Review Article

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Simulation technologies in dental education: achievements, limitations and prospects

Denis A. Moiseev, **Sergey A. Tregubov**, **Anastasia K. Shataylo**, **Fatma V. Gedik**, **Vladislav D. Stasevich**, **Victoria M. Sheveleva**, **Alexander I. Marushkov**

Pirogov Russian National Research Medical University, Moscow, Russia

moiseeff.den@yandex.ru

Abstract

INTRODUCTION. Modern dental education is facing the need for transformation in the context of a shortage of clinical bases, ethical constraints and growing demands on the quality of graduate training. Simulation technologies are considered as a key tool for solving these problems.

AIM. The purpose of this PICO study was to answer the following question: «Can simulation training be considered as an alternative to the traditional practical training of dental students? »

MATERIALS AND METHODS. A systematic review was conducted in accordance with the principles of PRISMA 2020. Publications for 2015-2025 were searched in 8 electronic databases (PubMed, Cochrane, Ebsco, Embase, Web of Science, ScienceDirect, SciELO and eLibrary). After eliminating duplicates and applying selection criteria, the review included 25 relevant publications.

RESULTS. Simulation technologies demonstrate significant potential in improving manual skills. The key advantages are the endless repeatability of procedures, instant feedback and objective evaluation. However, serious limitations have been identified: unrealistic tactile feedback, functional narrowness (64% of solutions focus only on dissection), high cost of equipment ($100,000+), resistance from teachers, and methodological heterogeneity of research. An important risk is the formation of «hyper-confidence» among students and a lack of clinical thinking due to the absence of the human factor in the simulations.

CONCLUSIONS. Despite impressive results in standardized procedures, simulation technologies cannot completely replace traditional learning. Their successful integration requires overcoming economic, methodological and pedagogical barriers. The future is seen in creating hybrid educational ecosystems, where technological precision is complemented by the development of empathy and clinical thinking, and open standards and international cooperation help overcome barriers.

Keywords: training, simulation technologies, dentistry, education, simulators, phantoms, virtual reality

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Симуляционные технологии в стоматологическом образовании: достижения, ограничения и перспективы

Д.А. Моисеев, **С.А. Трегубов**, **А.К. Шатайло**, **Ф.В. Гедик**, **В.Д. Стасевич**, **В.М. Шевелева**, **А.И. Марушков**

Российский национальный исследовательский медицинский университет имени Н.И. Пирогова, г. Москва, Российская Федерация

moiseeff.den@yandex.ru

Резюме

ВВЕДЕНИЕ. Современное стоматологическое образование сталкивается с необходимостью трансформации в условиях дефицита клинических баз, этических ограничений и растущих требований к качеству подготовки выпускников. Симуляционные технологии рассматриваются как ключевой инструмент для решения этих задач.

ЦЕЛЬ. Целью данного исследования (по PICO) было ответить на следующий вопрос: «Можно ли рассматривать симуляционное обучение как альтернативу традиционной практической подготовке студентов-стоматологов?».

МАТЕРИАЛЫ И МЕТОДЫ. Проведен систематический обзор в соответствии с принципами PRISMA 2020. Поиск публикаций за 2015-2025 гг. осуществлен в 8 электронных базах (PubMed, Cochrane,

Ebsco, Embase, Web of Science, ScienceDirect, SciELO и eLibrary). После исключения дубликатов и применения критериев выбора в обзор вошли 25 релевантных публикаций.
РЕЗУЛЬТАТЫ. Симуляционные технологии демонстрируют значительный потенциал в улучшении мануальных навыков. Ключевыми преимуществами являются бесконечная повторяемость процедур, мгновенная обратная связь и объективная оценка. Однако выявлены серьезные ограничения: нереалистичная тактильная обратная связь, функциональная узость (64% решений сфокусированы только на препарировании), высокая стоимость оборудования ($100,000+), сопротивление преподавателей и методологическая неоднородность исследований. Важным риском является формирование «гиперуверенности» у студентов и дефицит клинического мышления из-за отсутствия в симуляциях человеческого фактора.
ВЫВОДЫ. Несмотря на впечатляющие результаты в стандартизированных процедурах, симуляционные технологии не могут полностью заменить традиционное обучение. Их успешная интеграция требует преодоления экономических, методологических и педагогических барьеров. Будущее видится в создании гибридных образовательных экосистем, где технологическая точность дополняется развитием эмпатии и клинического мышления, а открытые стандарты и международное сотрудничество помогают преодолеть барьеры.

Ключевые слова: обучение, симуляционные технологии, стоматология, образование, тренажеры, фантомы, виртуальная реальность

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INTRODUCTION

Modern dental education is undergoing an active transformation driven by the rapid development of digital technologies and the shift in the paradigm of clinical training. Traditional educational approaches, based on work with phantom models and direct participation in patient care, are gradually being supplemented by innovative simulation technologies such as virtual reality (VR), augmented reality (AR), haptic simulators with tactile feedback, and artificial intelligence (AI) for clinical decision analysis [1–3]. These tools enable modeling of a wide range of clinical scenarios, ensuring safety, standardization, and high training efficiency.

