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Efficacy of typodont and simulation training in orthodontic education: a systematic review

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Abstract

This systematic review evaluates the efficacy of analogue and virtual typodont/simulation training in orthodontic education, focusing on its impact on clinical skills, motivation, and communication (PROSPERO ID# CRD42024560497). A comprehensive search across PubMed, the Cochrane Library, ERIC, and CINAHL identified 11 studies that examined various simulation-based learning approaches. The findings indicate that simulation-based training enhances short-term diagnostic accuracy, treatment planning, and practical skills in orthodontics, particularly in tasks such as bracket bonding and clinical reasoning. Simulations also fostered student engagement and motivation, bridging the gap between theoretical learning and practical application. However, challenges such as variability in simulation technologies, technical issues with advanced tools like VR, and the perception of increased workload were identified. While most students reported high satisfaction, the heterogeneity among study designs and training objectives limits generalizability. This review highlights the potential of simulation-based learning to enhance clinical preparedness in orthodontics and recommends further research to explore strategies for standardizing simulation tools, sustaining motivation, and evaluating long-term clinical outcomes.

Keywords Orthodontic education, Simulation-based learning, Typodont training, Clinical skills, Student motivation

Introduction

In orthodontic education, the development of clinical skills and confidence in students before they engage with real patients is critical. One of the most widely adopted approaches to achieve this is through the use of typodonts and simulation-based training [1–3]. These methods have evolved significantly in recent years, with both analogue and virtual simulations becoming integral to the educational experience. Typodonts, which are models of the human dentition, allow students to practice a range of procedures, from simple adjustments to more complex orthodontic treatments, in a controlled environment [4]. Simulations, particularly virtual ones, offer the opportunity to recreate clinical scenarios and conditions in a way that mimics real-world experiences more closely, preparing students to make clinical decisions and apply practical skills without the immediate pressure of treating actual patients [2, 5].

The increasing reliance on these training methods stems from the need to ensure that orthodontic students are not only knowledgeable but also proficient in their technical skills and decision-making abilities. Traditional clinical training, while invaluable, presents limitations in terms of patient availability, the range of clinical scenarios that can be experienced during training, and the potential risks involved when students are working with real patients [6]. Typodonts and simulations, by contrast, offer a risk-free, repeatable, and highly customizable means of education that provide unlimited training sessions [2]. They allow students to rehearse specific

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techniques, refine their skills, and build the confidence needed for clinical practice [2]. Moreover, as the complexity of orthodontic procedures grows and as technology in dentistry advances, these training methods offer students the ability to engage with cutting-edge tools and techniques [2, 7].

The move towards more virtual forms of simulation, including 3D models and virtual reality (VR), reflects broader trends in medical and dental education, where digital technologies are increasingly used to enhance learning [8]. Virtual simulations provide an immersive experience, allowing students to visualize complex anatomical structures, interact with digital tools, and receive real-time feedback. This can bridge the gap between theoretical knowledge and clinical practice, offering an educational experience that is more interactive and engaging compared to traditional methods [2, 8, 9]. These advancements in simulation technology also address some of the logistical challenges of analogue training methods, such as limited access to physical materials or time constraints in clinical labs [8].

However, while the benefits of typodont and simulation training are widely recognized, questions remain regarding their effectiveness in fully preparing students for clinical practice. Specifically, it is important to understand whether these methods can adequately equip students with the practical skills, clinical decision-making abilities, and confidence required to treat patients successfully in a real-world setting. This is particularly crucial in orthodontics, where precise technical skills and the ability to adapt to individual patient needs are paramount [10].

This systematic review aims to evaluate the efficacy of both typodont/simulation training in orthodontic education. By synthesizing the existing evidence, this review seeks to determine whether these training methods are sufficient to prepare students for the clinical challenges they will encounter when treating patients. Understanding the strengths and limitations of these approaches is essential for optimizing educational practices in orthodontics and ensuring that students are adequately prepared for their future roles as clinicians.

