virtual reality), comparison (other types of lectures), and outcome (higher educational value). The review question: Is virtual reality enhancing dental anatomy education? Secondary research question: How do participants evaluate the VR experience?

A comprehensive literature search was conducted across multiple databases, including PubMed, Scopus, Web of Science, and Google Scholar to identify relevant studies. The search included articles published up to May 2024. The following keywords and their combinations were used: "dental OR dentistry", "education OR teaching", "virtual AND reality OR VR", and "anatomy OR dental AND anatomy".

Study inclusion and exclusion criteria

Studies were included if they met the following criteria: Investigated the use of VR in anatomy education. Compared VR-based learning to other methods such as lecture-based teaching, 3D printed or natural models, or non-interactive 3D models. Reported outcomes related to learning effectiveness, knowledge retention, spatial understanding, and student engagement. Published in peer-reviewed journals and available in English.

Studies were excluded if they: Focused solely on augmented reality (AR) without VR. Did not provide comparative data between VR and traditional methods. Were

Table 1 Applications and benefits of VR in dental anatomy education

Application	Description	Benefits
Interactive Anatomy	Students explore a detailed 3D human body model	- Independent learning and exploration - Self-directed manipulation of structures Visualization of spatial relationships
Augmented Dissection	VR overlays information onto cadavers during dissection	- Combines traditional and digital learning - Provides real-time visualizations of physiological processes - Enhances understanding of anatomical structures
VR Patient Simulations	Medical professionals practice procedures in realistic virtual environments	- Safe and realistic training for complex scenarios - Improves decision-making skills and reduces errors - Enhances preparation for real-world patient care
Advanced Visualization Techniques	Visualize physiological processes in real time	- Understand dynamic bodily functions - Gain a holistic view of anatomy and physiology - Enhance comprehension of complex systems
Dental Anatomy and Procedures	Explore detailed virtual models of the oral cavity	- Practice dental techniques in a risk-free setting - Understand relationships between oral structures - Develop practical skills and confidence
Collaborative and Remote Education	Shared virtual spaces for collaborative learning	- Enables remote education - Fosters collaboration and peer support - Enhances learning through interaction
Continuous Professional Development	Ongoing training for healthcare professionals	- Rehearse complex procedures - Stay updated with latest techniques - Improve patient care and outcomes

conference abstracts, reviews, or editorials and were not available in full text.

Data extraction

Two independent reviewers (KB and SH) extracted data from the selected studies. Discrepancies were resolved through discussion and consultation with a third reviewer (HEF). The following data were extracted: study characteristics (author, year, country); participant demographics (number, age, gender); intervention details (type of VR system, duration of use); comparator details; outcomes measured (test scores, retention rates, spatial understanding, interest levels), board approval/informed consent, and key findings. For studies that provided qualitative data, thematic analysis was performed to identify common themes and insights related to the use of VR in anatomy education. This included student and instructor feedback on the advantages and challenges of VR technology. The primary and secondary outcomes measures included: Educational value and knowledge retention (pre- and post-intervention test scores). Accuracy, ease of use, and spatial understanding (assessed through practical exams and self-administered questionnaires). Student interest (measured by engagement scales and self-administered questionnaires).

Data synthesis and analysis

All analyses were conducted using SPSS v29 software (IBM SPSS Statistics for Windows, Version 29.0.2.0, Armonk, NY, USA). For studies reporting comparable quantitative test score data, effect sizes were calculated using standardized mean differences (SMD) with Hedges'd and 95% confidence intervals (CI). Forest plots were used to graphically visualize the findings, providing a clear representation of the effect sizes and their corresponding confidence intervals across the included studies. Heterogeneity among the studies was assessed using the I^2 statistic, which measures the percentage of total variation across studies due to heterogeneity rather than chance. An I^2 value greater than 50% was interpreted as indicating substantial heterogeneity, suggesting that the variation in effect sizes was likely due to differences between the studies rather than random variation. Due to the low number of available studies, no subgroup analyses were performed.

Publication bias was assessed using a funnel plot and Egger's test for asymmetry, where $p < 0.1$ in Egger's test indicates the presence of publication bias [28, 29]. P -values lower than 0.05 were considered significant. The quality of the included studies was assessed based on the Newcastle-Ottawa Scale (NOS). Each study was evaluated for potential selection, comparability, and reporting biases, where scores 0–3 represent low quality (high risk

of bias), 4–6 moderate quality (medium risk), and 7–9 high quality [30].

