

Reimagining Knee Surgery: The Promises and Pitfalls of Augmented and Virtual Reality in Orthopedic Training and Preoperative Planning

Kyriakos Bekas¹ (*), Alexandros Stamatopoulos², Ioannis Kechagias¹, Konstantinos Vamvakeros¹, Ioannis Bampis³, Achilleas Boutsiadis^{1,3}

(*) Corresponding author: kbekas@outlook.com.gr

1. 401 General Military Hospital of Athens, Orthopaedics Department, Athens, Greece

2. Great Western Hospitals NHS Foundation Trust, Orthopaedics Department, Swindon, UK

3. Bioclinic Advanced Shoulder Unit, Athens, Greece



Background: The integration of immersive technologies such as augmented reality (AR) and virtual reality (VR) is rapidly transforming orthopedic surgical practice, particularly in knee surgery. These technologies offer enhanced visualization, simulation-based education, and precise preoperative planning.

Purpose: To explore the current applications of AR and VR in knee surgery, with a focus on their role in surgical training and preoperative planning, while identifying associated limitations and future directions.

Methods: A narrative review was conducted of peer-reviewed literature published between 2014 and 2025 using databases including PubMed, Scopus, and Web of Science. The search focused on studies evaluating the clinical and educational use of AR and VR in knee surgery, with emphasis on simulation training, preoperative visualization, and intraoperative applications.

Results: VR-based simulation platforms have demonstrated efficacy in enhancing psychomotor skills and procedural confidence among orthopedic trainees. AR has shown promise in improving anatomical orientation and precision during preoperative planning, especially in ligament reconstruction and alignment-based procedures. However, both modalities face limitations such as high costs, technical integration challenges, limited haptic feedback, and varying user adaptability. While initial results suggest improved accuracy and learning outcomes, robust clinical trials linking these tools to long-term surgical outcomes remain limited.

Conclusion: AR and VR are emerging as powerful adjuncts in knee surgery education and planning. Despite promising early evidence, wider adoption is tempered by technical and financial barriers. Future research should focus on standardizing outcome measures and integrating AR/VR tools into validated surgical curricula.

What this study adds: This review synthesizes recent evidence on AR and VR in knee surgery and highlights their utility and constraints in training and preoperative workflows.

How this study might affect research, practice or policy: By synthesizing evidence spanning a full decade (2014–2025), this review offers a longitudinal perspective on the evolution of immersive technologies in knee surgery. The findings may aid curriculum designers, clinical educators, and surgical innovators in making evidence-informed decisions about the integration of AR and VR into orthopedic training and preoperative planning. This historical breadth provides valuable insight into emerging trends, persistent challenges, and the trajectory of future implementation across surgical education and practice.

Study Design: Narrative literature review

Level of evidence: Level V

Keywords: Augmented reality; virtual reality; knee surgery; surgical simulation; preoperative planning; orthopedic training

<https://doi.org/10.70885/hmsj.2025.08.003>

Introduction

Over the past decade, the landscape of orthopedic surgery has experienced a paradigm shift driven by emerging immersive technologies. Among these, Virtual Reality (VR)

and Augmented Reality (AR) have gained prominence for their ability to enrich both educational and clinical practices. VR simulators create immersive, three-dimensional representations of the surgical environment, allowing users to interact with virtual anatomical models and instruments. In

contrast, AR systems enhance the real-world surgical field by overlaying relevant digital information, such as imaging data, anatomical guides, or procedural cues, onto the physical operative space [1][2][3]. Their integration into knee surgery, a domain that demands anatomical accuracy, spatial awareness, and procedural confidence, has opened new avenues for both surgical training and preoperative planning.