Methods

This systematic review followed a protocol registered with PROSPERO (ID CRD42024560497), aimed at evaluating the effectiveness of analogue and virtual typodont/simulation training in orthodontic education. The primary outcomes of interest included clinical preparedness, skill acquisition, confidence, knowledge retention, and overall performance in clinical settings. By synthesizing the evidence from various studies, this review sought to provide a comprehensive overview of how these training methods influence orthodontic students' readiness for clinical practice.

Studies included were those focusing on orthodontic students participating in either analogue or virtual typodont/simulation training. Randomized controlled trials, cohort studies, cross-sectional studies, and qualitative research were all considered eligible. Exclusion criteria were applied to studies that did not focus on orthodontic education or lacked specific relevance to typodont/simulation training. Additionally, studies not available in English were excluded to ensure consistency and clarity in data extraction and analysis.

A detailed search strategy was implemented to capture a wide range of relevant studies. The search was conducted across multiple databases, including PubMed, the Cochrane Library, ERIC, and CINAHL, using terms such as "typodont training," "simulation training," "orthodontic education," "clinical preparedness," and "virtual training." To further enhance the search, reference lists of included studies were manually checked for additional relevant articles, and gray literature was reviewed to identify studies that might not have been indexed in the primary databases. The gray literature search included sources such as conference proceedings, institutional reports, and dissertations. Studies identified through these sources were screened using the same inclusion and exclusion criteria applied to database searches. The credibility of gray literature sources was assessed based on relevance, methodological rigor, and availability of sufficient data.

Data extraction was carried out by two independent reviewers using a standardized form to ensure uniformity across the studies. Key information such as study design, participant characteristics, training methods, outcomes measured, and the main findings were systematically extracted. During both the study selection and data extraction phases, any discrepancies between the reviewers were addressed through a structured process. Initial disagreements were discussed, and if consensus could not be reached, a third reviewer was consulted to adjudicate. This approach ensured transparency, minimized potential bias, and guaranteed consistency in data collection and interpretation, forming the basis for a reliable synthesis of the results.

The risk of bias in the included studies was assessed using appropriate tools depending on the study design. For randomized controlled trials, the Cochrane Risk of Bias Tool was used to evaluate potential biases across multiple domains [11]. Observational studies, on the other hand, were assessed using the Newcastle-Ottawa Scale, which provided a structured method to evaluate the selection of participants, comparability of study groups, and assessment of outcomes [12]. As with data extraction, two reviewers independently conducted the bias assessments, with disagreements resolved through discussion, ensuring that the quality of the studies was objectively evaluated.

Due to the heterogeneity in study designs, training objectives, and outcomes among the included studies, a narrative synthesis was deemed the most appropriate method for summarizing the evidence and identifying key themes across diverse research contexts. To assess the overall quality and strength of the evidence, the GRADE approach was applied, offering a clear framework to evaluate the confidence in the cumulative evidence and its implications for orthodontic education and policy [13].

Results

A total of 531 records were identified through database searches, which included PubMed, Cochrane Library, ERIC, and CINAHL. After the removal of 47 duplicate records, an additional 189 records were excluded based on preliminary filters, such as irrelevance to orthodontic education or language restrictions. This process resulted in 295 records that were screened based on their titles and abstracts. At this stage, 231 records were excluded for failing to meet the predefined inclusion criteria. The majority of these studies were excluded due to their lack of relevance to orthodontic education or simulation-based learning, while others focused on broader topics in dental education or reported outcomes unrelated to clinical preparedness or skill acquisition.

Following the title and abstract screening, 64 full-text reports were sought for further review. All reports were successfully retrieved and assessed for eligibility based on the inclusion and exclusion criteria outlined in the protocol. Of these, 53 studies were excluded. The primary reasons for exclusion included a lack of focus on orthodontic education or simulation-based training ($n=4$), the use of study designs that did not meet the inclusion criteria, such as narrative reviews or perspective papers ($n=47$), and insufficient methodological detail or the absence of measurable outcomes ($n=2$). These exclusions ensured that only studies providing robust and relevant data were included in the final synthesis. Ultimately, 11 studies were deemed eligible for inclusion in this systematic review (Fig. 1).