Results

Study selection and characteristics

In total, 178 results were retrieved from the initial database search. After removing duplicates, 128 records underwent title, keywords, and abstract screening. This excluded 44 records, leaving 84 for full-text retrieval, of which 4 were not retrieved. 80 full-text articles were assessed for inclusion eligibility which excluded 71 articles. Finally, nine studies were included in the final analysis (Fig. 1). Out of these, seven studies were included in the meta-analysis and eight in the personal evaluation analysis. These were peer-reviewed studies on the effects of VR in the education of dentistry-related applications, published between 2004 and 2024. All of these studies were randomized controlled trials; four used a between-subjects design, four used a within-subjects design, and one was observational. These studies included 563 eligible participants (547 1st–4th year dentistry students and 16 dentists). Student mean age based on reported data was 22.18 ± 2.32 . The sex distribution was 53.8% male and 46.2% female. Five studies were conducted in the USA, two in Germany, and one each in Saudi Arabia and Brazil.

Various VR modalities and software/hardware combinations were used in the study groups. The interventions for control groups included educational methods such as standard lecture-based sessions, visual inputs using either X-Ray or CBCT and non-interactive 3D models. Interactive models used naturally extracted teeth or 3D printed models. The duration of the interventions ranged from 15 to 20 min, through 2 h to three two-week sessions of 2.5–3 h per day. For all research studies, primary results were determined by evaluation of test scores or multiple-choice questionnaires (MCQ). Eight studies reported student personal evaluations and satisfaction levels with the VR system or the possibility of such an educational option. Study characteristics are presented in Table 2.

Inter-rater reliability

The inter-investigator reliability (Kappa) was calculated by evaluating the selected titles and abstracts, resulting in a Kappa value of 0.851. This indicates a high level of reliability between the reviewers [31].

Risk of bias assessment

According to the NOS, one study was assessed as high quality, six as moderate quality, and two as low quality with high reporting bias, as shown in Fig. 2. Due to the nature of the intervention, blinding of students and teachers during the study was not practical. Most studies were found to have a low risk regarding data