VR allows for complete immersion in simulated environments, offering trainees risk-free practice on realistic procedural models, while AR superimposes digital information onto real-world views, enhancing the surgeon's spatial understanding during planning and, to a lesser extent, intraoperative guidance. These tools are particularly valuable in orthopedic training, where the decline of traditional apprenticeship models and increased surgical complexity call for alternative educational strategies. Moreover, in procedures such as total knee arthroplasty (TKA), ligament reconstruction, or deformity correction, AR and VR have been used to improve anatomical orientation and procedural rehearsals [1][2][4][5][6][7][8][9][10].

Despite promising developments, significant barriers to widespread adoption remain. These include high implementation costs, a lack of standardized assessment frameworks, insufficient haptic feedback in VR simulators, and technical integration challenges in live surgical environments. The clinical validation of these technologies, especially in terms of long-term patient outcomes and operative efficiency, remains limited and fragmented across small-scale studies.

To date, much of the literature surrounding AR and VR in knee surgery has focused on isolated applications, often with varying outcomes and limited comparative analysis. A comprehensive narrative review is therefore warranted to synthesize recent findings, critically evaluate their utility, and examine current limitations.

The aim of this review is to explore the current and emerging roles of AR and VR in orthopedic knee surgery, with emphasis

on their application in surgical training and preoperative planning. Additionally, this paper discusses the technological, practical, and educational limitations that must be addressed to facilitate their responsible integration into clinical practice.

Materials and Methods

Study Design

This study was designed as a narrative literature review focusing on the application of AR and VR in knee surgery, with particular emphasis on their use in surgical training and preoperative planning. The goal was to identify, describe, and synthesize key findings in peer-reviewed literature while also discussing technical and clinical limitations associated with these technologies.

Search Strategy

A targeted literature search was performed across PubMed, Scopus, and Web of Science databases to identify relevant studies published between November 2014 and February 2025. The year 2014 was selected as a starting point because it marked the first wave of immersive VR tools validated in orthopedic literature and the emergence of commercial headsets which catalyzed AR/VR applications in surgery. Search terms included combinations of: augmented reality, virtual reality, knee surgery, orthopedic training, surgical simulation, preoperative planning, and AR in orthopedics or VR in orthopedics. A total of 172 potentially relevant studies were identified during the database search, of which 32 were duplicates and removed. Of the remaining 140 studies, 90 were excluded because they dealt with irrelevant aspects to this review. Of the remaining 50 articles selected for reading, only 24 finally met the criteria (**Figure 1**).

Only articles published in English in peer-reviewed journals were included. Reference lists of selected studies were screened for additional relevant publications.

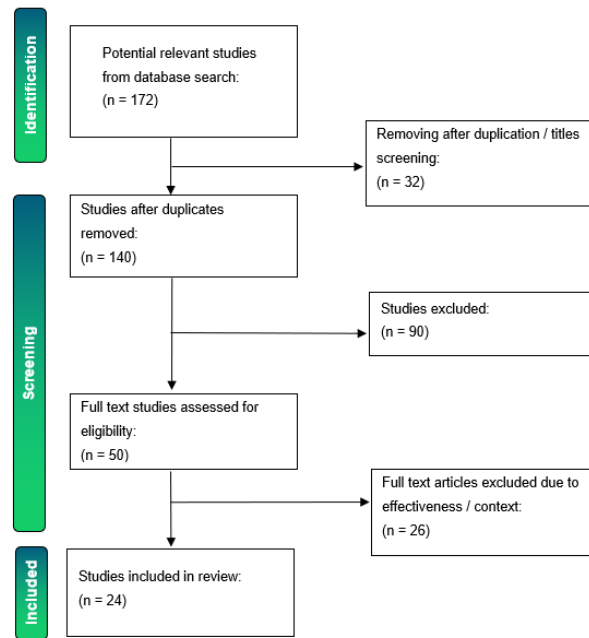


Figure 1. PRISMA flow chart.

Inclusion and Exclusion Criteria

Studies were included in this review if they met the following criteria: (1) the study involved the use of AR and/or VR technologies within the context of knee surgery; (2) the primary focus was on applications related to surgical training, simulation, or preoperative planning; (3) the study provided original data, clinical evaluation, or a comprehensive review of immersive technology in orthopedic practice; and (4) the article was published in a peer-reviewed journal between November 2014 and February 2025.

