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Research Article

Virtual reality and biofeedback in surgical training: a review and proposal for comparative study between novice and experienced surgeons

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Summary

Virtual reality (VR) is increasingly adopted in surgical education as a safe and controlled environment for developing technical and non-technical skills. Parallel to this, physiological biofeedback has emerged as a promising method for assessing stress, workload, and cognitive performance during complex tasks. This review explores the current evidence on VR and biofeedback in surgical training, highlighting their synergistic potential. We discuss how VR simulations replicate operative scenarios with high fidelity and how biofeedback parameters such as heart rate variability and galvanic skin response can provide objective insights into surgeon performance and stress regulation. We then outline a pilot study design in which novice and experienced surgeons are placed in a VR operating room scenario, with biofeedback metrics recorded. We hypothesise that experienced surgeons will demonstrate more stable physiological responses and superior task performance, reflecting greater resilience and expertise. Such findings could inform adaptive, personalised training models that adjust difficulty levels or provide targeted feedback in real time. Integrating VR and biofeedback into surgical education has the potential to enhance skill acquisition, improve stress management, and bridge the gap between simulation and the operating room.

Key words: biofeedback, cognitive load, simulation, surgical education, surgical training, virtual reality

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Introduction

Surgical training requires not only technical skill but also the ability to maintain performance under conditions of stress and uncertainty. Traditional apprenticeship-based models are increasingly supplemented by simulation, allowing for deliberate practice without risk to patients. Virtual reality (VR) has become a cornerstone of surgical simulation, offering immersive, repeatable, and adaptable environments for learning procedural steps, instrument handling, and team coordination.

At the same time, there is growing recognition that a surgeon's physiological and cognitive responses to stress directly influence performance and patient

outcomes. Biofeedback technologies, such as electrocardiography, galvanic skin response sensors, eye tracking, and electroencephalography, can help quantify stress and workload in real time. Integrating these tools into VR-based training provides a novel opportunity to capture objective metrics of surgical performance.

The cognitive load theory (Sweller 1988, 2010) highlights that working memory has a limited capacity, and performance deteriorates when cognitive load exceeds this threshold. Several studies have demonstrated that physiological markers, such as heart rate variability (HRV), pupil dilation, and eye-tracking patterns, correlate with cognitive load during surgical tasks (Zakeri et al. 2020; Tam et al. 2024).

The aim of this review is threefold: (1) to summarise current applications of VR in surgical training; (2) to highlight evidence on biofeedback as a performance assessment tool; and (3) to propose a study comparing novice and experienced surgeons in a VR operating room scenario, with biofeedback as a primary measure of physiological response.

Methods of the review

Relevant literature was identified through PubMed, Scopus, and Web of Science using combinations of the following keywords: virtual reality, surgical training, simulation, biofeedback, heart rate variability, galvanic skin response, and cognitive load. Articles published in English up to 2025 were considered. Both experimental and review studies focusing on surgical or high-stakes training environments were included.

Inclusion criteria: (1) Peer-reviewed studies published in English up to 2025, (2) Experimental, observational, or review studies examining VR, biofeedback, or cognitive load in surgical or high-stakes procedural training, (3)Studies reporting physiological, behavioural, or performance-related outcomes.

Exclusion criteria: (1) Non-peer-reviewed sources, editorials, or opinion papers, (2) Studies without measurable outcomes, (3) Studies unrelated to simulation, cognitive load, surgical skills, or VR environments

Virtual reality in surgical training

VR simulators have been available for more than a decade and provide immersive platforms for practising surgical skills. A systematic review has demonstrated the effectiveness of immersive VR (iVR) in improving skill acquisition and transfer to real-life OR settings among medical students, residents, and staff surgeons (Mao et al. 2021). Extended reality simulators have similarly shown enhanced performance metrics in robot-assisted surgery training compared to no additional training. Such technologies support scalable, objective, and risk-free training (Bric et al. 2016). Virtual reality (VR) offers several advantages in surgical training in open, laparoscopic and robotic surgery (Lange et al. 2000; Bric et al. 2016; Pulijala et al. 2018; Mao et al. 2021). It provides a risk-free environment where trainees can repeatedly practice procedures without compromising patient safety (Lange et al. 2000; McKnight et al. 2020). VR enables standardised exposure to a wide range of clinical scenarios, ensuring consistent learning opportunities regardless of the availability of cases in the operating room. Moreover, it facilitates the development of psychomotor and spatial skills essential for minimally invasive and robotic surgery. Learners ben-

