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Challenges of Integrating Robotic Surgical Procedures into Graduate Medical Education: State of The Art Review.

Desafíos de la Integración de los Procedimientos Quirúrgicos Robóticos en la Educación Médica de Posgrado: Revisión del Estado del Arte.

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Abstract.
Introduction. Robotic surgery is progressively transforming postgraduate medical education (PME); however, its integration into training programs remains heterogeneous, with persistent shortcomings in access, curriculum standardization, resident autonomy, and competency assessment. **Objective.** To synthesize and map the main challenges associated with integrating robotic surgical procedures into PME across seven domains: access, curriculum, institutional support, resident experience, assessment, barriers, and outcomes. The guiding question was: What are the challenges of integrating robotic surgical procedures into postgraduate medical education? **Methods.** A narrative thematic review was conducted of peer-reviewed studies published in 2025, in English, and indexed in PubMed, Scopus, and Web of Science. Studies that evaluated the integration of robotic procedures into residency or fellowship programs and addressed at least one of the predefined domains were included. Studies unrelated to GME, technical reports without training outcomes, opinion pieces, preprints, duplicates, and non-robotic training programs were excluded. Ten studies met the inclusion criteria. Data were extracted using a standardized framework, and no meta-analysis was performed. **Results.** The programs reported unequal access to robotic platforms, dual-console systems, simulators, and protected training time, resulting in fragmented, competency-based curricula with poorly defined milestones and inconsistent institutional support. Although residents showed high motivation, hands-on experience was variable, and autonomy at the console was limited. Available assessment tools showed potential but lacked robust validation and formal alignment with accreditation standards. Implementation

was further constrained by high costs, a shortage of trained instructors, medico-legal concerns, workflow limitations, and structural inequalities. The results showed improvements in simulation metrics and processes, while the transfer to independent surgical competence and improved clinical outcomes was inconsistent. **Conclusions.** The integration of robotic surgery into advanced medical training remains limited by inequities in access and an inconsistent curricular and institutional infrastructure. Its advancement will require standardized, competency-based training pathways, equitable access to technology, and sustained investment in faculty development, simulation, mentorship, and validated assessment systems.

Keywords: Robotic Surgical Procedures, Robot Assisted Surgery, Robot Enhanced Procedures, Graduate Medical Education, Specialized Healthcare Training, Systematic Review.

Resumen.
Introducción. La cirugía robótica está transformando progresivamente la educación médica de posgrado (GME); no obstante, su incorporación en los programas de formación continúa siendo heterogénea, con deficiencias persistentes en el acceso, la estandarización curricular, la autonomía del residente y la evaluación de competencias. **Objetivo.** Sintetizar y mapear los principales desafíos asociados con la integración de procedimientos quirúrgicos robóticos en la GME a través de siete dominios: acceso, currículo, apoyo institucional, experiencia del residente, evaluación, barreras y resultados. La pregunta guía fue: ¿cuáles son los desafíos de integrar procedimientos quirúrgicos robóticos en la educación médica de posgrado? **Métodos.** Se realizó una revisión temática narrativa de estudios revisados por pares, publicados en 2025, en idioma inglés e indexados en PubMed, Scopus y Web of Science. Se incluyeron estudios que evaluaran la integración de procedimientos robóticos en programas de residencia o beca y abordaran al menos uno de los dominios predefinidos. Se excluyeron estudios no relacionados con GME, informes técnicos sin resultados formativos, artículos de opinión, preprints, duplicados y entrenamientos no robóticos. Diez estudios cumplieron los criterios de inclusión. Los datos se extrajeron mediante un marco estandarizado y no se realizó metaanálisis. **Resultados.** Los programas reportaron acceso desigual a plataformas robóticas, sistemas de doble consola, simuladores y tiempo de formación protegido, lo que dio lugar a currículos fragmentados y basados en la competencia, con hitos poco definidos y apoyo institucional inconsistente. Aunque los residentes mostraron alta motivación, la exposición práctica fue variable y la autonomía en la consola limitada. Las herramientas de evaluación disponibles demostraron potencial, pero carecieron de validación robusta y alineación formal con los estándares de acreditación. La implementación se vio restringida además por los elevados costos, la escasez de docentes capacitados, preocupaciones médico-legales, limitaciones del flujo de trabajo y desigualdades estructurales. Los resultados evidenciaron mejoras en métricas de simulación y procesos, mientras que la transferencia a la competencia quirúrgica independiente y a mejores resultados clínicos fue inconsistente. **Conclusiones.** La integración de la cirugía robótica en la GME sigue limitada por inequidades en el acceso y una infraestructura curricular e institucional inconsistente. Su avance requerirá itinerarios formativos estandarizados y basados en competencias, acceso equitativo a la tecnología e inversión sostenida en desarrollo docente, simulación, mentoría y sistemas de evaluación validados.