Exclusion criteria were established to ensure relevance and quality. Studies were excluded if they: (1) focused on non-orthopedic or non-knee-related procedures; (2) discussed only robotic-assisted surgery without the use of immersive visualization technologies such as AR or VR; (3) were published solely as conference abstracts, letters to the editor, editorials, or non-peer-reviewed commentaries; or (4) were not available in full text or were written in languages other than English. Additionally, studies that mentioned AR/VR only tangentially, without substantive analysis or evaluation of these technologies, were also excluded.

Data Extraction and Synthesis

Following the screening and selection process, eligible studies were reviewed in full, and key data were extracted manually using a standardized form. Extracted variables included the first author, year of publication, study type (e.g., randomized trial, observational study, technical report, or

review), specific AR or VR technology used, target surgical procedure or training module, study population, and key outcomes measured. Where available, technical limitations, user feedback, and implementation challenges were also recorded.

To organize and synthesize the findings, a thematic analysis approach was employed. Studies were grouped according to their primary domain of application: (1) Surgical Training and Simulation, (2) Preoperative Planning, (3) Intraoperative Assistance, and (4) Patient Education and Outcomes. Within each thematic category, findings were summarized narratively, emphasizing the reported benefits, limitations, and quality of supporting evidence. This method allowed for a comprehensive yet structured interpretation of the literature, consistent with the narrative review format and the goals of the present study.

Results

Surgical Training and Simulation

Multiple studies have demonstrated the efficacy of VR-based simulation platforms in enhancing surgical education for orthopedic trainees. These systems replicate procedural workflows, anatomical landmarks, and surgical tools in immersive 3D environments. Notably, VR simulators have been associated with improved psychomotor skills, accelerated learning curves, and greater procedural confidence among novice surgeons [1][2][4][5][6][7][8][9][10].

Additionally, a study from Tronchet et al. showed that junior residents that received supplementary VR training in knee arthroscopy, had a significant difference in heart rate variability compared to untrained residents during the final assessment of their technical skills at six months [11].

Bartlett et al. evaluated the impact of VR simulation in knee arthroscopy training and reported a significant improvement in technical performance metrics [12]. Similarly, Hasan et al. highlighted the educational benefits of immersive VR platforms, noting their ability to provide real-time feedback, repetitive practice, and risk-free failure [13]. Cannon et al. also demonstrated that residents trained on a high realistic VR arthroscopic knee simulators showed a greater skill level in the operating room compared with the control group [14].

A more recent study demonstrated the transferability of skills acquired on hybrid VR simulators to both bench-top and cadaveric models, suggesting that technical competencies gained through virtual training may translate meaningfully to the operating room [15]. This finding supports the role of VR simulation in diagnostic knee arthroscopy and meniscectomy skills, not only as a preparatory tool but also as a potential adjunct for standardizing surgical training and monitoring resident progression across training programs.

Despite these advantages, limitations persist. Many simulators have limited kinesthetic fidelity, which is crucial in orthopedic procedures requiring force modulation [16][17]. Furthermore, variability in software fidelity, hardware costs, and the absence of standardized assessment protocols challenge their broader integration into surgical curricula.

Preoperative Planning

AR and VR technologies have increasingly been used to support preoperative planning in complex knee procedures, such as total knee arthroplasty (TKA), ligament reconstruction, and corrective osteotomies. By overlaying patient-specific imaging data (CT or MRI) onto 3D models, AR facilitates enhanced anatomical visualization and surgical rehearsal.

Verhey et al. demonstrated the feasibility of using AR overlays for preoperative planning, allowing surgeons to manipulate models of bone structures, identify alignment issues, and anticipate surgical steps more accurately [2]. In cases involving deformity correction, AR-assisted planning tools improved the alignment precision and shortened planning time compared to traditional methods [12].