In the context of a global shortage of clinical training facilities and ethical restrictions associated with practicing on real patients, simulation technologies are becoming an indispensable component of preparing future dentists. The COVID-19 pandemic demonstrated the necessity of remote and hybrid learning formats, where VR/AR simulators and online simulation platforms played a critical role in maintaining continuity of the educational process. Increasing demands for the quality of healthcare require graduates to possess not only theoretical knowledge but also well-developed practical skills, which cannot be achieved without repeated performance of procedures in a controlled environment [3–5].

However, the implementation of simulation technologies faces several challenges. These include high equipment costs, the need to adapt educational curricula, an insufficient evidence bases on long-term effectiveness, and resistance from instructors accustomed to traditional teaching approaches. There is also a risk of excessive virtualization of education, which may lead to a lack of real clinical experience for students. It is crucial to focus on maintaining a balance between technological innovations and fundamental principles of clinical training, as well as to assess the impact of simulators on the level of professional competence among graduates [3; 6–8].

In this systematic review, we conducted a critical analysis and synthesis of current data on the role of simulation technologies in dental education, highlighting key achievements, methodological limitations, and future perspectives for integration of these technologies into the educational process.

MATERIALS AND METHODS

The methodology of this study complies with the requirements for systematic reviews and meta-analyses as outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 (PRISMA-P) guidelines.

The objective of this study (according to the PICO framework) was to address the following question: “Can simulation-based training be considered an alternative to traditional practical education for dental students?” The elements of the review related to the population (P), intervention (I), comparison (C), and outcome (O) are presented in Table 1.

Table 1. Eligibility criteria (PICO)

Таблица 1. Критерии отбора (PICO)

Criteria	Elements
Population (P)	Dental students
Intervention (I)	Simulation-based training
Comparison (C)	Training without simulation
Outcome (O)	Acquisition of practical skills within the educational curriculum

Information sources. The search for publications was conducted across eight electronic databases: PubMed, Cochrane, EBSCO, Embase, Web of Science, ScienceDirect, SciELO, and eLibrary, covering the period from 2015 to 2025.

Electronic search strategy. The following keywords and Boolean operators (in both Russian and English) were used with MeSH terminology: “(dental education [MeSH] OR dental students) AND (simulation training [MeSH])”. Identification and screening of sources were performed by six researchers (S.A., A.K., V.D., V.M., A.I., F.V.) with support from a seventh reviewer (D.A.) to resolve unclear and conflicting results. Additionally, the reference lists of identified papers were reviewed and relevant studies were selected manually.

Data collection process. The search was performed by six researchers (S.A., A.K., V.D., V.M., A.I., F.V.) with the support of a seventh author (D.A.), and the latest update was conducted on July 30, 2025. No language restrictions were applied. After removing duplicates and automatically marked irrelevant records, articles were screened by title and abstract in accordance with the inclusion criteria described below.

Inclusion criteria. The review included peer-reviewed articles evaluating the training of healthcare professionals using simulation technologies, including such fields of dentistry as prosthodontics, oral surgery, maxillofacial surgery, restorative dentistry, and pediatric dentistry. Studies involving the use of simulation technologies in dental anesthesia and emergency dental care were also included. After data extraction, all selected studies were analyzed, systematized, and summarized without differentiating between study designs included in this systematic review.

Exclusion criteria. Publications were excluded if they were descriptive papers lacking structured results and conclusions; studies with insufficient data for extraction; studies not involving dental students; studies without assessment of student learning outcomes; letters to the editor; commentaries; and unpublished work.

Quality assessment. All articles selected for inclusion in this systematic review were assessed for methodological quality, reporting standards, and compliance with the STROBE statement.

Risk of bias. Controversial decisions regarding inclusion or exclusion of studies were resolved through discussion. Disagreements led to a joint re-assessment until consensus was reached. The decisive vote was held by D.A.

Initially, publications were screened by date, title, and abstract (1,875 publications). Duplicates were removed to ensure all remaining publications were represented once. Subsequently, papers were selected based on title, abstract, and conclusions. A total of 589 publications were excluded due to lack of relevance. The selection and analysis process are presented as a flow diagram (Fig. 1).

According to the eligibility criteria, 25 publications were finally included in the systematic review.

RESULTS

Technological advancements and limitations

Simulation technologies integrated into dental education represent a dual phenomenon: on the one hand, they introduce a new era of unprecedented precision and accessibility in training, while on the other hand, they expose systemic contradictions inherent to technological progress itself. Modern VR-simulators such as the Simodont dental trainer (MOOG, Netherlands) and DentSim (Image Navigation, USA) demonstrate strong performance in developing manual skills compared to conventional preclinical methods [9], enabling students to achieve an overall occlusal convergence angle of 12.46° versus 15.22° among those trained traditionally – a statistically significant difference even for experienced clinicians. One of the distinctive features of Simodont is the inclusion of a radiographic image for each case, allowing students to diagnose and plan treatment relying both on the virtual anatomy and radiographic data, thereby closely replicating clinical environments [9; 10]. A comparison of selected virtual and conventional simulators is provided in Table 2.