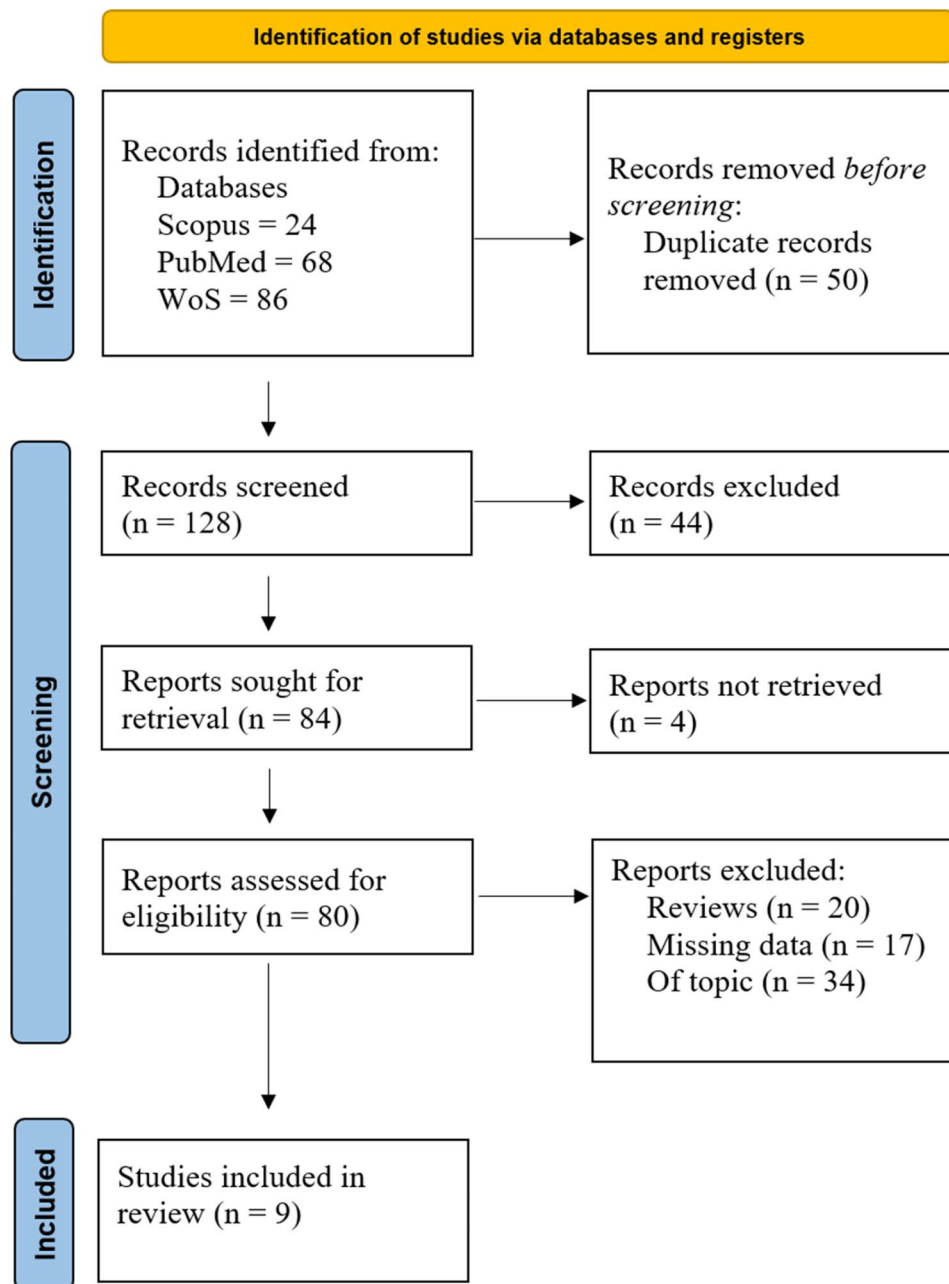


Fig. 1 PRISMA flow diagram

completeness and selective reporting. The assessment examined whether the studies avoided selective outcome reporting by ensuring that all outcomes were adequately reported in the manuscripts. Additional information to study informed consent/board approval, bias, and personal evaluation is presented in Table 3.

Data analysis – virtual reality applications and personal evaluation

Seven studies with 13 comparable variables provided data from 486 dentistry students concerning the application

of VR technology compared to lecture-based education, using X-ray, CBCT, or 3D models. In these studies, the authors used various types of VR software/hardware combinations to evaluate the effects on students’ theoretical or practical (visual) knowledge after the VR intervention. The overall effect size suggests a moderately positive effect of VR technology in dental anatomy education (SMD=0.74) that is statistically significant with $p=0.05$. This means that lectures, X-rays, and CBCTs were less effective in enhancing students’ knowledge compared to VR, however, compared to training with physical