efit from immediate, objective performance feedback, which supports self-assessment and targeted skill improvement. In addition, VR enhances engagement and motivation, fostering active participation compared to traditional didactic methods. Collectively, these advantages highlight VR as a valuable adjunct to conventional surgical education.

Biofeedback in surgical performance monitoring

Biofeedback refers to the measurement of physiological signals that reflect stress and workload. Commonly analysed parameters include:

- Heart rate variability (HRV): Reflects autonomic regulation and cognitive effort;
- Galvanic skin response (GSR): Indicates sympathetic arousal/stress levels;
- Pupillometry: Tracks pupil dilation correlating with cognitive load;
- Eye tracking: Provides insight into attention and mental workload.

Studies suggest that novices display higher heart rates, reduced HRV, and elevated GSR during surgical tasks, consistent with increased stress, while experienced people typically show physiological stability, indicating better resilience. Data on biofeedback and surgeons in the literature is scarce (Kelly et al. 2023).

Biofeedback captures physiological signals that reflect stress, cognitive workload, and attentional demand. The most frequently used measures include (Table 1):

Table 1. Biofeedback in surgical performance monitoring.

Biofeedback Measure	Physiological Basis	Interpretation	Typical Findings in Novices
Heart Rate Variability (HRV)	Autonomic nervous system balance	Lower HRV - higher stress/ cognitive demand	Reduced HRV, elevated HR
Galvanic Skin Response (GSR)	Sympathetic arousal	Higher peaks - increased stress	Larger and more frequent peaks
Pupillometry	Locus coeruleus - norepinephrine system	Pupil dilation - increased cognitive load	Larger fluctuations
Eye Tracking	Visual attention distribution	Fixation patterns reflect workload & expertise	More erratic, less efficient gaze paths

Integrating VR and biofeedback

Combining VR with biofeedback enables immersive simulation while concurrently monitoring cognitive and emotional states (Rockstroh et al. 2020; Mao et al. 2021; Lüddecke and Felnhofer 2022). VR-supported HRV biofeedback interventions have demonstrated improvements in stress indicators, user experience, and engagement compared to traditional methods (Bisson et al. 2007; Repetto et al. 2009; Frank et al. 2010; Lüddecke and Felnhofer 2022). Broader VR-biofeedback approaches show efficacy in promoting relaxation, reducing mind wandering, and supporting focused attention. A systematic overview confirms the viability of physiological monitoring in VR for assessing arousal, stress, and cognitive workload (Halbig and Latoschik 2021).

Recently, adaptive frameworks using HRV and eye-tracking were developed to adjust VR difficulty based on detected cognitive load.

Studying virtual reality biofeedback (VR-BF) in health, still does not clearly demonstrate that it is superior to traditional biofeedback. However, findings

suggest that VR-BF may offer benefits in terms of motivation, user experience, engagement, and attentional focus (Lüddecke and Felnhofer 2022).

The combination of virtual reality and biofeedback has shown benefits in anxiety and pain in patients after surgery (Prabhu et al. 2020; Orgil et al. 2023; Prabhu et al. 2024).

Proposed study: Comparing Novice and Experienced Surgeons.

Participants: Novice group: 10–15 surgical residents.

Experienced group: 10–15 attending surgeons with > 5 years of independent experience.

Hypotheses: (1) Expert surgeons will demonstrate greater physiological stability (higher HRV, lower GSR peaks, less pupillary fluctuation) compared with novices. (2) Biofeedback metrics will correlate with technical performance. (3) Eye-tracking efficiency will distinguish expertise levels more reliably than HRV or GSR.

Methods

Participants will perform a standardised VR surgical task (e.g., laparoscopic scenario) using a high-fidelity simulator. Real-time biofeedback will be recorded – HRV and GSR.