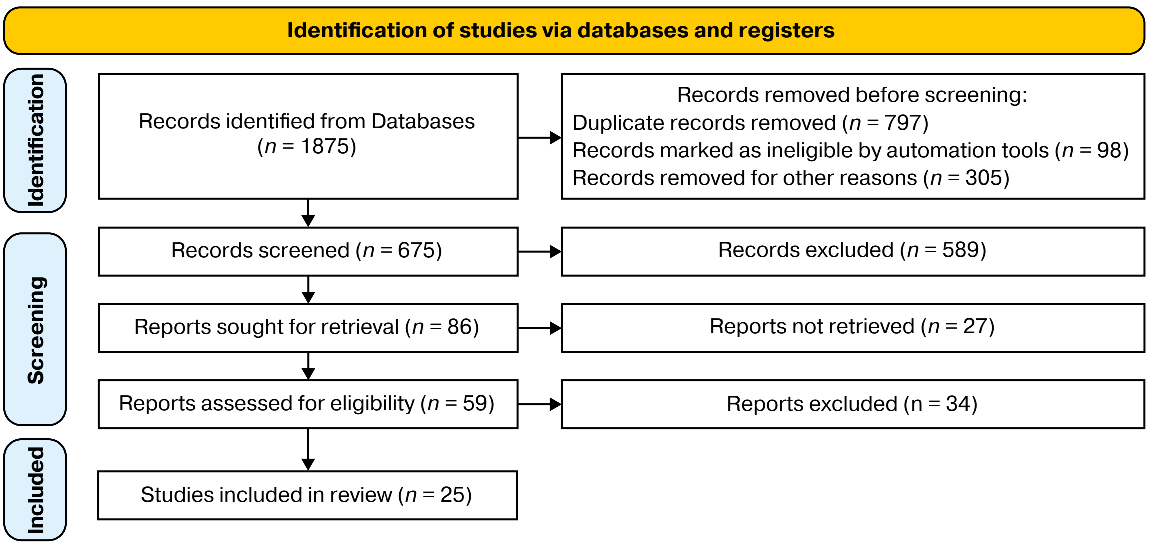

Fig. 1. Criteria for the selection of publications

Рис. 1. Критерии отбора публикаций

This progress is driven by the unique combination of infinite procedure repetition and instant feedback converting every mistake into a learning opportunity and every movement into a refined algorithm. Devices like Mirrosistant (Xuanyu, China), integrating a physical mirror with virtual exercises, redefine instrument-handling skills: a 26% reduction in procedural time and a 15% improvement in performance accuracy [11] indicate not only effectiveness but the emergence of a new educational paradigm where digital metrics replace subjective instructor assessments.

However, behind this seemingly flawless technological image lies a complex network of constraints. Haptic feedback intended to imitate tissue resistance remains unrealistic: 79% of Simodont users report a "plastic-like" dentin texture [12], while 50% of students using HVRS (Haptic Virtual Reality Simulator, SensAble Inc.) describe the sensation as "cutting through butter" [13]. These descriptions are not merely complaints but indicators of a fundamental issue: algorithms simulating mechanical tissue properties overlook their biological variability. Differences in density between healthy and carious dentin, or in the elasticity of enamel in young versus elderly patients, remain outside current digital modelling, contributing to a potentially risky gap between virtual training and real clinical practice.

Technological limitations are also reflected in functional narrowness: while 64% of commercial solutions are focused on tooth preparation [14], critical aspects such as soft-tissue interaction (tongue, lips) and saliva control remain largely unexplored terrain for developers. Attempts to integrate simulators into surgical disciplines resemble navigating a minefield: in orthognathic surgery, where precision is measured in fractions of a millimeter, even advanced systems such as NeuroTouch (CAE Healthcare, Canada) show inaccuracies that are unacceptable in real-world practice [15].

Technical inconsistencies aggravate these challenges: 3D-glasses required in Simodont prevent the use of magnification systems – essential tools in contemporary dentistry [12]. This reflects a mismatch between engineering ideals and clinical reality: students who spend years perfecting techniques on virtual trainers may struggle when encountering real patients with anatomical variations and human factors that disrupt standardized algorithms [16]. As highlighted by Bakr et al., despite rapid development of VR in dental education, current simulators cannot fully replace supervised mentorship because they lack the element of real verbal communication and psychological variability of patients [17].

The emergence of open-source platforms such as OpenSimulator (opensimulator.org) challenges commercial dominance, enabling institutions to tailor modules to specific clinical objectives [14]. Artificial intelligence (AI), capable of analyzing more than 120 parameters of student movements [7; 18], transforms simulators from passive trainers into active "digital mentors" predicting up to 78% of clinical errors before they occur [15].

Nevertheless, these technological breakthroughs require deeper conceptual reflection. When algorithms begin to dictate what constitutes "ideal preparation", there is a risk of losing clinical reasoning – the very creative component distinguishing a clinician from a technician. Achieving a balance between digital precision and medical intuition becomes a key challenge for educational systems striving to train thoughtful clinicians capable of adapting to the unpredictability of real practice.

In this context, simulation technologies should not be viewed as a panacea but as a powerful catalyst of transformation, whose full potential will be realized only through their thoughtful integration into the wider ecosystem of healthcare education – where digital accuracy complements, but does not replace, human expertise.