Table 2 Overview of included studies

Study (country) Study design	Participants (gender) mean age	Study group / Controls	Modality used	Control modality	Duration	Evaluation	Ref.
Jasinevicius, 2004 (USA) RCT-BS	28 dentistry students after finishing the first year (23 M:5 F) N/A	15 / 13	virtual reality simulation units: Classic DentSim	non-computer assisted units: KaVo Simulator	Three two-week sessions of 2.5–3 h per day	Comparison of tooth preparations from randomly selected envelopes – 3 from each student combined from all three sessions divided into Class I, Class II, and full gold crown.	[39]
von Sternberg, 2007 (Germany) RCT-BS	41 students with no apicectomy experience (N/A) N/A	20 / 21	VOXEL-MAN on a cadaveric porcine jaw	no prior apicectomy training	3 sessions of VR at basic, advanced and expert training	By grading of evaluated parameters (1 = best – 6 = worst), preservation of vital structures, defect volume, deviation from the intended extent of resection (2 mm) and the time required to complete the procedure	[40]
Kim-Berman, 2019 (USA) RCT-WS	109 first-year dental students, only 61 eligible (N/A) N/A	61 / self	Virtual Dental Library using Arthea software and Android device	Real tooth identification tests	Two occasions	VR real tooth identification tests (1) 25 questions; (2) 50 questions Final 40 MCQ test	[41]
Zorzal, 2020 (Brazil) OS	16 dentists (12 M:4 F) 23–64 years	16 / -	IMPLANT a virtual reality educational tool	none	20–30 min	SUS questionnaire workload analysis using NASA-TL	[42]
Reymous, 2020 (Germany) RCT-WS	42 third-year dental students (N/A) N/A	42 / self	VR software VRED 2018 and head-mounted display	1. Radiograph 2. CBCT	2 h	A questionnaire of 31 questions divided into 3 parts: based on a radiograph, CBCT, VR	[43]
Mahrous, 2021 (USA) RCT-WS	70 first-year dental students after dental anatomy course (30 M:40 F) 23.3 ± 1.9 y	70 / self	AR/VR HMD and an iPhone	1. natural human tooth 2. 3D virtual model 3. physical 3D printed model	During the experiment	A questionnaire of 17 questions. Educational value was the degree to which the modality contributed to the student's understanding of dental anatomy	[44]
Kim-Berman, 2023 (USA) RCT-WS	90 first-year dental students (40 M:50 F) 22.9 ± 2.74	90 / self	Immersive View VR software with Oculus Rift	3D imaging – 6 min 32 s CBCT – 6 min 26 s	VR software – 10 min 50 s + 30-min learning session using VR/CBCT	Three 10-item MCQ tests for each of the three time points, preintervention (T1), immediate postintervention (T2), and 2 weeks postintervention (T3)	[45]
Alsufyani, 2023 (Saudi Arabia) RCT-BS	69 first-year dental students (42 M:27 F) < 20–35; > 20–34	34/35	Oculus Quest 2 VR software by Black Dune Studio	conventional educational lecture for 30 min	15–20 min	Quiz of 20 MCQ questions	[46]
Samuel, 2024 (USA) RCT-BS	52 s-year students 94 3rd + 4th year students G1 25.6 years; G2 26–27.5 years	52/94	Oculus Rift S + VARIANT-VR haptic enabled iPadOS with Vuforia	Traditional training methods (lectures, anatomical landmarks)	30 min per student	Post-training surveys immediately after the session and after the first clinical experiences	[47]

RCT-BS: randomized controlled trial between subjects; RCT-WS: randomized controlled trial within subjects; OS: observational study

	Selection (max 4 stars)	Comparability (max 2 stars)	Outcome (max 3 stars)	Total
Jasinevicius et al. 2004 (USA)	***	**	*	6
von Sternberg et al. 2007 (Germany)	***	**	*	6
Kim-Berman et al. 2019 (USA)	**	-	*	3
Zorzal et al. 2020 (Brazil)	*	**	-	3
Reymus et al 2020 (Germany)	**	**	*	5
Mahrous et al 2021 (USA)	**	**	*	5
Kim-Berman et al. 2023 (USA)	***	**	**	7
Alsufyani et al. 2023 (Saudi Arabia)	***	**	*	6
Samuel et al. 2024 (USA)	***	**	*	6

Fig. 2 Risk of bias assessment according to the Newcastle-Ottawa Scale

Table 3 Additional information on study quality and personal evaluation

Author, year (Country)	Board-approved or Informed Consent	The study reported blinding or potential bias	Personal evaluation	Ref
Jasinevicius et al. 2004 (USA)	Yes	The trainers were not informed whether the students had received virtual surgery training.	N/A	[39]
von Sternberg et al. 2007 (Germany)	No	Authors who were blind to the identity of the grouping visually evaluated the preparations; participants received a monetary stipend at the end of the study, without prior knowledge	Self-assessment by the students	[40]
Kim-Berman et al. 2019 (USA)	No	Students were given extra credit in the preclinical dental anatomy continuation course for participating	Post survey questionnaire	[41]
Zorzal et al. 2020 (Brazil)	Yes	-	Post survey questionnaire SUS questionnaire	[42]
Reymus et al. 2020 (Germany)	Yes	-	Post survey questionnaire Issues with interacting with VR	[43]
Mahrous et al. 2021 (USA)	Yes	-	Post survey questionnaire	[44]
Kim-Berman et al. 2023 (USA)	Yes	-	Post survey questionnaire	[45]
Alsufyani et al. 2023 (Saudi Arabia)	Yes	-	Post survey questionnaire	[46]
Samuel et al. 2024 (USA)	Yes	Participants self-selected into the study, possibly influencing motivation. Different levels of prior clinical experience between study and control groups could influence outcomes.	Self-Reported Confidence Levels	[47]

teeth, or quality printed models, VR shows slightly lower scores. In the analysis, high heterogeneity was observed ($I^2=0.97$). In Fig. 3 we can see a forest plot comparing the effectiveness of VR-based anatomy education to traditional lecture-based teaching methods, indicating a moderately positive effect.