Palabras clave: Procedimientos Quirúrgicos Robotizados, Cirugía Asistida por Robot, Procedimientos Asistidos por Robot, Educación de Postgrado en Medicina, Formación Sanitaria Especializada, Revisión Sistemática.

1. Introduction

Robotic surgery has emerged as a transformative force across surgical specialties, with implications for both clinical performance and graduate medical education. Early exposure can enhance trainees' technical dexterity and spatial understanding, yet programs report uneven access to platforms and cases, variable autonomy, and heterogeneity in curricular structure and competency assessment (1-4). These opportunities and constraints place robotic training at the confluence of pedagogy, technology, and systems factors that must be addressed to ensure safe, effective learning pathways.

In this context, contemporary innovations—particularly validated simulation, real-time performance feedback, and AI-enabled analytics—are reshaping how curricula can be tailored to learner needs and institutional realities. Integrating simulation and artificial intelligence (AI) within structured, specialty-specific curricula offers a route to standardization, progression-based milestones, and scalable skills acquisition, while global collaboration can help harmonize expectations and resources across programs (5-7). At the same time, rapid platform evolution demands continuous curricular updates, and institutional support is needed to operationalize these approaches equitably (4, 8).

However, implementation is not without challenges. Programs contend with technical reliability and interoperability concerns; the need to validate simulation as an assessment tool; substantial acquisition and maintenance costs, with implications for equity; and ethical and regulatory questions related to patient safety, accountability, and data governance (6-11). Despite these barriers, the potential benefits of structured learning, trainee engagement, and patient-centered outcomes underscore the importance of a current, integrative synthesis that spans access, curriculum, support, experience, evaluation, barriers, and outcomes. This leads us to the research question: What are the challenges of integrating robotic surgical procedures into graduate medical education?

2. Methods

The reporting of information sources and search methods follows PRISMA-S (Preferred Reporting Items for Systematic reviews and Meta-Analyses literature search extension) (12). The completed PRISMA-S checklist is provided in Supplementary Table S1.

Eligibility Criteria

We considered peer-reviewed studies (2025; English) that explicitly examined the integration of robotic surgical procedures into graduate medical education (GME)—residency or fellowship—mapped to the domains access, curriculum, support, experience, evaluation, barriers, and outcomes. Eligible works were situated in academic or applied training settings (e.g., multi-institutional residency programs, simulation curricula, needs-assessment surveys, retrospective case-log analyses, and program evaluations) and reported on at least one of the specified domains. We included empirical designs such as randomized or quasi-experimental simulation studies, cross-sectional surveys/cohorts, retrospective analyses, mixed-methods, and structured narrative reviews grounded in explicit educational frameworks. We excluded documents outside GME (e.g., undergraduate or CME without resident/fellow focus), studies on robotic platforms lacking an educational component, purely technical performance reports without trainee-level outcomes, opinion pieces/editorials without methodological grounding, preprints or unpublished materials, duplicates, and studies focused on non-robotic surgery or general minimally invasive training without a robotic integration lens.