Procedure

Collect baseline physiological data.

Perform a VR scenario with time pressure and scripted complications.

Record performance metrics: completion time, errors, and motion efficiency.

Anticipated outcomes

Experienced surgeons will show more stable HRV and lower GSR peaks.

Performance measures correlate with biofeedback, validating physiological markers as indicators of expertise.

Impact

The study could reveal objective biomarkers of surgical expertise and pave the way for adaptive, personalised simulation systems that dynamically adjust based on a trainee's physiological state.

Discussion

This review highlights the growing opportunities to create a more holistic model of surgical training by combining virtual reality (VR) simulation with physiological biofeedback. While VR has matured considerably as an educational tool, offering high-fidelity visual, haptic, and procedural replication, there is increasing recognition that technical skill alone does not fully predict operative safety or success (Heard et al. 2025). Real-world surgical performance is the combination of motor skills, cognitive load, situational awareness, emotional regulation, and stress resilience (Kiernan and Rahman 2015). Integrating biofeedback into VR environments provides a new understanding of these competencies.

Beyond the acquisition of psychomotor skills, modern VR systems serve as platforms for non-technical skill training, including decision-making, communication, and crisis response; exposure to rare but critical scenarios, which can be a challenging experience during residency; standardised assessment, helping overcome the variability of clinical case exposure and a safe failure platform, allowing trainees to learn through error without patient harm (Halbig and Latoschik 2021). These capabilities align with contemporary theories of cognitive apprenticeship and deliberate practice, where feedback, repetition, and graduated challenge are central to expertise development.

The cognitive load theory provides an essential framework for interpreting physiological responses during surgical performance. A surgeon must manage intrinsic load (task complexity), extraneous load (interface, equipment and distractions), and germane load (learning processes) (Almukhtar et al. 2025; Wu et al. 2025). When the cumulative load exceeds working memory capacity, errors and inefficiencies increase.

Biofeedback markers offer an objective view of these dynamics. In high-load situations, trainees may show elevated sympathetic arousal, reduced cognitive flexibility, and poorer motor control. Understanding when and why cognitive overload occurs could improve curriculum design and ensure that learning occurs at an optimal challenge point.

Although biofeedback is promising, the degree to which each metric reflects surgical workload varies. HRV is highly sensitive to stress but influenced by respiration, emotional arousal, and movement. However, GSR captures acute sympathetic spikes, but it lacks specificity (Lüddecke and Felnhofer 2022; Orgil et al. 2024).

A multimodal approach may provide superior reliability compared with any single metric. Further validation in a real operating room environment is needed to establish ecological validity.

One of the most transformative implications of VR-biofeedback integration is the potential for adaptive and personalised training. For example, those demonstrating low cognitive engagement could be challenged with increased scenario complexity or unexpected intraoperative events. Also, trainees at risk of burnout or performance decline could be identified.

The integration of physiological monitoring introduces new ethical questions (Houghton et al. 2024; Jiwa et al. 2025).

Although promising, VR-biofeedback integration faces several challenges (Table 2).

Table 2. VR-biofeedback challenges.

Challenge	Expanded explanation	Potential solutions
Hardware and cost	High-fidelity VR, eye tracking, and HRV systems are expensive.	Shared institutional centres; modular, consumer-grade wearables; cloud-based processing.
Technical standardisation	Variability in sensors, sampling rates, and software pipelines hinders comparison.	Development of open-source benchmarks and consensus reporting guidelines.
Environmental interference	Lighting, movement artifacts, and temperature can affect readings.	Calibration protocols; noise-filtering algorithms; standardisation of testing environments.
Cognitive overload	Showing real-time biofeedback during tasks may distract learners.	Use feedback only during debriefing; incorporate graded exposure to stress-management techniques.
Educator training	Instructors often lack experience interpreting physiological data.	Dedicated faculty workshops; integration into simulation centre training programs.