The included studies utilized a range of designs, including randomized controlled trials, quasi-experimental studies, cross-sectional surveys, mixed methods, and Delphi methods. Participants were primarily orthodontic students, with sample sizes ranging from 10 to 108. The training methods examined varied across studies, including VR simulations, case-based education, blended learning, 3D printed models, and scenario simulations. These studies measured outcomes related to clinical education, such as student perceptions, learning motivation, communication skills, and diagnostic performance, providing a comprehensive overview of the efficacy of typodont/simulation training in orthodontic education (Table 1).

The risk of bias for the randomized controlled trials included in the review was generally low across key domains. All studies had a low risk in the randomization process, deviations from intended interventions, and handling of missing outcome data. However, there was some concern regarding the measurement of outcomes in two studies due to reliance on self-reported data, though the overall bias remained low for these studies. The remaining study had no concerns across all domains, resulting in a consistent low risk of bias (Table 2).

The observational studies included in the review were assessed using the NOS, and overall quality was generally high. Most studies received strong scores in the selection and comparability categories, with several studies achieving the maximum score for outcome assessment. Total scores ranged from 6 to 9, with the majority of studies scoring 7 or higher, indicating low to moderate risk of bias. Two studies attained the highest scores, reflecting robust study designs with strong selection processes, comparability between groups, and comprehensive outcome assessments (Table 3).

Discussion

Key themes emerging from recent studies on typodont and simulation training in orthodontics include enhanced attention and engagement, improved learning outcomes, heightened motivation, and strengthened communication and collaboration skills.

Attention and engagement

Simulation-based learning significantly enhances attention and engagement in orthodontic education by creating interactive and stimulating environments. Tools such as case-based scenarios, VR platforms, and 3D models allow students to engage actively with realistic clinical cases, promoting sustained focus and participation [14, 15]. The immersive nature of VR and 3D models further heightened student engagement by replicating real clinical conditions. This immersive learning experience allowed students to manipulate digital tools and interact with orthodontic models in a way that closely mirrored real-world practice, leading to increased involvement and attention [5, 16]. These highly interactive simulations not only captured student interest but also created a dynamic learning environment that fostered sustained engagement and attention throughout the learning process. However, evidence for long-term engagement effects remains limited, requiring further exploration.