Nevertheless, the integration of AR tools into standard workflows remains inconsistent due to limited software compatibility, learning curves, and regulatory concerns around digital surgical aids.

Intraoperative Assistance

Though not the primary focus of this review, AR has shown preliminary utility in intraoperative guidance. AR headsets and projection systems can overlay anatomical landmarks or virtual guides onto the operative field [18]. Jud et al. found AR useful in improving spatial orientation and screw placement accuracy during orthopedic procedures [4]. Additionally, in a single-center study conducted by Sakellariou et al., AR was evaluated for its efficacy in primary TKA procedures [19]. The study reported that the use of AR resulted in improved alignment accuracy, with postoperative mechanical axis deviation averaging less than 1.5°, and a reduction in outliers compared to conventional techniques. Additionally, the integration of AR did not significantly prolong operative time, suggesting that such technology can enhance surgical precision without compromising efficiency. However, clinical use remains experimental due to concerns about device ergonomics, field-of-view limitations, and real-time latency.

Patient Education and Outcomes

A smaller but growing body of literature suggests that VR-based tools can aid in patient education, enhancing understanding of procedures and improving informed consent. Some studies also report reductions in preoperative anxiety through immersive VR sessions [20]. Jud et al. also reported that AR has the potential to serve as a time-efficient, risk-reducing, and accuracy-enhancing tool in orthopedic surgery [4]. While their findings primarily emphasize intraoperative applications, the same principles of enhanced spatial understanding and visual clarity may be extended to patient education, where AR can improve comprehension of anatomical structures, procedural steps, and postoperative expectations. However, direct correlations between AR/VR use and improved surgical outcomes (e.g., recovery time, complication rates) remain poorly studied and warrant further investigation.

A comparative overview of the reported advantages and limitations of AR and VR across these four domains is summarized in **Table 1**.

Table 1. Summary of advantages and limitations of AR and VR in knee surgery.

Application Area	AR Advantages	VR Advantages	Shared Limitations
Surgical Training	Enhances real-time anatomical overlay	Immersive, repeatable skill practice	Limited haptic feedback, high initial cost
Preoperative Planning	3D visualization of imaging data	Virtual rehearsal of complex procedures	Integration into existing workflows
Intraoperative Assistance	Navigation overlay for precision	Limited application	Limited outcome data, usability during live procedures
Patient Education	Augmented visuals for explanation	Interactive simulations for comprehension	Cost-effectiveness not well established

AR: Augmented Reality, VR: Virtual Reality

Discussion

Key Findings and Interpretation

This review highlights the growing utility of AR and VR as adjunctive tools in orthopedic knee surgery, particularly in the domains of surgical training and preoperative planning. Collectively, the evidence suggests that immersive technologies are reshaping the learning curve for trainees and enhancing visualization for practicing surgeons, albeit with varying degrees of validation and integration.

VR-based simulators offer a compelling solution to the challenges of traditional apprenticeship models in orthopedic training. They provide a safe, repeatable, and feedback-driven environment that has been shown to improve technical performance, procedural confidence, and engagement among trainees [1][2][4][5][13][21][22][23]. Their ability to simulate procedural environments and provide structured, repeatable learning experiences makes them particularly valuable when traditional educational pathways are interrupted. The COVID-19 pandemic underscored the vulnerability of subspecialty training, demonstrating that periods of disruption in surgical education for residents and practicing surgeons are not only possible but likely in times of crisis (**Figure 2**). In such contexts, immersive technologies like VR simulations offer a resilient alternative by enabling continuous, remote-access training that is independent of operating room availability or in-person instruction [24].

VR has emerged as a transformative tool in surgical education, offering a cost-effective and scalable alternative to traditional training methods. A study published by Goh et al. highlights that immersive VR not only enhances the quality of surgical training but also reduces associated costs.

Compared to conventional bioskills training, VR demonstrated a greater effect on skill improvement for surgical trainees at a lower cost [1].