Conclusion

Virtual reality, combined with biofeedback, offers a powerful framework for surgical training, equipping learners with immersive rehearsal and measurable stress monitoring. The proposed pilot study comparing novice and expert surgeons can uncover physiological markers of expertise, enabling the development of adaptive, individualised training that enhances performance and patient safety.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statements

The authors declared that no clinical trials were used in the present study.

The authors declared that experiments on humans or human tissues were performed for the present study.

Informed consent from the humans, donors or donors' representatives: Medical University - Pleven.

The authors declared that no experiments on animals were performed for the present study.

The authors declared that no commercially available immortalised human and animal cell lines were used in the present study.

Use of AI

During the preparation of this work, the authors used ChatGPT to complete grammar and spelling checks. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the contents of the publication.

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Data availability

All of the data that support the findings of this study are available in the main text.

References

Almukhtar A, Caddick V, Naik R, Goble M, Mylonas G, Darzi A, Orihuela-Espina F, Leff DR (2025) Objective assessment of cognitive workload in surgery: a systematic review. Annals of surgery 281: 942–951. https://doi.org/10.1097/SLA.0000000000006370

Bisson E, Contant B, Sveistrup H, Lajoie Y (2007) Functional balance and dual-task reaction times in older adults are improved by virtual reality and biofeedback training. CyberPsychology & Behavior 10: 16–23. https://doi.org/10.1089/cpb.2006.9997

Bric JD, Lumbard DC, Frelich MJ, Gould JC (2016) Current state of virtual reality simulation in robotic surgery training: a review. Surgical Endoscopy 30: 2169–2178. https://doi.org/10.1007/s00464-015-4517-y

Frank DL, Khorshid L, Kiffer JF, Moravec CS, McKee MG (2010) Biofeedback in medicine: who, when, why and how? Mental Health in Family Medicine 7: 85–91. https://doi.org/10.1016/j.cardfail.2011.06.306

Halbig A, Latoschik ME (2021) A systematic review of physiological measurements, factors, methods, and applications in virtual reality. Frontiers in Virtual Reality 2: 1–32. https://doi.org/10.3389/frvir.2021.694567

Heard JR, Ghaffar U, Ma R, Yang CH, Assel M, Wagner C, Sonn GA, Goh AC, Saikali S, Patel V, Vickers A, Hu JC, Hung AJ (2025) Surgical performance metrics for 1-year patient-reported outcomes after radical prostatectomy. JAMA Surgery 160: 674–680. https://doi.org/10.1001/jamasurg.2025.0931

Houghton N, Prionas A, Kneebone R, Papalois V (2024) Ethics of training surgeons. The British Journal of Surgery 111(12): znae252. https://doi.org/10.1093/bjs/znae252

Jiwa A, Cameron MM, Ademuyiwa AO, Adisa A, Aguilera Arévalo ML, Bahrami Hessari M, Bhangu A, Brennan PM, Clark N, Cresswell K, Czerwinska I, D'Adderio L, Gunn E, Haque PD, Ikegwuonu T, Lawani I, Morton D, Nganwa A, Ntirenganya F, Pius R, Ramos de la Medina A, Samuel S, Shaw CA, Tabiri S, Townsend RC, Varghese C, Ghosh D, Harrison EM (2025) Continuous physiological monitoring for the detection of postoperative deterioration: a protocol for a multistage, multicentre, international, prospective cohort study. BMJ Open 15: e104463. https://doi.org/10.1136/bmjopen-2025-104463

Kelly NA, Althubaiti A, Katapadi AD, Smith AG, Nyirjesy SC, Yu JH, Onwuka AJ, Chiang T (2023) Association of vibrotactile biofeedback with reduced ergonomic risk for surgeons during tonsillectomy. JAMA Otolaryngology–Head & Neck Surgery 149: 397–403. https://doi.org/10.1001/jamaoto.2023.0044

Kiernan F, Rahman F (2015) Measuring surgical performance: A risky game? The surgeon: Journal of the Royal Colleges of Surgeons of Edinburgh and Ireland 13: 213–217. https://doi.org/10.1016/j.surge.2014.12.001

Lange T, Indelicato DJ, Rosen JM (2000) Virtual reality in surgical training. Surgical Oncology Clinics of North America 9: 61–79. https://doi.org/10.1016/S1055-3207(18)30169-8