Methodological heterogeneity and validation

Simulation technologies positioned as a new standard in dental education remain embedded in a system where fragmented research protocols and the absence of unified validation criteria create an illusion of progress that conceals a substantial evidence gap. Analysis of the methodological landscape reveals an alarming trend: the vast majority of studies on VR-based training and haptic simulators operate in parallel domains, as if examining different phenomena altogether. In maxillofacial surgery, for example, only 10 out of 35 studies meet rigorous randomized controlled trial criteria, while the rest fluctuate between descriptive reports and observational accounts where control groups are replaced with subjective instructor impressions. This asymmetry leads to contradictory conclusions: while some authors celebrate a 25% improvement in osteotomy accuracy achieved through simulation training, others report statistically insignificant differences, leaving the question of real technology effectiveness unresolved [2].

Table 2. Comparison of virtual and traditional simulators
Таблица 2. Сравнение виртуальных и традиционных симуляторов

Parameter	Simodont (MOOG, Netherlands)	Virteasy (VirTeaSy Dental, France)	Kavo (KaVo Dental GmbH, Germany)
Model personalization	Yes [1]	No [10]	No
Objective assessment	120+ parameters [1; 12]	20 parameters [10]	instructor's subjective assessment
Cost per hour of use	15$ [1; 12]	10$ [10]	45$
Haptic feedback	6.7/10 [1; 12]	5.2/10 [10]	9.2/10

In dentistry, the situation is further complicated by fragmented approaches to validation, where ambitious claims about an educational “revolution” are supported by superficial assessments. Validation in dental education is defined as a process of gathering evidence to substantiate the interpretation and use of performance outcomes. It is considered a hypothesis to be empirically verified by prioritizing and testing key assumptions. Messick’s model structures the evidence across content, process, internal structure, relationships, and consequences of learning. The eight-step approach includes defining the construct, identifying decision points, selecting instruments, data acquisition and analysis, and evaluating the applicability of results. Such a systematic framework strengthens training quality and links skill assessment to real clinical outcomes. More rigorous justification and proof of assessment significance are required to ensure educational impact [8].

A representative example is the Simodont platform: despite its ability to differentiate novice from advanced learners using more than 120 performance metrics, it remains blind to the essential question – how well do these metrics translate into the ability to avoid iatrogenic perforation or select the most appropriate anesthesia technique for an anxious patient? [7].

The lack of long-term investigations further restricts the validity of conclusions regarding simulation technologies: 89% of studies on haptic training devices are limited to three-month follow-up periods, producing a perception of success that dissolves when transitioning to real-world clinical settings. Local initiatives, such as Japanese emergency care programs focusing on simulation of hypertensive crises during dental procedures, remain linguistically isolated: only 12% of Asian studies are accessible in English, limiting the availability of valuable data to the global community [19]. This fragmentation not only slows scientific progress but also reinforces an academic hierarchy where “Western” technologies dominate and regional developments remain marginalized.

Methodological gaps manifest in clinical practice with concerning clarity. Conflicting recommendations – where some studies advocate VR-training as a breakthrough in pediatric dentistry while others document a lack of measurable benefit – place faculty in a difficult position [10; 13]. Simulators validated exclusively on junior learners fail to support advanced training, as demonstrated in neurosurgical education, where 78% of systems were never evaluated with experienced surgeons [15]. Even more concerning, institutions heavily investing in virtual tools risk producing a generation of “digital-dependent” clinicians unable to manage unpredictable real-patient scenarios [16].

Examples of methodological insufficiency serve as strong cautionary notes. The studies by Zafar et al., in which 89.9% of students expressed enthusiasm for VR-based anesthesia training but none passed objective clinical competence testing, reveal the gap between subjective satisfaction and real proficiency [13; 20]. Adoption of Messick-based validation, mandatory control group inclusion, and development of international research registries similar to CONSORT are not bureaucratic exercises but essential safeguards for evidence-based education [2; 14]. Focusing on translational outcomes – such as those measurable by the McGagh scale – shifts attention from “attractive metrics” to the true ability of simulators to support real clinical success [14].

However, these measures alone cannot resolve inherent systemic contradictions. High-fidelity simulators like NeuroTouch, exceeding $300,000 in cost, remain inaccessible for 80% of institutions, rendering evidence-based technology a privilege rather than a standard [15]. Moreover, a dramatic increase in publication volume (from 10 to more than 200 papers over a decade) has not been accompanied by growth in methodological quality: only 15% of studies meet Level 1A evidence, while the remainder demonstrate a high risk of systematic bias [16].

This disconnects – between quantity and quality, innovation and accessibility – questions the feasibility of developing universal standards in a world where technological inequality becomes a new form of educational segregation. The solution lies not in mechanical standardization but in a conceptual shift: simulation technologies should be evaluated as components of a comprehensive educational ecosystem, where digital precision is complemented by clinical judgment and artificial intelligence serves to enhance – not replace – human expertise. Only through such systemic realignment can methodological chaos give way to a coherent framework in which each study becomes a foundation stone for future progress – ensuring that technology remains in service of the clinician and the patient, not the reverse.