These findings highlight the potential of VR to democratize surgical education, making high-quality training accessible to a broader range of learners, regardless of geographical or financial constraints. Nevertheless, quantifying the clinical value of these technologies, particularly when integrated with robotic or other advanced surgical systems, remains an unmet need. A recent prospective study evaluating arthroscopic skills among medical students and residents demonstrated that while both groups improved significantly in task completion time and movement efficiency, residents performed faster, with less camera motion and fewer inadvertent cartilage contacts. Interestingly, students exhibited steeper learning curves in certain metrics, likely reflecting their lower baseline experience levels [23]. This underscores that learning trajectories in VR environments are influenced by user background, system design, and procedural complexity. Persistent challenges include the lack of haptic realism, limited standardization of metrics and high implementation costs. Notably, few VR platforms have been incorporated into formal curricula or validated against long-term clinical outcomes.

Similarly, AR has emerged as a valuable tool in preoperative planning, enabling patient-specific anatomical visualization and surgical rehearsal. Studies demonstrate improved spatial understanding, particularly in procedures with complex bony alignment, such as osteotomies and total knee arthroplasty [1][2][12]. Despite these benefits, AR applications face integration challenges, including hardware limitations, workflow disruptions, and surgeon adaptation curves.



Figure 2. Use of VR surgical simulation during the COVID-19 pandemic. With restrictions on in-person clinical exposure and cadaveric labs, VR platforms allowed trainees to continue developing procedural competencies in a safe, remote-access format, when traditional resources were unavailable.

While intraoperative applications of AR are promising, their clinical use is still in its infancy. Technical issues such as latency, field-of-view constraints, and ergonomic fatigue limit their reliability in real-time procedures [5]. The use of immersive technologies in patient education shows potential but remains underexplored in knee-specific pathways.

Comparison with Prior Research

The findings of this review are consistent with earlier literature emphasizing the role of AR and VR in orthopedic training. Prior reviews have focused broadly on musculoskeletal applications; however, this review specifically targets knee surgery, where procedural repetition, precision, and anatomical complexity converge to benefit most from immersive interventions, by synthesizing evidence spanning a full decade of research in knee surgery.

A recent meta-analysis by Sun et al. concluded that VR significantly improves surgical task performance compared to no training, but its superiority over traditional methods remains inconclusive [5]. Our review adds depth by focusing on orthopedic-specific studies and underscores the need for better-designed comparative trials.

Clinical Implications

For orthopedic educators and surgical departments, AR and VR offer scalable opportunities to enhance both surgical

training and preoperative planning. However, the adoption of these technologies should be guided by robust evidence and a clear understanding of their cost-benefit ratio. Integration into clinical and educational environments must be strategic and well-structured to maximize value.

Institutions considering implementation might begin with pilot programs embedded within existing training modules to evaluate usability and impact. Collaboration with multidisciplinary simulation centers can further support the design, delivery, and refinement of AR/VR-based education. Additionally, investment should be directed toward platforms that demonstrate measurable, transferable learning outcomes that align with existing competency frameworks.

Importantly, AR and VR technologies are best positioned as adjuncts, not replacements, to traditional surgical mentorship and direct operative experience. Their role should be to complement hands-on training by reinforcing anatomical understanding, procedural planning, and skill acquisition in a safe, repeatable, and feedback-rich environment.

Limitations

Although this review covers a wide range of literature, the strength of general conclusions is limited by the heterogeneity of the studies, by potential selection bias, lack of quantitative synthesis, and subjectivity in interpreting themes. Few of the included articles used validated assessment tools or standardized outcome measures, and

their designs ranged widely from observational assessments to pilot simulations. Furthermore, many did not have long-term follow-up or control groups, which made it difficult to evaluate long-term clinical impact. It is difficult to make direct comparisons or extrapolate results from one platform or procedure to another because of this inconsistency. To improve the body of evidence supporting immersive technology in orthopedic surgery, future studies should place a higher priority on methodological rigor, consistent metrics, and clinical validation.