Information Sources and Search Strategy

We searched in PubMed, Scopus, and Web of Science. The window spanned January 2025 to September 2025, with searches performed between September 25 and 26, 2025 (last update: September 26, 2025). No geographic limits were applied; records in English were eligible. Full, exact strategies as run are provided in Supplementary Table S2. Reporting of information sources and search methods followed the PRISMA-S extension. The completed PRISMA-S checklist is available as Supplementary Table S1. All records retrieved from the databases were exported (RIS/CSV), consolidated in a shared spreadsheet by A.H.L.L., and deduplicated using Rayyan (13). QCRI's duplicate detection plus manual verification. Deduplicated records were screened independently in Rayyan by nine investigators (R.J.L.L., J.H.V.V., J.D.C.B., H.E.M.D., J.A.C.O., A.M.S., P.C.A.M., G.P.Z.Z., and A.H.L.L.). Disagreements at title/abstract were adjudicated by G.P.Z.Z. by discussion. The same group reviewed full texts, with any remaining discrepancies resolved by A.H.L.L. Screening occurred between September 29 and 30, 2025. We identified 13 records (3 databases; 13 registers). Three duplicates were removed, leaving 10 records for title/abstract screening. Ten reports were assessed at full text, and 10 studies were included in the review.

3. Results

Study Selection

All articles that meet the eligibility criteria, adhere to the temporal restriction (2025), and are available in open access will be included in the review. Studies will be screened for relevance based on their abstracts and full texts, with a focus on those directly addressing the research question: "What are the challenges of integrating robotic surgical procedures into graduate medical education?" Articles that do not meet these criteria will be excluded (Figure 1) (14).

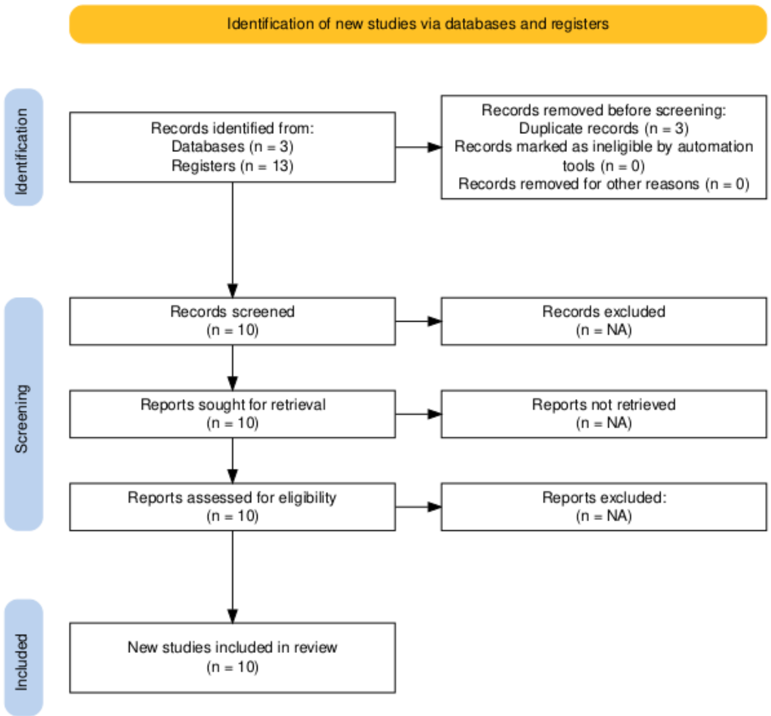

Figure 1. PRISMA 2020 flow diagram.

Data synthesis

Given the substantial heterogeneity across the included studies—spanning experimental simulator-based comparisons (e.g., fNIRS-tracked cognitive workload on robotic vs. laparoscopic tasks), retrospective analyses of national residency case logs, multi-institutional cohort video-ratings using GEARS/C-SATS, pan-regional and national needs-assessment surveys, trainee- and society-led Delphi/position statements, narrative reviews, and retrospective clinical series—we did not prespecify nor undertake a quantitative meta-analysis. Instead, we applied a narrative thematic synthesis organized around seven domains (access, curriculum, support, experience, evaluation, barriers, and outcomes): (i) we summarized study characteristics and mapped each paper's contributions to these domains; (ii) we extracted and reported key quantitative findings from empirical work—such as shorter task times and reduced cognitive workload on robotic simulators relative to laparoscopy, correlations between historical case volume and GEARS performance, trends in resident primary-surgeon roles within ACGME case logs, survey-derived estimates of simulator/dual-console availability and timing of exposure (including very high response rates in some settings), and consensus magnitudes (e.g., ≥80% agreement with 82/141 statements in a trainee Delphi)—without statistical pooling; and (iii) we integrated qualitative insights from consensus statements, narrative reviews, and free-text survey responses to articulate cross-cutting challenges (e.g., inequitable platform access, resource and accreditation constraints, variable faculty mentorship and credentialing pathways, competing demands that limit hands-on experience) and to derive implications for GME design (e.g., staged curricula with early exposure, protected simulation time, dual-console mentorship models, competency-based assessment with validated tools, and use of registries for longitudinal evaluation). Sensitivity analyses and publication bias assessments were not applicable given the diversity of study types and the absence of a pooled quantitative synthesis.