Economic and organizational barriers

Simulation technologies, often promoted as a vehicle for democratizing dental education, reveal a critical paradox in practice: instead of reducing disparities between educational systems, their implementation amplifies the divide between digitally empowered learners and those with limited technological access. Economic realities expose a structural imbalance in which equipment costs function as a social filter, excluding entire regions from innovation. Premium simulators such as Simodont – priced at more than $100,000 – have become symbols of a new educational divide: while 80% of institutions in the United States and European Union integrate VR-based training into the curriculum, the adoption rate in African and South American countries barely reaches 9%, forcing students to rely on outdated phantom models from the 1980s [19; 21]. Even Japan, recognized for its advanced health education ecosystem, reports that 60% of programs still rely on early-2000s simulators with limited functionality and no validated performance metrics [19].

The true cost of these technologies, however, lies in the hidden financial commitments that destabilize institutional budgets post-implementation. Annual maintenance for Simodont amounts to 15–20% of the purchase price, supplemented by recurring expenses such as software upgrades costing approximately $10,000, faculty training exceeding $5,000 per instructor, and continuous IT infrastructure modernization. These cumulative outlays transform simulators from strategic investments into high-risk budgetary liabilities [3; 12]. Institutions adopting systems such as Mirrosistant report reallocating up to 25% of their operating budget to digital infrastructure at the expense of clinical placements [11]. Promises of long-term cost reductions – such as a projected 30% savings in materials – fail to materialize when amortization timelines overtake the functional lifespan of the equipment, leaving universities with obsolete systems and unrecouped investments [12].

Organizational constraints further exacerbate economic variance. The transition to simulation-centered education demands radical curricular redesign, a change met with resistance from 34% of faculty who perceive technological platforms as threats to traditional expertise and pedagogical authority [10]. A generational divide becomes operational: instructors with decades of experience using phantom-based training often decline to invest 40–60 hours required to master VR interfaces, while administrations are reluctant to finance faculty retraining at $2,000–$5,000 per individual [4]. At the infrastructural level, 55% of institutions are unable to meet baseline performance requirements for simulation software, resulting in degraded system operation characterized by lag and rendering failures [11; 21].

User experience reflects this systemic tension. Although 89.9% of students report high satisfaction with VR-training in anesthesia, 56.4% reject the notion that it can replace real procedures, citing a lack of emotional and procedural stressors inherent to direct patient care [15]. Global adoption also introduces anthropometric bias: systems designed for standard European craniofacial features inadequately represent anatomical characteristics typical of Asian populations – such as narrower root canal morphology and enamel mineralization patterns – undermining training relevance in regional clinical contexts [12; 19; 21].

These constraints feed a cycle that limits innovation. Restricted funding reduces development of learning modules for high-complexity specialties such as endodontics and periodontology, diminishing the interest of industry partners who tend to support more commercially visible domains [14]. Nevertheless, several emerging models challenge traditional cost barriers. Public-private partnerships (e.g., Bandiaky et al.), in which pharmaceutical companies offset up to 50% of simulator acquisition costs in exchange for anonymized training data, represent a hybrid solution bridging commercial and educational priorities [14]. Open-source simulation platforms – reducing total cost of ownership by approximately 40% through collaborative development and modular expansion – provide an accessible alternative to proprietary monopolies [4]. International standardization such as ISO 23907:2025, focused on interoperability and validation requirements, may additionally decrease integration costs, though only if implemented without suppressing regionally developed innovations previously sidelined by restrictive patent ecosystems [12; 19].

Paradoxes, however, persist. Institutions adopting VR systems report enrollment increases up to 25%, yet remain at constant risk of technological obsolescence as each software update demands renewed capital investment [4]. "Path dependency" perpetuates outdated practices: 62% of universities continue to rely on low-cost phantoms not due to superior outcomes but due to institutional inertia prioritizing entrenched workflows over pedagogical advancement [16].

Within this environment, simulation technologies function not merely as instructional tools but as diagnostic instruments revealing structural contradictions in contemporary health education – torn between innovation and feasibility, digital progress and equitable access. Resolving these contradictions requires a paradigm shift from technology-centric modernization to a values-driven framework in which simulation serves as a means to achieve educational justice, ensuring that digital transformation enhances, rather than restricts, clinical training opportunities worldwide.

Psychological and pedagogical aspects

Simulation-based technologies, positioned as a universal driver for enhancing dental education, exert an ambivalent influence on learner psychology and teaching strategy, generating a complex mix of aspiration and dissatisfaction. On one hand, they provide a sense of safety, enabling students to make errors without risk to patients. While the reduction in anxiety during initial clinical procedures is well documented [15; 20], a substantial proportion of learners struggle to adapt to real-life variability due to the limited diversity of simulated scenarios [16]. On the other hand, the technologies themselves generate new stressors: 50% of Simodont users report frustration caused by delayed haptic feedback, and 32% of novices abandon VR training after the first sessions, describing the experience as "digital disorientation", where physical perception fails to align with the virtual environment [13; 18]. This contradiction – reduced fear of real procedures accompanied by the emergence of technology-specific anxiety – reflects the broader psychological challenges of the digital era, in which promised comfort often comes with unpredictable cognitive burdens.