Lüddecke R, Felnhofer A (2022) Virtual reality biofeedback in health: a scoping review. Applied Psychophysiology and Biofeedback 47: 1–15. https://doi.org/10.1007/s10484-021-09529-9

Mao RQ, Lan L, Kay J, Lohre R, Ayeni OR, Goel DP, Sa D (2021) Immersive virtual reality for surgical training: a systematic review. The Journal of Surgical Research 268: 40–58. https://doi.org/10.1016/j.jss.2021.06.045

McKnight RR, Pean CA, Buck JS, Hwang JS, Hsu JR, Pierrie SN (2020) Virtual reality and augmented reality—translating surgical training into surgical technique. Current

Reviews in Musculoskeletal Medicine 13: 663–674. https://doi.org/10.1007/s12178-020-09667-3

Orgil Z, Johnson L, Karthic A, Williams SE, Ding L, Kashikar-Zuck S, King CD, Olbrecht VA (2023) Feasibility and acceptability of perioperative application of biofeedback-based virtual reality versus active control for pain and anxiety in children and adolescents undergoing surgery: protocol for a pilot randomised controlled trial. BMJ Open 13: e071274. https://doi.org/10.1136/bmjopen-2022-071274

Orgil Z, Karthic A, Bell NF, Heisterberg LM, Williams SE, Ding L, Kashikar-Zuck S, King CD, Olbrecht VA (2024) Use of biofeedback-based virtual reality in pediatric perioperative and postoperative settings: observational study. JMIR Perioperative Medicine 7: e48959. https://doi.org/10.2196/48959

Prabhu VG, Stanley L, Morgan R (2020) A biofeedback enhanced adaptive virtual reality environment for managing surgical pain and anxiety. International Journal of Semantic Computing 14: 375–393. https://doi.org/10.1142/S1793351X20400152

Prabhu VG, Stanley L, Morgan R, Shirley B (2024) Designing and developing a nature-based virtual reality with heart rate variability biofeedback for surgical anxiety and pain management: evidence from total knee arthroplasty patients. Aging & Mental Health 28: 738–753. https://doi.org/10.1080/13607863.2023.2270442

Pulijala Y, Ma M, Pears M, Peebles D, Ayoub A (2018) Effectiveness of immersive virtual reality in surgical training – a randomised control trial. Journal of Oral and Maxillofacial Surgery 76: 1065–1072. https://doi.org/10.1016/j.joms.2017.10.002

Repetto C, Gorini A, Vigna C, Algeri D, Pallavicini F, Riva G (2009) The use of biofeedback in clinical virtual reality: the INTREPID project. Journal of Visualised Experiments: JoVE 33: e1554. https://doi.org/10.3791/1554

Rockstroh C, Blum J, Göritz AS (2020) Combining VR and biofeedback. Journal of Media Psychology 32: 176–186. https://doi.org/10.1027/1864-1105/a000270

Sweller J (1988) Cognitive Load During Problem Solving: Effects on Learning. Cognitive Science 12: 257–285. https://doi.org/10.1207/s15516709cog1202_4

Sweller J (2010) Cognitive Load Theory: Recent Theoretical Advances. In: Plass JL, Moreno R, Brünken R (Eds) Cognitive Load Theory. Cambridge University Press, 29–47. https://doi.org/10.1017/CBO9780511844744.004

Tam A, Bateman S, Buckingham G, Wilson M, Melendez-Torres G, Vine S, Clark J (2024) The effects of stress on surgical performance: a systematic review. Surgical Endoscopy 39: 77–98. https://doi.org/10.1007/s00464-024-11389-3

Wu Y, Zhu Y, Zheng B (2025) Enhancing surgical training through cognitive load assessment. Laparoscopic, Endoscopic and Robotic Surgery. https://doi.org/10.1016/j.lers.2025.06.001

Zakeri Z, Mansfield N, Sunderland C, Omurtag A (2020) Physiological correlates of cognitive load in laparoscopic surgery. Scientific Reports 10: 12927. https://doi.org/10.1038/s41598-020-69553-3