Students' personal evaluation of the VR experience was analyzed based on two distinguishing factors. First the system's accuracy, ease of use, and spatial understanding. Second student interest. The analyses were carried out using a pre-calculated effect size based on questionnaires normalized to a scoring system of 1 to 3, where

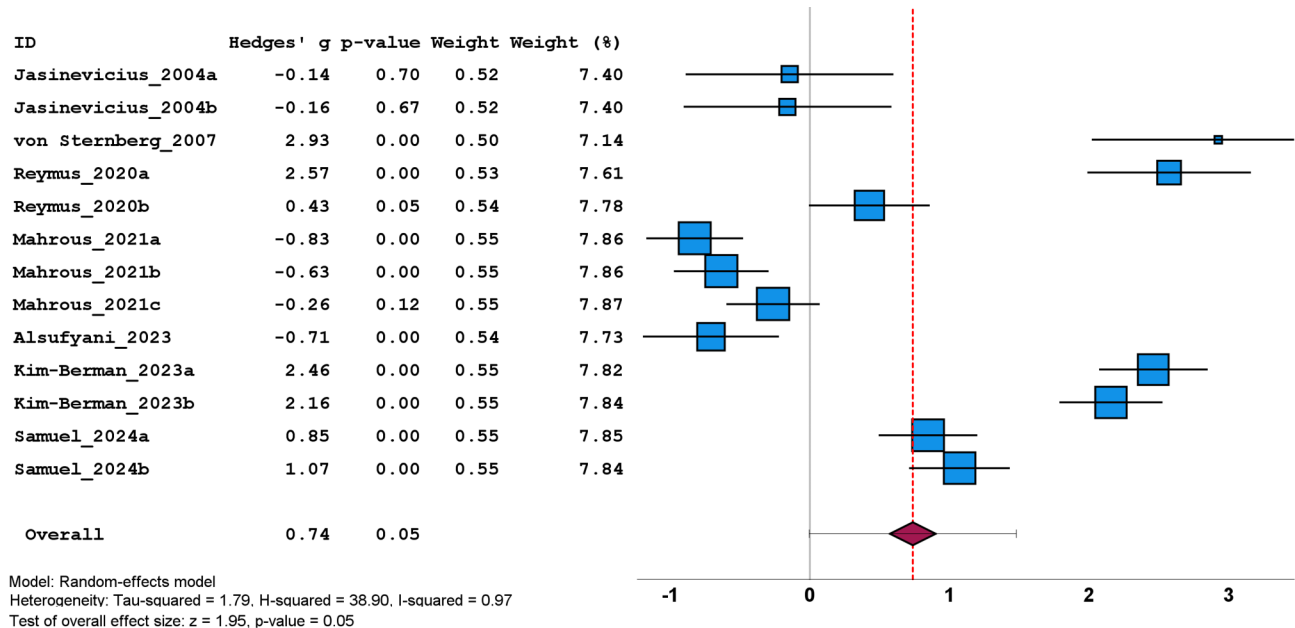


Fig. 3 Effectiveness of VR vs. other types of lectures

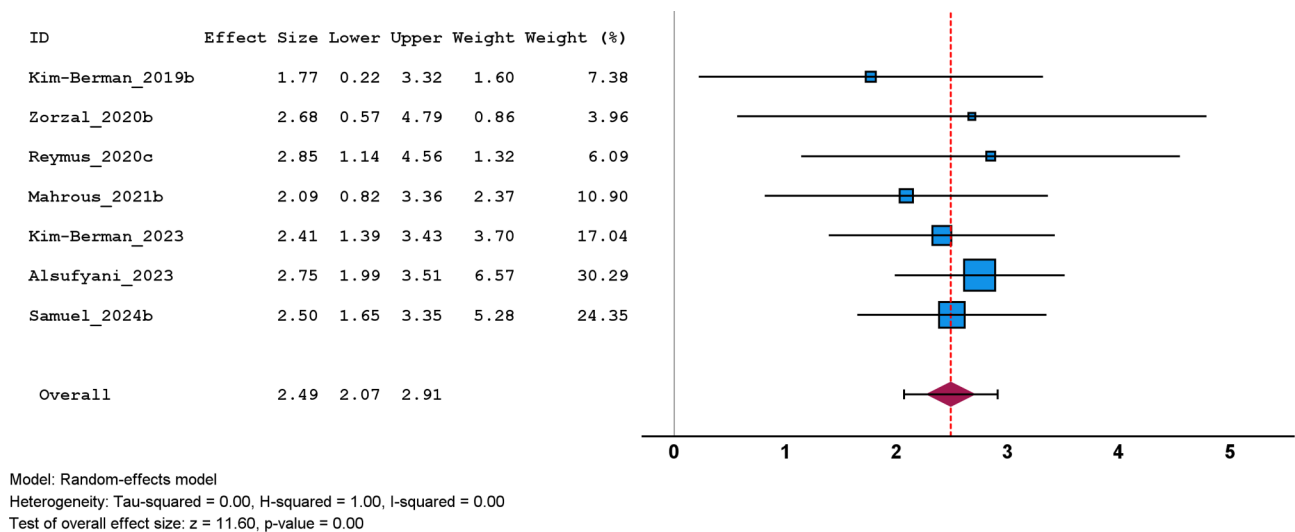


Fig. 4 Personal evaluation: accuracy, ease of use, and spatial understanding compared to other educational methods

1 is the worst and 3 represents the best score. The forest plot in Fig. 4 illustrates the comparison between VR-based learning and hands-on clinical experience or training with physical models, such as printed anatomical models and physical teeth. Results show, that while VR is regarded as very accurate and easy to use, it falls short compared to clinical experience and training with physical models (SMD=2.49, 95% CI=2.07 to 2.91). The effect sizes in most studies favor physical models and clinical experience, indicating that while VR is beneficial, it does not fully replace the tactile and practical learning obtained through direct interaction with physical objects.

Figure 5 displays a summary of students' personal evaluations of VR in anatomy education, highlighting their feedback on engagement. The majority of students reported a strong interest in VR technology, with positive feedback on its usability and the immersive experience it provides. Students appreciated the ability to visualize and interact with 3D anatomical structures, which enhanced their understanding and retention of the material. Two studies reported rare cases of discomfort, disorientation, diplopic image, and VR sickness.