Confidence built through simulation also demonstrates a dual nature. Students practicing cavity preparation with Mirrosistant show a 25% increase in self-efficacy, improved precision of manual movements, and enhanced spatial perception, as if digital performance metrics reveal otherwise invisible nuances [11]. However, such confidence may be unstable: 22% of high-performing Simodont graduates make clinical errors driven by overconfidence in skills acquired exclusively in virtual environments [16]. Gamification increases learning motivation by up to 40% through badges and ranking systems, transforming practice into a competitive quest. At the same time, external rewards risk overshadowing intrinsic professional commitment, shifting focus toward performance metrics rather than understanding the true clinical rationale behind procedures [1; 22].

A central challenge lies in the development of clinical reasoning – the core competency that differentiates a doctor from a technical operator. Many systems prioritize mechanical skill execution (90% of maxillofacial surgery simulators overlook differential diagnostic decision-making), thus shaping “digital craftsmen” who perform flawless preparations in sterile virtual conditions but show uncertainty in managing patients with comorbidities such as diabetes or cardiovascular disease [1; 2]. The absence of a “human factor” – a child resisting treatment, an anxious patient trembling in the chair, or cognitive limitations in elderly individuals – results in a concerning gap: 67% of educators report that VR-trained graduates demonstrate weaker empathy and less nuanced patient communication, resembling interactions with automated assistants – technically correct, yet emotionally constrained [4].

Automated feedback creates another dilemma. Detailed performance reports – up to 45 objective parameters in Simodont – accelerate skill acquisition by 35% [10]. However, such “digital hyper-supervision” can suppress reflective thinking: learners rely on algorithmic evaluation and lose the habit of critical self-assessment. DentSim-based research shows a paradoxical trend: students who independently reflected for at least 15 minutes after a session achieved 20% superior results, yet only 12% demonstrated this behavior without system prompting, as though internal judgement had been replaced by automated analytics [22].

The impact of technology may escalate into distortion of clinical professionalism. In Japanese programs, where 45% of students trained primarily on simulators exhibited “robotized” behavior, local anesthesia became a purely technical execution lacking patient interaction or explanation [19]. Overconfidence developed in virtual environments led to clinical errors in 22% of graduates – as if the digital avatar obscured the fact that a real patient’s pain cannot be reduced to binary input [16].

Mitigating these risks requires balanced instructional design rather than withdrawal from innovation. Hybrid learning models that align VR simulation with role-playing sessions – featuring standardized patients portraying anxiety or behavioral challenges – help align digital accuracy with human empathy [4; 19]. Incorporating scenario-based decision modules where treatment planning depends on patient history, not just drill angulation, shifts educational emphasis toward diagnostic judgement and holistic reasoning [2; 14]. Training faculty to interpret simulator-generated data – not as surveillance, but as a tool for structured, individualized skill development – transforms simulation from a controlling mechanism into an enabler of educational personalization [4; 22].

Application of simulation technologies across dental disciplines: comparative analysis

Simulation technologies implemented in dental education exhibit significant variability in performance, reflecting the intrinsic link between the technological maturity of digital tools and the clinical complexity of each discipline (Table 3).

In restorative dentistry – where procedural standardization is high – platforms such as Simodont Dental Trainer and Virteasy (VirTeaSy Dental, France) demonstrate consistently strong outcomes [10; 23]. Their effectiveness is driven by advanced analytic modules that assess up to 120 performance parameters, including applied force and handpiece trajectory, transforming each motion into an objective digital metric subject to ongoing optimization [12].

In prosthodontics – a field highly dependent on anatomical personalization – technology confronts a distinct human-machine interaction barrier. The integration of patient-specific 3D scans into Simodont supports clinically relevant preparation training and reduces errors during crown and post-and-core procedures [1]. However, editing STL files remains labor-intensive, requiring up to two hours per case and shifting focus toward engineering workflows rather than clinical decision-making [1].

Maxillofacial surgery, with its demand for sub-millimeter precision, serves as a stress test for current simulation capabilities. The persistent discrepancy between virtual excellence and operative performance highlights technological limitations in replicating real-tissue biomechanics – elasticity, vascular response, and dynamic changes during surgical manipulation. Even anatomically accurate 3D-printed phantoms remain static constructs within a highly dynamic surgical reality [2].

Pediatric dentistry – where success depends equally on technical proficiency and behavioral management – exposes yet another technological gap. VR systems such as SIMtoCARE Dente (Simtronics, Germany), which enable pulpotomy access training on primary teeth, improve students’ anatomical understanding but overlook the primary determinant of clinical success: interaction with a child patient [24].

Table 3. Comparison of simulation technologies in different dental disciplines

Таблица 3. Сравнение симуляционных технологий в разных стоматологических дисциплинах

Discipline	Skill Improvement	Main Barrier	Promising Technology
Therapeutic Dentistry	+	Lack of realistic haptic feedback	AI-adaptive simulators [18]
Prosthetic Dentistry	+ [1]	Labor-intensive personalization	Cloud-based clinical case libraries [1]
Oral and Maxillofacial Surgery (OMFS)	+25% [2]	Absence of skill transfer	3D-printed biomimetic phantoms [15]
Pediatric Dentistry	+30% [9; 24]	Limited gamification	Interactive AI-driven avatars [9; 24]
Periodontology	+20% [14]	Shortage of specialized solutions	AR with biological feedback [14]

Attempts to fill this gap using interactive avatars still fall short. Current behavioral algorithms remain simplistic and cannot reproduce the emotional complexity of pediatric communication. Interestingly, although users praise VR-based anesthesia for its precision, 50% criticize the systems as "over-idealized", noting that virtual pediatric patients are "too perfect to be real" [13]. Augmented reality overlays – for example, mapping inflammatory zones on gingival models – remain limited by an inability to simulate bleeding dynamics or biomaterial consistency changes seen in periodontal disease.