Outcomes

The outcomes of this review focus on how the integration of robotic surgery into graduate medical education (GME) is being shaped across seven analytic domains. Regarding Access, studies documented uneven availability of robotic platforms, dual consoles, and simulators across programs and regions, with survey data indicating that only a subset of trainees have routine console access (e.g., ≈64% reported a console at their institution) and many lack structured opportunities during working hours. In Curriculum, proposed tiered frameworks—progressing from simulation and dry/wet labs to supervised console work and train-the-trainer models—are emerging, yet curricula remain fragmented, with a notable share of respondents unaware of any dedicated programmatic pathway and limited clarity on progression milestones. Concerning Support, outcomes underscored the need for institutional commitment (protected time, funded simulation, accredited instructors, and dual-console capacity), which remains inconsistent, particularly outside high-resource centers. For Experience, trainees reported high motivation but variable hands-on exposure and autonomy at the console; some studies flagged displacement by fellows and concerns about erosion of open/manual skills without hybrid exposure. In Evaluation, objective metrics (e.g., GEARS via expert/video review, task-time efficiency, and neurocognitive workload indices) demonstrated sensitivity to skill acquisition and correlated with historic case volume, while Delphi-based consensus supported proficiency-based progression and benchmarked credentialing (≥80% agreement on multiple statements); however, validity evidence and alignment with formal accreditation standards are still limited. In Barriers, high costs, instructor shortages, time constraints, medico-legal concerns, and structural inequities—especially in low- and middle-income contexts—impede equitable implementation and slow the transition from bedside assistance to console competence. Finally, in Outcomes, studies reported improved technical accuracy and efficiency in simulated and selected clinical tasks and framework-driven promises of safer training, but also highlighted trends of rising robotic case volumes accompanied by constrained resident console participation, raising concerns about preparedness for independent practice without standardized, scaffolded access and robust assessment. Collectively, these outcomes emphasize that the central challenges in integrating robotic procedures into GME lie not in pedagogical potential but in standardization, equitable access, sustained institutional support, and rigorous evaluation that ensure progressive autonomy and patient safety.

Data Extraction

Data were extracted with a standardized form structured around pre-specified items and contextualized to the seven domains relevant to the research question—access, curriculum, support, experience, evaluation, barriers, and outcomes—regarding the integration of robotic surgical procedures into graduate medical education. For each included study, the form captured: Author(s), Year of publication, Country of origin, Aim/purpose, Population and sample size, Methodology/study design, Type of intervention (with comparator and duration, if applicable), Outcomes (and how measured), and domain-specific fields aligned to our framework (Access, Curriculum, Support, Experience, Evaluation, Barriers, and Outcomes). Discrepancies in data extraction were resolved by consensus and, when necessary, with adjudication by a third reviewer. Items not reported (NR) were explicitly noted, and the country of study was inferred from author affiliations when absent (Supplementary Table S3).

4. Discussion

This discussion critically examines the integration of robotic surgery into graduate medical education across seven interconnected domains: (i) Access, underscoring how platform availability, cost, and limited protected console time constrain equitable exposure; (ii) Curriculum, emphasizing the need for coherent, competency-based sequencing from simulation to supervised bedside and console roles with clear progression criteria; (iii) Support, highlighting requirements for faculty development, proctoring, credentialing policies, and reliable institutional logistics and simulation resources; (iv) Experience, noting the importance of longitudinal case exposure, structured pre-briefing and debriefing, and deliberate entrustment to secure meaningful trainee participation; (v) Evaluation, calling for validated, specialty-specific assessments that link objective metrics to milestones and credentialing decisions; (vi) Barriers, addressing safety concerns during early learning curves, workflow disruptions, resource competition, vendor dependence, and regulatory uncertainty; and (vii) Outcomes, recognizing gains in simulator performance and selected process indicators while acknowledging limited and mixed evidence for transfer to independent operative competence, patient outcomes, and cost-effectiveness. Together, these domains offer an integrated perspective on the promise and limits of robotic training in GME, while identifying priorities for standardization, rigorous multi-site evaluation, and sustainable resourcing (1, 15-23).