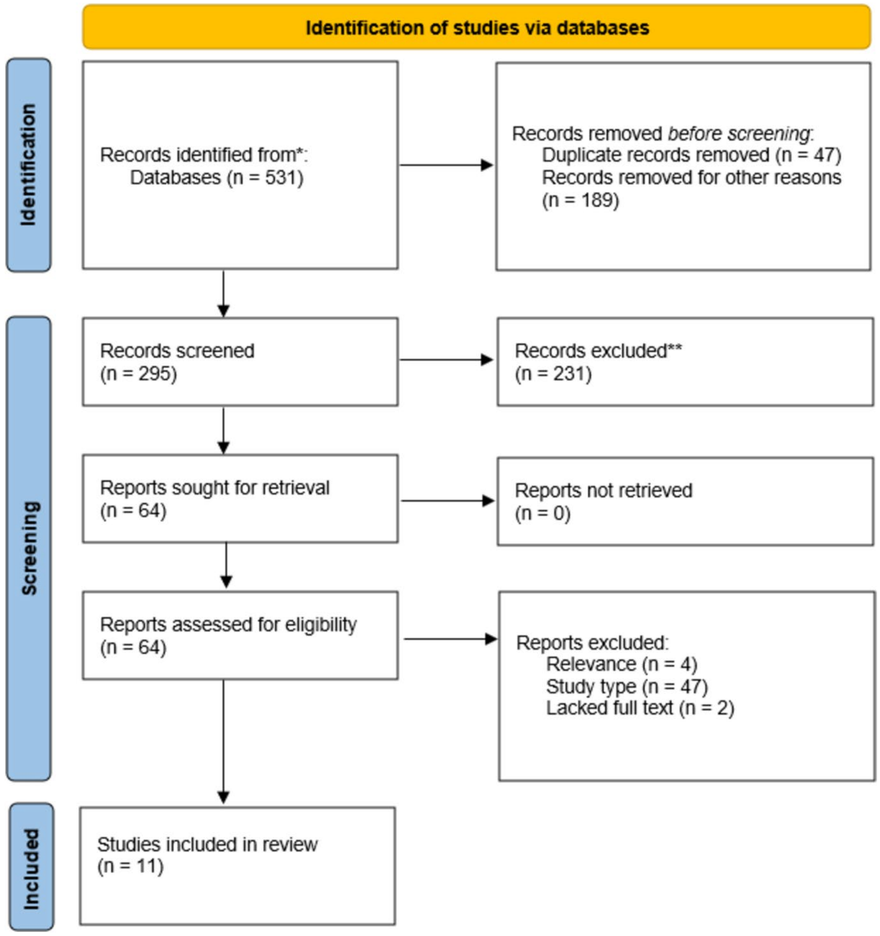

Fig. 1 PRISMA flow diagram

Effectiveness of learning

Simulation-based learning has appears to be effective in helping students develop critical clinical skills, particularly in areas such as diagnosis, treatment planning, and orthodontic procedures like bracket bonding. Simulations provide an interactive and hands-on learning experience, allowing students to practice essential clinical tasks in a risk-free environment. For example, the use of 3D models and virtual simulations enabled students to enhance their diagnostic accuracy and decision-making skills by engaging with real-time, complex orthodontic cases [5, 18]. Additionally, virtual typodont simulations allowed students to visualize and manipulate orthodontic biomechanics, leading to a deeper understanding of force distribution and tooth movement [23].

Beyond current typodont applications, 3D printing has demonstrated broader potential in dental education, particularly in endodontics and implantology, where it replicates real-life tissue properties and color for surgical training [24]. Although such tactile feedback is less critical in orthodontics, 3D-printed CBCT scan data could aid students in analyzing complex anatomical structures, such as impacted teeth requiring intricate movement planning. This highlights an opportunity to integrate 3D printing into orthodontic education to enhance students' spatial and procedural understanding in challenging cases.

Simulations also play an effective role in bridging the gap between theoretical knowledge and practical application in the short term. By providing students with realistic clinical scenarios, simulations allowed them to directly apply theoretical concepts in practice, reinforcing their learning in a more meaningful and integrated manner. Customized 3D-printed typodonts, for example, helped students transition from preclinical to clinical practice by simulating real dental procedures and operative positioning [19]. Similarly, VR simulations offered students repeated opportunities to practice key orthodontic skills, such as bracket bonding, while applying theoretical knowledge to improve their clinical competence [21]. This ability to bridge theory and practice underscores the overall effectiveness of simulation-based learning in