A key conclusion from this comparative analysis is that technological maturity is inversely proportional to clinical complexity. Where training focuses predominantly on mechanical skills (tooth preparation, modeling), progress is tangible. Where competence depends on simultaneous integration of motor execution, diagnostic reasoning, and patient interaction (oral surgery, maxillofacial surgery, pediatric dentistry), simulation technology currently lags behind, reinforcing existing educational imbalances.

Market forces amplify this discrepancy: approximately 75% of commercially available simulators target highly automatable tasks, while comprehensive, cognitively demanding scenarios remain underrepresented due to development complexity [2; 4].

Future progress will require convergence across technology domains. AI-driven analytics capable of assessing not only motor performance but also patterns of clinical decision-making could elevate simulation systems into platforms supporting true diagnostic competence. Development of biomimetic materials with variable elasticity, capable of replicating transitions from healthy to inflamed gingival tissues, may narrow the gap between simulated training and real periodontal interventions [6].

Ultimately, achieving breakthrough effectiveness necessitates a paradigm shift – from a predominantly technical training orientation toward a holistic educational model, where each simulation module contributes to a deeper understanding of the multifactorial nature of dental practice.

CONCLUSION

The integration of simulation technologies into dental education has evolved beyond a mere skills-training tool, becoming a catalyst for systemic transformation in professional preparation. Their capability to reproduce clinical scenarios with high fidelity establishes a foundation for producing practitioners whose procedural competencies are refined in advance of patient contact, reducing risk and accelerating readiness. Nevertheless, this apparent efficiency conceals a complex spectrum of unresolved challenges that merit critical examination.

On one side, AI-enhanced training platforms demonstrate a strong adaptation to individual learning trajectories, facilitating dynamic interaction between student and system and increasing operational precision. On the other, their expanding role introduces fundamental concerns regarding the essence of clinical education, where tactile perception and human-centered communication remain core professional competencies.

Financial considerations further emphasize a structural imbalance: technologies positioned as instruments of educational democratization can, in practice, intensify disparities. Leading institutions implement predictive analytics and advanced haptic systems, while others rely on outdated physical models, expanding the global gap in learning outcomes. Methodological limitations – scarcity of long-term evidence, variability in validation frameworks – risk creating an impression of progress unsupported by robust data.

Ethical constraints frame additional strategic risks. Personalized 3D patient models raise concerns about data governance and privacy. Machine-learning feedback, if not continuously audited, may embed and perpetuate bias originating from training datasets.

Despite these barriers, the contradictions inherent to simulation-based education generate opportunities for constructive evolution. The strategic objective should not be to replace traditional hands-on clinical instruction, but to establish hybrid educational ecosystems in which digital accuracy is complemented by human empathy and decision-making depth. Interdisciplinary collaboration, development of open technological standards, and prioritization of ethical compliance can transition simulators from high-cost innovations to instruments of globally accessible education.

Simulation technologies therefore represent an early phase in the broader evolution of dental training. Forward progress demands a balanced approach – leveraging algorithmic precision while preserving the cognitive and interpersonal dimensions of clinical expertise. Under such conditions, dental education can produce professionals who are fully equipped to meet the operational, ethical, and societal challenges of contemporary healthcare delivery.

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INFORMATION ABOUT THE AUTHORS

Denis A. Moiseev – Cand. Sci. (Med.), Head of the Laboratory of Simulation Technologies in Dentistry, Associate Professor of the Department of Therapeutic Dentistry Institute of Dentistry, Pirogov Russian National Research Medical University, 1 Ostrovityanova Str., Moscow 117997, Russian Federation; https://orcid.org/0000-0001-7811-7741

Sergey A. Tregubov – Technician of the Laboratory of Simulation Technologies in Dentistry Institute of Dentistry, Pirogov Russian National Research Medical University, 1 Ostrovityanova Str., Moscow 117997, Russian Federation; https://orcid.org/0000-0001-7315-8237

Anastasia K. Shataylo – Student of the Institute of Dentistry, Pirogov Russian National Research Medical University, 1 Ostrovityanova Str., Moscow 117997, Russian Federation; https://orcid.org/0009-0001-3921-6365

Fatma V. Gedik – Student of the Institute of Dentistry, Pirogov Russian National Research Medical University, 1 Ostrovityanova Str., Moscow 117997, Russian Federation; https://orcid.org/0009-0004-4929-4334

Vladislav D. Stasevich – Student of the Institute of Dentistry, Pirogov Russian National Research Medical University, 1 Ostrovityanova Str., Moscow 117997, Russian Federation; https://orcid.org/0009-0003-3517-1563