Access

Access to robotic surgical training remains inconsistent across regions and specialties. Evidence from Japan and Europe indicates that surgical residents do not have uniform exposure to robotic systems or simulators, which limits equitable opportunities for skill acquisition (15, 18, 24). In Japan, training availability remains largely dependent on institutional resources and the prioritization of attending surgeons (15, 25). The European Robotic Surgery Consensus survey reported inequities linked to the concentration of robotic platforms in tertiary centers (18, 26). Programs in the United States demonstrate broader access through mandatory case-logging systems and simulation-based curricula (21, 23, 27, 28). However, disparities persist across specialties, as orthopedic and reconstructive programs continue to show lower exposure than urology and thoracic surgery (1, 20, 24). These findings confirm that access inequity remains a determinant of educational outcomes in robotic surgery training at the international level (26, 27, 29).

Curriculum

Robotic surgery curricula remain fragmented, with limited standardization across institutions. Consensus frameworks recommend structured, competency-based progression that integrates simulation, mentorship, and independent performance (17, 21, 32). Data from Europe and Japan indicate that numerous programs operate without national curricular guidelines, relying on local or self-directed models (4, 15, 18). Orthopedic training shows similar gaps, with minimal formal integration of robotic skills (1). A Delphi consensus among trainees in the United Kingdom emphasizes the need for alignment between specialties and unified competency benchmarks (19, 24). The lack of coordination across programs sustains variability in proficiency and safety standards (30, 31). Therefore, establishing an international framework with standardized milestones and assessments remains a critical educational priority (17, 21, 32).

Support

Institutional and faculty support are essential components of effective robotic surgery education. Programs endorsed by surgical societies, such as ACPGBI, ERSC, and STS, demonstrate more stable structures through mentorship and accreditation processes (17, 18, 21, 33). Nevertheless, several European training centers report limited institutional oversight and faculty availability (18, 34). In Japan, similar challenges are documented regarding the shortage of trained mentors and dedicated time for robotic training (15). Evidence from simulation-based interventions demonstrates that structured supervision improves both task performance and cognitive efficiency (16, 28, 35). Consistent faculty engagement and institutional investment are therefore necessary to maintain quality, sustainability, and accessibility in robotic education programs (36, 37).

Experience

Residents' experiences in robotic surgery programs vary depending on institutional capacity and supervision. In the United States, urology trainees report increased participation but limited independence at the console (23, 38). In Japan and Europe, trainees often encounter restricted hands-on experience, primarily due to hierarchical structures and limited availability of robotic sessions (15, 18, 39, 40). Similar conditions are described in orthopedic and reconstructive training, where most procedures are conducted under consultant control (1, 20). Simulation-based learning has been shown to improve performance and reduce cognitive workload during robotic tasks (16, 33). These results indicate that experiential variability affects both confidence and progression, reinforcing the importance of structured opportunities for practical engagement throughout training (19, 37, 41).

Evaluation

Assessment strategies for robotic surgery remain diverse and inconsistently implemented. Objective simulator metrics and cognitive workload analyses have proven useful in measuring trainee performance (16, 42, 43). Consensus guidelines recommend validated tools such as GEARS and OSATS for standardized evaluation (17, 21, 44). Despite these recommendations, several programs still lack formal mechanisms for evaluation (18, 45). A Delphi study in the United Kingdom proposed a combined approach involving simulator data, intraoperative evaluation, and structured feedback (19, 46). Emerging technologies such as C-SATS have been evaluated for reliability, although inconsistencies between algorithmic and expert assessments have been observed (22, 47). These findings highlight the need for validated, multimodal, and transparent evaluation systems that align with curricular objectives (48, 49).