Table 1 Research studies included

Study	Study Design	Participant Characteristics	Training Methods	Outcomes Measured	Main Findings
Balos Tuncer et al. (2022) [14]	Cross-sectional	108 students	Case-based orthodontic education	Student perceptions, ability to interpret orthodontic data	Increased motivation and diagnostic skills; 60% found it improved attention and learning without extra burden
Chen et al. (2023) [15]	Randomized cross-over	102 students	VR simulating orthodontic treatment	Learning motivation, learning experience	VR showed higher student engagement and learning satisfaction compared to PowerPoint analysis
Ho et al. (2022) [5]	Mixed methods	40 students	3D digital dental models (e-models)	Perception of e-models, diagnostic performance	Higher acceptance of e-models, increased mouse-clicks in diagnostic tasks, and improved diagnostic performance
Huang et al. (2022) [16]	Survey-based study	82 students	VR for orthodontic bracket bonding	System usability, student perception, orthodontic skills	High usability and positive perceptions, VR identified as effective for practical skill improvement
Kaggal Lakshmana Rao et al. (2020) [17]	Delphi study	10 expert orthodontists	Delphi method to identify challenges in education	Challenges in orthodontic education	Consensus on educational challenges, need for curriculum refinement and more practical training
Lai et al. (2024) [18]	Experimental	13 novice orthodontists, 3 experts	3D printed simulation for impacted maxillary canines	Clinical reasoning, diagnostic accuracy	3D models enhanced novices' understanding and treatment planning for impacted canines
Lee et al. (2022) [19]	Cross-sectional	45 students	Simulated practice using 3D-printed customized typodonts	Student perceptions, effectiveness of simulation	Positive feedback from 80% of students, suggested improvements to the typodonts and manikins
Lin-na et al. (2023) [20]	Quasi-experimental	40 students	Scenario simulation combined with case teaching	Doctor-patient communication skills	Simulation significantly improved communication skills and patient satisfaction
Liu et al. (2022) [21]	Cross-sectional	94 students	Online virtual orthodontic curriculum with programmatic assessment	Performance on pre-clinical training and theoretical knowledge	High student satisfaction (98%); improved theoretical and practical skills; mean total score: 91.99%
Maresca et al. (2014) [22]	Randomized controlled trial	81 students	Blended learning (online modules + face-to-face) for preclinical endodontics	Manual skills in root canal therapy, conceptual knowledge	BL group scored higher on manual skill exercises ($p = 0.0067$) but no significant difference in conceptual knowledge
Mirmoghtadaie et al. (2022) [23]	Quasi-experimental	50 students	Non-wax typodont vs. virtual typodont methods	Knowledge, attitudes, and performance in orthodontics	Both methods improved learning, but virtual typodont was more effective for understanding biomechanics

Table 2 Cochrane risk of bias summary

Study	Randomization Process	Deviations from Intended Interventions	Missing Outcome Data	Measurement of the Outcome	Selection of the Reported Result	Overall Bias
Lin-na et al. (2023) [20]	Low risk	Low risk	Low risk	Some concern (self-reported)	Low risk	Low risk
Chen et al. (2023) [15]	Low risk	Low risk	Low risk	Some concern (self-reported)	Low risk	Low risk
Maresca et al. (2014) [22]	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk

Table 3 NOS Summary

Study	Selection	Comparability	Outcome	Total Score
Balos Tuncer et al. (2022) [14]	3	2	2	7
Ho et al. (2022) [5]	3	1	2	6
Huang et al. (2022) [16]	3	2	2	7
Liu et al. (2022) [21]	3	2	2	7
Mirmoghtadaie et al. (2022) [23]	3	2	2	7
Kaggal Lakshmana Rao et al. (2020) [17]	4	1	3	8
Lai et al. (2024) [18]	4	2	3	9
Lee et al. (2022) [19]	4	2	2	8

orthodontic education. However, the long-term retention of these competencies remains underexplored.

Motivation and interest in learning

Simulation-based learning has had a notably positive impact on student motivation, with many learners reporting increased interest in orthodontic practice and a greater enthusiasm for further learning. The use of engaging and interactive simulations, such as case-based scenarios and VR, allowed students to actively participate in their learning experience, which heightened their motivation. For instance, students engaged in case-based learning reported that the real-world relevance of the simulated cases significantly increased their motivation to continue learning and deepened their interest in orthodontic practice [14]. Similarly, the immersive nature of VR simulations created a dynamic and engaging environment that further stimulated students' interest in mastering orthodontic procedures, as compared to traditional teaching methods [15].

However, sustaining this high level of motivation over time can be challenging, as the initial novelty of simulations like VR may gradually diminish. While students initially responded with high engagement and motivation, some studies observed that the impact of these simulations decreased as students became more familiar with the technology. Over time, the differences in motivation between VR-based learning and traditional methods narrowed, suggesting that the novelty effect plays a significant role in the initial boost of motivation [15].