Potential Risks and Ethical Considerations

Although AR and VR have the potential to revolutionize surgical workflows, there are several risks that need to be considered. One issue is an excessive dependence on simulation-based learning, which, if not counterbalanced by operational exposure, may result in a lack of real-world decision-making experience. Another risk is decontextualized learning, in which knowledge gained in a virtual environment might not be entirely applicable to the intricacies of real surgery. Usability issues have been brought up by user reports of motion sickness, possible visual strain, and ergonomic fatigue from extended headset use. Additionally, platforms that gather user data present cybersecurity and privacy issues, especially when incorporated into hospital systems [25]. Fair access to technology across institutions and geographical areas remains an ethical consideration.

The development and implementation of AR and VR in knee surgery must be balanced with ethical responsibility. This includes ensuring that the benefits of these technologies are realized while minimizing potential risks and respecting the rights and autonomy of patients. As immersive technologies continue to evolve, it is crucial to establish clear guidelines and regulations to govern their use in surgical practice.

Future Directions

As immersive technologies continue to evolve, future research should prioritize the generation of high-quality clinical evidence to support their integration into orthopedic practice. Specifically, randomized controlled trials comparing AR and VR with conventional training and planning methods are essential to establish their true effectiveness and cost-efficiency. These studies should not only assess short-term technical performance but also evaluate long-term skill retention and impact on patient outcomes.

In parallel, longitudinal studies tracking the performance of trainees exposed to immersive simulations could provide valuable insight into the durability of learning and its translation into operative competence. Developing standardized, validated metrics to assess proficiency within VR and AR environments will also be critical, allowing for

objective benchmarking and comparison across platforms and institutions.

Cost-effectiveness analyses are equally important to guide institutional investment, particularly in resource-constrained settings. These should consider not only the upfront costs of hardware and software but also the potential return on investment through reduced training time, improved surgical accuracy, and enhanced patient safety.

From a technological standpoint, future innovation should aim to address current limitations in haptic feedback, visual realism, and device ergonomics. Enhanced tactile fidelity and more intuitive user interfaces will be key to improving immersion and adoption, especially in procedures requiring fine motor control and force modulation.

Finally, collaborative efforts between clinicians, educators, engineers, and software developers will be vital to ensure that AR and VR tools are designed with real-world surgical workflows in mind. By fostering interdisciplinary development and user-centered design, the orthopedic community can accelerate the responsible and meaningful integration of immersive technologies into clinical training and practice.

Conclusions

AR and VR are reshaping the educational and planning paradigms of knee surgery. VR has shown considerable promise in enhancing surgical training through immersive simulation, while AR contributes to improved anatomical visualization and procedural planning. Despite encouraging early outcomes, significant barriers—including cost, limited tactile feedback, and integration challenges—continue to impede widespread adoption. As the field advances, high-quality comparative studies and standardized evaluation tools will be essential to validate these technologies and facilitate their responsible integration into orthopedic practice.

Open access statement

This is an open-access article distributed under the terms of the Creative Commons Attribution Licence for Commercial and Non-Commercial Purposes (**CC BY 4.0**, see <https://creativecommons.org/licenses/by/4.0/>), which allows free use, distribution, adaptation, and commercial use of a work, provided proper credit is given to the creator.

Source of funding

There was no funding for this study.

Conflict of interest

No conflict of interest.