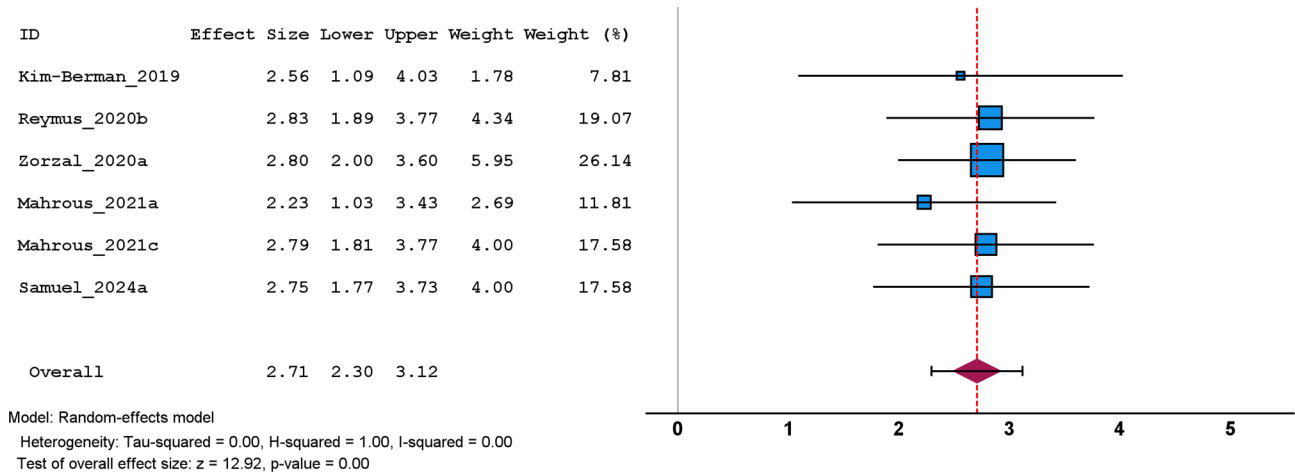


Fig. 5 Personal evaluation: interest and engagement levels

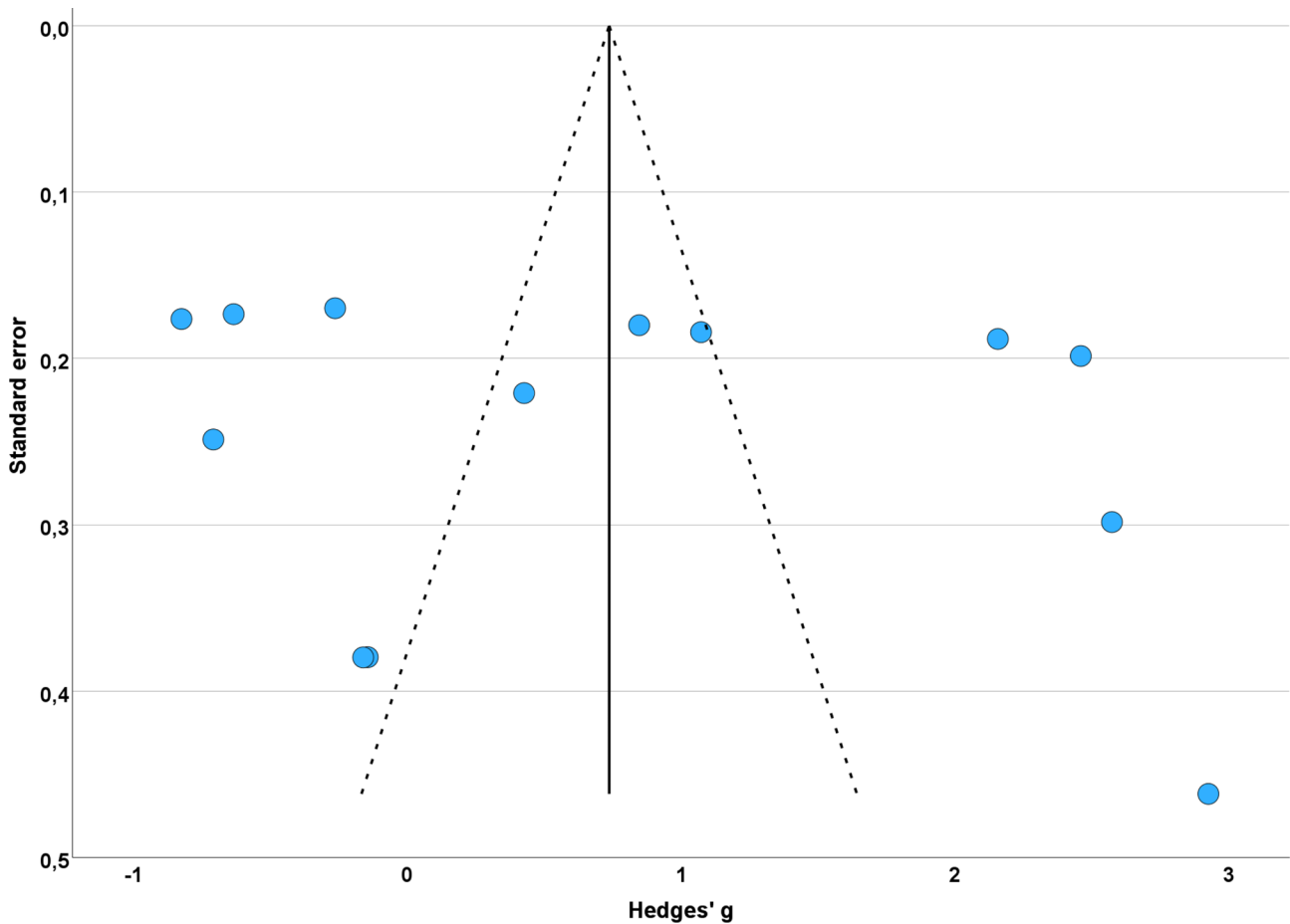


Fig. 6 Funnel plot of effect sizes for clinical trials included in the meta-analysis

Publication bias and sensitivity analysis

For the primary analyses, funnel plots were created to check for the risk of publication bias (Fig. 6). The shape of the funnel plot appeared reasonably symmetrical, suggesting no major publication bias. Although several studies were located outside the 95% confidence intervals,

this can occur due to random variation or differences in study methodologies. Additionally, Egger’s test showed non-significant asymmetry ($p=0.882$), further indicating that there was no significant publication bias in this review.