Collaboration and communication

Simulation-based learning has been instrumental in fostering collaboration and enhancing communication skills among students. Through group-based simulations, such as case-based and scenario-based learning, students had the opportunity to work together on complex orthodontic cases, improving both their teamwork and peer communication skills. These simulations encouraged active dialogue and problem-solving in a collaborative environment, with over 83% of students reporting improved interactions with classmates as they worked through the simulated scenarios [14]. The cooperative nature of these exercises not only strengthened their ability to communicate within a team but also allowed students to better articulate clinical diagnoses and treatment plans, further refining their professional communication abilities [14].

Scenario-based simulations, in particular, were highly effective in improving doctor-patient communication. These simulations mirrored real-life clinical interactions, requiring students to engage in role-playing both as doctors and patients, thereby practicing communication in a controlled, simulated environment. This dual approach allowed students to refine critical interpersonal skills, such as empathy, active listening, and patient education, which are crucial in orthodontic practice. Studies showed a marked improvement in communication skills among students who participated in these simulations, with significantly higher scores on communication assessment scales compared to those who received traditional lecture-based training [20]. Additionally, these scenario-based exercises enhanced students' ability to manage patient expectations and emotions, fostering a more patient-centered approach to care that is essential for successful orthodontic treatment [20].

Confidence and preparation for clinical practice

Simulation-based learning has shown significant short-term benefits in building students' confidence and preparing them for clinical practice. Repeated practice in controlled, simulation-based environments, such as VR and case-based scenarios, allowed students to gain experience in handling complex clinical tasks. However, the long-term retention of these skills and their application in real-world practice remain unclear, as most studies did not assess outcomes beyond the training period. For example, in VR simulations, students could repeatedly perform procedures and receive real-time feedback, which significantly enhanced their technical abilities and confidence in their clinical skills [16]. Similarly, case-based learning scenarios helped students gain confidence in interpreting clinical data and making diagnostic decisions, giving them a solid foundation for patient care [21].

Simulations facilitate the transition from preclinical to clinical practice by providing realistic, hands-on experiences. For example, 3D-printed typodonts allow students to practice critical clinical tasks in a risk-free setting, reducing anxiety and improving readiness for real-world challenges [19]. These simulations helped reduce anxiety and uncertainty by familiarizing students with clinical workflows and the challenges they would encounter in actual patient care. While these methods have shown clear short-term benefits in preparing students for clinical tasks, the long-term retention of these competencies and their real-world application remain unclear. Future studies should aim to track student performance post-graduation to assess the.

Perceived burden and student workload

While simulation-based learning often requires additional preparation and involvement, students generally perceived the workload as manageable and beneficial to their learning. The immersive and interactive nature of simulations necessitated extra effort in terms of preparation and engagement. However, the majority of students reported that the advantages of this type of learning outweighed any additional strain on their schedules. For instance, over 75% of participants in case-based simulations indicated that they did not find the added workload burdensome, with only a small percentage (6.5%) feeling that the simulations significantly increased their workload [14]. This suggests that while simulation-based learning demands more time and effort, students recognize its value in enhancing their clinical skills and confidence.

Student satisfaction

Overall, students expressed high levels of satisfaction with simulation-based learning methods, particularly those involving VR, 3D models, and blended learning environments. The interactive and immersive nature of these tools provided a more engaging and enjoyable learning experience compared to traditional methods. For instance, students consistently rated VR simulations as highly beneficial, citing increased engagement and practical skill development as key factors contributing to their satisfaction [15, 16]. Similarly, blended learning environments, which combined online modules with hands-on practice, were preferred for their flexibility and convenience, allowing students to learn at their own pace while still benefiting from face-to-face instruction [22]. This combination of digital and physical learning methods proved to be highly effective in enhancing both student satisfaction and learning outcomes. Simulation methods also cater to diverse student preferences, with many favoring a blended approach combining digital tools like e-models and physical typodonts. This adaptability enhances student satisfaction by accommodating individual learning styles [5].

Gender differences in learning

Gender differences were observed in students' experiences with simulation-based learning, particularly in the use of technology such as VR. In some studies, male students reported higher confidence levels in navigating and mastering simulation technologies compared to their female counterparts. For example, male students were more likely to express confidence in using the VR system independently, often requiring less technical support and demonstrating greater comfort with repeated use of the simulation platform [16]. This gender gap in confidence may reflect broader trends in technology use and familiarity, where male students tend to have more experience with digital tools and are therefore more inclined to engage with simulation-based learning environments [16].