Acknowledgments

None

References

1. Goh GS, Lohre R, Parvizi J, Goel DP. Virtual and augmented reality for surgical training and simulation in knee arthroplasty. *Arch Orthop Trauma Surg.* 2021 Dec 1;141(12):2303–12. DOI: 10.1007/s00402-021-04037-1
2. Verhey JT, Haglin JM, Verhey EM, Hartigan DE. Virtual, augmented, and mixed reality applications in orthopedic surgery. *Int J Med Robot Comput Assist Surg MRCAS.* 2020 Apr;16(2):e2067. DOI: 10.1002/rcs.2067
3. Dhillon J, Tanguilig G, Kraeutler MJ. Virtual and Augmented Reality Simulators Show Intraoperative, Surgical Training, and Athletic Training Applications: A Scoping Review. *Arthrosc J Arthrosc Relat Surg Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc.* 2025 Feb;41(2):505–15. DOI: 10.1016/j.arthro.2024.12.017
4. Jud L, Fotouhi J, Andronic O, Aichmair A, Osgood G, Navab N, et al. Applicability of augmented reality in orthopedic surgery - A systematic review. *BMC Musculoskelet Disord.* 2020 Feb 15;21(1):103. DOI: 10.1186/s12891-020-3110-2
5. Sun P, Zhao Y, Men J, Ma ZR, Jiang HZ, Liu CY, et al. Application of Virtual and Augmented Reality Technology in Hip Surgery: Systematic Review. *J Med Internet Res.* 2023 Mar 10;25:e37599. DOI: 10.2196/37599
6. Rebolledo BJ, Hammann-Scala J, Leali A, Ranawat AS. Arthroscopy skills development with a surgical simulator: a comparative study in orthopaedic surgery residents. *Am J Sports Med.* 2015 Jun;43(6):1526–9. DOI: 10.1177/0363546515574064
7. Lohre R, Bois AJ, Pollock JW, Lapner P, McIlquham K, Athwal GS, et al. Effectiveness of Immersive Virtual Reality on Orthopedic Surgical Skills and Knowledge Acquisition Among Senior Surgical Residents: A Randomized Clinical Trial. *JAMA Netw Open.* 2020 Dec 28;3(12):e2031217. DOI: 10.1001/jamanetworkopen.2020.31217
8. Aïm F, Lonjon G, Hannouche D, Nizard R. Effectiveness of Virtual Reality Training in Orthopaedic Surgery. *Arthrosc J Arthrosc Relat Surg Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc.* 2016 Jan;32(1):224–32. DOI: 10.1016/j.arthro.2015.07.023
9. Lohre R, Bois AJ, Athwal GS, Goel DP, Society (CSES)* on behalf of the CS and E. Improved Complex Skill Acquisition by Immersive Virtual Reality Training: A Randomized Controlled Trial. *JBJS.* 2020 Mar 18;102(6):e26. DOI: 10.2106/JBJS.19.00982
10. Walbron P, Common H, Thomazeau H, Hosseini K, Peduzzi L, Bulaid Y, et al. Virtual reality simulator improves the acquisition of basic arthroscopy skills in first-year orthopedic surgery residents. *Orthop Traumatol Surg Res OTSR.* 2020 Jun;106(4):717–24. DOI: 10.1016/j.otsr.2020.02.013
11. Tronchot A, Maximen J, Casy T, Common H, Thomazeau H, Jannin P, et al. The influence of virtual reality simulation on surgical residents' heart rate during an assessment of arthroscopic technical skills: A prospective, paired observational study. *Orthop Traumatol Surg Res OTSR.* 2024 Dec;110(8):103915.
12. Bartlett JD, Lawrence JE, Stewart ME, Nakano N, Khanduja V. Does virtual reality simulation have a role in training trauma and orthopaedic surgeons? *Bone Jt J.* 2018 Dec 1;100-B(5):559–65. DOI: 10.1302/0301-620X.100B5.BJJ-2017-0977.R1
13. Hasan LK, Haratian A, Kim M, Bolia IK, Weber AE, Petrigliano FA. Virtual Reality in Orthopedic Surgery Training. *Adv Med Educ Pract.* 2021 Nov 10;12:1295–301. DOI: 10.2147/AMEP.S332411