Victoria M. Sheveleva – Student of the Institute of Dentistry, Pirogov Russian National Research Medical University, 1 Ostrovityanova Str., Moscow 117997, Russian Federation; https://orcid.org/0009-0002-7510-4878

Alexander I. Marushkov – Student of the Institute of Dentistry, Pirogov Russian National Research Medical University, 1 Ostrovityanova Str., Moscow 117997, Russian Federation; https://orcid.org/0009-0002-0055-6677

ИНФОРМАЦИЯ ОБ АВТОРАХ

Моисеев Денис Александрович – к.м.н., заведующий лабораторией симуляционных технологий в стоматологии, доцент кафедры терапевтической стоматологии Института стоматологии, ФГАОУ ВО «Российский национальный исследовательский медицинский университет имени Н.И. Пирогова», 117997, Российская Федерация, г. Москва, ул. Островитянова, д. 1; https://orcid.org/0000-0001-7811-7741

Трегубов Сергей Андреевич – техник лаборатории симуляционных технологий в стоматологии Института стоматологии, ФГАОУ ВО «Российский национальный исследовательский медицинский университет имени Н.И. Пирогова», 117997, Российская Федерация, г. Москва, ул. Островитянова, д. 1; https://orcid.org/0000-0001-7315-8237

Шатайло Анастасия Константиновна – студент Института стоматологии, ФГАОУ ВО «Российский национальный исследовательский медицинский университет имени Н.И. Пирогова», 117997, Российская Федерация, г. Москва, ул. Островитянова, д. 1; https://orcid.org/0009-0001-3921-6365

Гедик Фатма Ведатовна – студент Института стоматологии, ФГАОУ ВО «Российский национальный исследовательский медицинский университет имени Н.И. Пирогова», 117997, Российская Федерация, г. Москва, ул. Островитянова, д. 1; https://orcid.org/0009-0004-4929-4334

Стасевич Владислав Дмитриевич – студент Института стоматологии, ФГАОУ ВО «Российский национальный исследовательский медицинский университет имени Н.И. Пирогова», 117997, Российская Федерация, г. Москва, ул. Островитянова, д. 1; https://orcid.org/0009-0003-3517-1563

Шевелева Виктория Михайловна – студент Института стоматологии, ФГАОУ ВО «Российский национальный исследовательский медицинский университет имени Н.И. Пирогова», 117997, Российская Федерация, г. Москва, ул. Островитянова, д. 1; https://orcid.org/0009-0002-7510-4878

Марушков Александр Иванович – студент Института стоматологии, ФГАОУ ВО «Российский национальный исследовательский медицинский университет имени Н.И. Пирогова», 117997, Российская Федерация, г. Москва, ул. Островитянова, д. 1; https://orcid.org/0009-0002-0055-6677

AUTHOR'S CONTRIBUTION

Denis A. Moiseev – made a substantial contribution to the study concept and design; participated in data acquisition, analysis, or interpretation; drafted the manuscript or provided critical revision for important intellectual content; gave final approval of the version to be published.

Sergey A. Tregubov – made a substantial contribution to the study concept and design; participated in data acquisition, analysis, or interpretation; drafted the manuscript or provided critical revision for important intellectual content.

Anastasia K. Shataylo – participated in data acquisition, analysis, or interpretation; drafted the manuscript or provided critical revision for important intellectual content.

Fatma V. Gedik – participated in data acquisition, analysis, or interpretation; drafted the manuscript or provided critical revision for important intellectual content.

Vladislav D. Stasevich – participated in data acquisition, analysis, or interpretation; drafted the manuscript or provided critical revision for important intellectual content.

Victoria M. Sheveleva – participated in data acquisition, analysis, or interpretation; drafted the manuscript or provided critical revision for important intellectual content.

Alexander I. Marushkov – participated in data acquisition, analysis, or interpretation; drafted the manuscript or provided critical revision for important intellectual content.

ВКЛАД АВТОРОВ

Д.А. Моисеев – существенный вклад в замысел и дизайн исследования; сбор данных или анализ и интерпретацию данных; подготовка статьи или ее критический пересмотр в части значимого интеллектуального содержания; окончательное одобрение варианта статьи для опубликования.

С.А. Трегубов – существенный вклад в замысел и дизайн исследования; сбор данных или анализ и интерпретацию данных; подготовка статьи или ее критический пересмотр в части значимого интеллектуального содержания.

А.К. Шатайло – сбор данных или анализ и интерпретацию данных; подготовка статьи или ее критический пересмотр в части значимого интеллектуального содержания.

Ф.В. Гедик – сбор данных или анализ и интерпретацию данных; подготовка статьи или ее критический пересмотр в части значимого интеллектуального содержания.

В.Д. Стасевич – сбор данных или анализ и интерпретацию данных; подготовка статьи или ее критический пересмотр в части значимого интеллектуального содержания.

В.М. Шевелева – сбор данных или анализ и интерпретацию данных; подготовка статьи или ее критический пересмотр в части значимого интеллектуального содержания.

А.И. Марушков – сбор данных или анализ и интерпретацию данных; подготовка статьи или ее критический пересмотр в части значимого интеллектуального содержания.