While male students appeared to have a stronger affinity for the use of digital simulations, both male and female students demonstrated short-term benefits in skill acquisition and learning outcomes from simulation-based methods [16]. However, there is insufficient evidence to determine whether these benefits persist over time, how they translate into long-term professional competence, or if they differ significantly in real-world clinical settings.

Curriculum improvement and technology integration

Expert consensus highlights the pressing need for reform in orthodontic education, particularly regarding the inclusion of more hands-on training and practical experience. The current curriculum in many institutions is heavily focused on theoretical learning, which limits students' ability to apply their knowledge in real-world clinical settings [17]. Studies have identified a significant gap in practical training, especially during the preclinical and clinical phases, which can hinder the development of essential clinical skills. For example, experts in orthodontic education agree that providing more opportunities for hands-on experience is critical to better preparing students for clinical practice [17]. This disconnect between theory and practice underscores the need for curriculum reform that places a greater emphasis on experiential learning.

One of the most effective ways to address these gaps is through the integration of modern technologies, such as VR and 3D simulations, into the orthodontic curriculum. These technologies allow students to engage with realistic clinical scenarios in a controlled, immersive environment, providing them with the opportunity to practice essential clinical procedures without the risk of harm to patients. By simulating complex orthodontic cases, VR and 3D models enable students to bridge the gap between theoretical knowledge and practical application, reinforcing their understanding of key concepts while improving their clinical skills [17]. The incorporation of these tools into the curriculum not only enhances student learning outcomes but also helps them build the confidence needed to transition successfully into real-world practice.

Web 2.0 technologies provide an additional avenue for enhancing simulation-based learning. For instance, virtual typodonts shared online enable students to practice shared decision-making, receive real-time feedback, and engage in collaborative clinical problem-solving [25]. By offering a flexible, 24-hour accessible platform for training, Web 2.0 tools could supplement traditional simulation methods, providing a more interactive and adaptable learning environment. Integrating these technologies into orthodontic curricula could further improve student engagement and accessibility.

Challenges in simulation-based learning

Despite the overall positive impact of simulation-based learning in orthodontic education, several challenges were identified across the included studies. One common challenge was the perception of additional workload associated with case-based learning scenarios. While most students reported that the benefits outweighed the extra effort, a minority found the increased preparation time burdensome [14]. Technical challenges were also frequently reported, particularly in studies involving VR platforms. Although VR was generally effective in enhancing learning motivation and engagement, some students struggled with the learning curve and technical issues associated with the use of advanced digital tools [15]. Additionally, several studies also emphasized the need for a more balanced approach to integrating digital simulations with traditional methods. For example, while e-models were well received, students expressed a preference for using them alongside physical models, suggesting that digital tools alone may not fully replace traditional learning methods [5]. This blended approach was seen as more effective in ensuring students gained both practical and digital skills.

Future directions

Simulation-based training methods, while central to orthodontic education, hold significant potential for broader application in dental education. These methods, including typodonts, 3D models, and VR, can be adapted to other specialties such as prosthodontics and pediatric dentistry, where manual precision and clinical decision-making are equally critical. For instance, 3D-printed models can enhance crown and bridge preparation techniques, while scenario-based VR simulations may play an essential role in training students to manage pediatric patient behavior. Expanding the use of these methods across dental disciplines would foster a more comprehensive and interdisciplinary learning environment, equipping students with skills applicable to various clinical contexts.

While the studies included in this review highlight the short-term benefits of simulation-based training, the long-term retention of skills and their real-world application remain underexplored. Longitudinal studies are needed to evaluate whether the competencies developed through these training methods persist over time and lead to improved clinical outcomes. Tracking the clinical performance of students post-graduation could provide valuable insights into the durability and efficacy of these approaches in practice.