A sensitivity analysis was performed to confirm the reliability of the results, due to significant heterogeneity (>75%). When any individual study was excluded from the model, the significant effect of VR on examination scores remained consistent, with the pooled SMD staying at 0.74 (95% CI: 0.00–1.52), similar to the original results (SMD=0.74, 95% CI: 0.00-1.47).

Discussion

The integration of VR in anatomy education offers numerous benefits, including enhanced visualization of spatial relationships, and overcoming the limitations of 2D examination methods [32]. Moreover, VR applications are slowly getting hold in many dental specialties from education to stress elevation using VR animation in child dentistry [33]. Dentistry is a specialized field, with a high emphasis on anatomical knowledge. VR allows dental students to explore detailed virtual models of the oral cavity, simulate dental procedures, and gain an almost hands-on experience in a safe and controlled environment. Our study on VR in dental anatomy education produced similar results to a recent study by Zhao et al. on VR effectiveness in teaching general anatomy, where exposure to VR moderately improved test scores in students [22]. The moderately positive impact of VR leads to an improved understanding of dental anatomy; however, our findings suggest that, when compared to clinical practice exposure, current VR hardware and particularly software are not as highly regarded.

Virtual reality (VR) technology in dental anatomy education, while offering immersive and detailed visualizations, comes with certain limitations. One significant drawback is the high cost of VR equipment, which can be prohibitive for many educational institutions [34]. Additionally, the technology requires substantial technical support and maintenance. Users often experience physical discomforts such as head pain, eye strain, and nausea due to prolonged use of VR headsets, a phenomenon known as “VR sickness [35].” These symptoms can reduce the effectiveness of VR as a learning tool by limiting the duration for which students can comfortably use the technology [36]. Moreover, the initial learning curve associated with mastering VR interfaces can be steep, potentially detracting from the time spent on actual anatomical studies. Despite these challenges, ongoing advancements in VR technology aim to mitigate these issues, making it a more viable option for education in the future.

Future developments may include even more realistic simulations and systems to mimic the tactile experience of dissection. Mannequin simulators with VR and advanced haptic feedback are already used in otorhinolaryngology [37]. It is only a matter of time before VR becomes more affordable, accessible, and accurate.

This will push its integration into educational curricula, potentially becoming a standard component of medical and dental training programs [38]. The ideal approach to anatomy education likely lies in a blended learning model that combines the strengths of VR with traditional methods. This hybrid approach allows students to benefit from the hands-on experience of cadaver dissection, the theoretical knowledge from lectures, and the interactive, immersive capabilities of VR. Such a comprehensive educational strategy will foster a deeper and more nuanced understanding of human anatomy, better preparing future generations of medical and dental professionals.

Limitations of this review are mainly low sample size due to lack of more available research. Most studies don't have a control group that complicates the comparing of scores from given educational methods. Also, most studies mainly reported post-intervention information. Age and gender information in some studies were unable to be obtained. Last, studies should report more on VR sickness and complications of using the headset.

Conclusions

The results of this meta-analysis underscore the potential of VR technology to enhance anatomy education by providing a more interactive and engaging learning experience compared to traditional lecture-based methods. VR has been shown to improve the comprehension of complex anatomical structures and offers a valuable supplement to traditional teaching methods. However, VR does not entirely replace the benefits of hands-on clinical experience and physical models, which provide essential tactile feedback and practical skills. The positive reception from students suggests a promising future for integrating VR into anatomy curricula.

By embracing VR technology, educational institutions can provide a richer, more engaging learning experience that empowers students with a profound understanding of the human body, ultimately improving the quality of healthcare provided by future professionals. Future research should explore ways to combine VR with physical models to leverage the strengths of both approaches and maximize educational outcomes.

Abbreviations

VR	Virtual reality
SMD	Standardized mean difference
CI	Confidence Interval
CBCT	Cone Beam Computed Tomography
3D	Three-dimensional
2D	Two-dimensional
AR	Augmented reality
COVID-19	Coronavirus disease 2019
NOS	Newcastle-Ottawa Scale
MCQ	Multiple-choice questionnaire
RCT-BS	Randomized controlled trial between subjects
RCT-WS	Randomized controlled trial within subjects
OS	Observational study

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Author contributions

KB and SH designed the study, collected data, analyzed results, and wrote the first manuscript; HEF and AT contributed to manuscript revisions, third opinion, and methodology. All authors read and approved the final manuscript.

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Data availability

The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations**Ethics approval and consent to participate**

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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