14. Cannon WD, Garrett WE, Hunter RE, Sweeney HJ, Eckhoff DG, Nicandri GT, et al. Improving residency training in arthroscopic knee surgery with use of a virtual-reality simulator. A randomized blinded study. *J Bone Joint Surg Am.* 2014 Nov 5;96(21):1798–806. DOI: 10.2106/JBJS.N.00058
15. Tronchot A, Casy T, Vallee N, Common H, Thomazeau H, Jannin P, et al. Virtual reality simulation training improve diagnostic knee arthroscopy and meniscectomy skills: a prospective transfer validity study. *J Exp Orthop.* 2023;10(1):138. DOI: 10.1186/s40634-023-00688-8
16. Vaghela KR, Trockels A, Lee J, Akhtar K. Is the Virtual Reality Fundamentals of Arthroscopic Surgery Training Program a Valid Platform for Resident Arthroscopy Training? *Clin Orthop.* 2022 Apr 1;480(4):807–15. DOI: 10.1097/CORR.0000000000002064
17. Anetzberger H, Reppenhagen S, Eickhoff H, Seibert FJ, Döring B, Haasters F, et al. Ten hours of simulator training in arthroscopy are insufficient to reach the target level based on the Diagnostic Arthroscopic Skill Score. *Knee Surg Sports Traumatol Arthrosc Off J ESSKA.* 2022 Apr;30(4):1471–9. DOI: 10.1007/s00167-021-06796-3
18. Chen F, Cui X, Han B, Liu J, Zhang X, Liao H. Augmented reality navigation for minimally invasive knee surgery using enhanced arthroscopy. *Comput Methods Programs Biomed.* 2021 Apr 1;201:105952. DOI: 10.1016/j.cmpb.2021.105952
19. Sakellariou E, Alevrogiannis P, Alevrogianni F, Galanis A, Vavourakis M, Karampinas P, et al. Single-center experience with Knee+TM augmented reality navigation system in primary total knee arthroplasty. *World J Orthop.* 2024 Mar 18;15(3):247–56. DOI: 10.5312/wjo.v15.i3.247
20. Rahm S, Wieser K, Bauer DE, Waibel FW, Meyer DC, Gerber C, et al. Efficacy of standardized training on a virtual reality simulator to advance knee and shoulder arthroscopic motor skills. *BMC Musculoskelet Disord.* 2018 Dec 16;19(1):150. DOI: 10.1186/s12891-018-2072-0
21. Capitani P, Zampogna B, Monaco E, Frizziero A, Moretti L, Losco M, et al. The role of virtual reality in knee arthroscopic simulation: a systematic review. *Musculoskelet Surg.* 2023 Mar;107(1):85–95. DOI: 10.1007/s12306-022-00744-7
22. Palet MJ, Antúnez-Riveros M, Barahona M. Construct Validity of a Virtual Reality Simulator for Surgical Training in Knee Arthroscopy. *Cureus.* 2021 Dec 25;13(5):e15237. DOI: 10.7759/cureus.15237
23. Putzer D, Dammerer D, Baldauf M, Lenze F, Liebensteiner MC, Nogler M. A Prospective Assessment of Knee Arthroscopy Skills Between Medical Students and Residents-Simulator Exercises for Partial Meniscectomy and Analysis of Learning Curves. *Surg Innov.* 2022 Jun;29(3):398–405. DOI: 10.1177/15533506211037792

24. Lohre R, Warner JJP, Morrey BR, Athwal GS, Morrey ME, Mazzocca AD, et al. Mitigating Surgical Skill Decay in Orthopaedics Using Virtual Simulation Learning. JAAOS Glob Res Rev. 2021 Oct;5(10):e21.00193. DOI: 10.5435/JAAOSGlobal-D-21-00193
25. Raja US, Al-Baghli R. Ethical concerns in contemporary virtual reality and frameworks for pursuing responsible use. Front Virtual Real [Internet]. 2025 Jan 30 [cited 2025 Jul 29];6. Available from: <https://www.frontiersin.org/journals/virtual-reality/articles/10.3389/frvir.2025.1451273/full> DOI: 10.3389/frvir.2025.1451273