To maximize the impact of simulation-based learning, educators should consider integrating these methods into orthodontic curricula through practical strategies. A blended learning approach that combines simulation technologies with traditional teaching methods, such as typodonts alongside lectures and clinical shadowing, can provide students with a well-rounded educational experience. Simulations can also be tailored to specific clinical tasks, such as bracket placement or wire bending, ensuring that students develop targeted competencies in a controlled environment. Additionally, institutions should invest in cost-effective yet high-fidelity simulation tools to make advanced technologies accessible to a broader range of students.

Faculty training programs are essential to help educators effectively implement and adapt these tools for diverse student needs. Incorporating repeated practice opportunities within curricula can address skill retention and boost student confidence. Furthermore, ongoing assessment and feedback mechanisms, such as performance metrics integrated into VR simulations, can help monitor student progress and identify areas requiring improvement.

Future research should also focus on standardizing simulation technologies and evaluation metrics to enable meaningful comparisons across studies. The variations in simulation fidelity, software quality, and immersive features identified in this review underline the need for consistent tools and reporting standards. Comparative research examining traditional methods alongside blended and purely digital approaches could help determine optimal combinations that balance cost, accessibility, and efficacy.

Strengths and limitations

This systematic review offers several strengths that contribute to its relevance and rigor in assessing the effectiveness of typodont and simulation-based learning in orthodontic education. One major strength is the comprehensive inclusion of diverse simulation methods—ranging from case-based learning and VR to 3D models—providing a broad perspective on the various ways simulation technologies can enhance clinical skills, motivation, and communication. Additionally, the use of multiple study designs, including randomized controlled trials, cross-sectional studies, and quasi-experimental designs, adds depth and robustness to the findings. The inclusion of both objective assessments (such as diagnostic performance) and subjective reports (such as student satisfaction) strengthens the review by offering a well-rounded evaluation of simulation-based learning outcomes.

However, this review also has some limitations that should be considered. The included studies exhibited considerable variability in their research designs, participant characteristics, and training objectives. This heterogeneity presents challenges in directly comparing outcomes and may limit the generalizability of the findings. Additionally, the variability in VR technology used across the included studies represents a significant limitation. The studies utilized a range of VR systems differing in levels of sophistication, including variations in software fidelity, hardware quality, and immersive features such as visual and auditory components. These discrepancies may have influenced the outcomes, as the educational efficacy of VR tools can depend heavily on the quality of the technology used. For instance, higher-fidelity systems with realistic simulations may provide a more engaging and effective learning experience compared to basic systems with limited functionality. This inconsistency makes direct comparisons between studies challenging and limits the generalizability of findings.

Several studies relied on self-reported outcomes, which may introduce bias and limit the objectivity of the results. Additionally, variability in evaluation metrics, particularly in assessing clinical competence and learning outcomes, posed challenges to synthesizing findings. These uncertainties highlight the need for standardized, validated tools to ensure consistency and comparability across studies.

Conclusion

Typodont and simulation-based learning has shown significant short-term benefits in orthodontic education, enhancing students' clinical skills, diagnostic abilities, communication, and overall preparedness for clinical training. However, the long-term retention of these skills and their translation to patient care remain uncertain, underscoring the need for longitudinal studies to evaluate their enduring impact. To ensure the sustained effectiveness of simulation-based learning, future research should prioritize strategies for maintaining student motivation as the novelty of these technologies diminishes over time. Additionally, longitudinal studies are needed to evaluate how these methods impact clinical performance post-graduation. Curriculum development should aim to integrate simulation technologies alongside traditional approaches, leveraging their strengths while addressing existing challenges such as variability in software fidelity and student preferences. By embracing these advancements and addressing current gaps, simulation-based learning can remain a central component of orthodontic training, equipping students with the skills and confidence needed to meet the evolving demands of modern orthodontic practice.

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Authors' contributions
M.B. conceptualized the study and was also in charge of data curation, formal analysis, investigation, methodology, writing—original draft preparation, and writing—review and editing. Z.B. and K.K. provided supervision.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

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Not applicable.

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