Barriers

Persistent barriers continue to hinder the implementation of comprehensive robotic training. Equipment costs, scarcity of qualified trainers, and institutional inequalities are consistently reported across studies (8, 15, 18, 21, 50, 51). Cognitive workload analyses reveal elevated mental demands among novice trainees, emphasizing the need for preparatory simulation exposure (9, 16). Limited program time, competition for console use, and variable supervision further restrict participation (17, 19, 39, 52). Specialty-specific barriers also exist, including low case volumes in orthopedic surgery (1) and consultant-led models in reconstructive procedures (20, 53). Addressing these obstacles requires institutional and policy-level strategies that combine financial investment, faculty development, and equitable scheduling practices (2, 5, 54).

Outcomes

Structured robotic training has demonstrated favorable educational and clinical results across multiple specialties. Simulator-based programs are associated with improved performance and reduced cognitive workload (16, 45, 47). Longitudinal studies in urology and thoracic surgery show progressive increases in procedural participation and self-efficacy following the implementation of structured curricula (21, 23, 46, 55). International initiatives such as ACPGBI and ERSC report improved patient safety and procedural consistency when standardized frameworks are adopted (17, 18, 45, 56). Delphi-based recommendations also suggest enhanced collaboration and quality assurance in robotic training environments (1, 19). Overall, evidence across disciplines indicates that standardized curricula, institutional support, and objective evaluation methods are key elements for achieving optimal educational and clinical outcomes in robotic surgery (45-47).

Limitations and Strengths

Among the limitations of this review is the relatively small corpus of eligible studies (ten in total) and their considerable heterogeneity in design, aims, populations, and outcomes, which prevented conducting a quantitative synthesis or meta-analysis. Several included sources were narrative reviews, consensus statements, or professional position papers without primary empirical data, thereby limiting the strength of inference and the generalizability of conclusions. Even among empirical studies, many relied on cross-sectional surveys, single-institution reports, or pilot simulator-based trials with short-term follow-up and modest sample sizes, constraining causal interpretation and long-term outcome evaluation. Additionally, most of the available evidence was published in 2025, reflecting the nascent state of research on robotic surgical education and suggesting that ongoing or unpublished studies may not yet be captured. Publication bias cannot be excluded, as the review focused exclusively on English-language, peer-reviewed literature indexed in PubMed, Scopus, and Web of Science. Outcome measures across studies were also highly variable, often emphasizing simulator proficiency, cognitive workload, or case participation rates, while broader endpoints such as independent competence, patient outcomes, and cost-effectiveness were seldom assessed in depth.

In contrast, this review exhibits notable strengths. It adhered to PRISMA-S standards, employed a multi-database search strategy, and implemented a transparent, two-phase screening process in Rayyan, with independent reviewers and consensus-based resolution. The synthesis was structured across seven analytic domains (Access, Curriculum, Support, Experience, Evaluation, Barriers, and Outcomes), allowing systematic mapping of evidence across diverse specialties and regions. Standardized data extraction captured study characteristics, methodological features, and domain-specific contributions, ensuring reproducibility and traceability. This structured approach not only enhances methodological rigor and transparency but also establishes a comprehensive foundation for future empirical research and policy development in robotic surgery education within graduate medical training.

Future Directions

Next-step research should move beyond descriptive surveys, single-center reports, and pilot simulator trials by adopting multicenter randomized and longitudinal designs that directly compare structured, competency-based robotic curricula with unstructured or opportunistic exposure models. Future investigations must incorporate objective, validated endpoints—such as procedural autonomy, GEARS or OSATS score progression, intraoperative performance metrics, and the long-term transfer of skills to patient outcomes—while also examining ethical and institutional dimensions, including data governance, equity of access, and the sustainability of training infrastructure. To enable comparability, studies should report intervention fidelity, mentorship frameworks, and standardized performance metrics aligned with specialty-specific benchmarks. Implementation science and mixed-method approaches are needed to evaluate the feasibility, cost-effectiveness, and scalability of robotic training models across diverse geographic and resource settings. Moreover, collaborative co-design involving educators, program directors, residents, and accrediting bodies, alongside faculty development in simulation and AI-assisted assessment, will be critical to integrate robotic surgery education safely, ethically, and sustainably into graduate medical curricula.

5. Conclusions

- Integrating robotic surgical procedures into graduate medical education is hampered first and foremost by uneven access, which determines who gets meaningful exposure and who does not. Limited platform availability, constrained dual-console capacity, and scarce protected time fragment opportunities for deliberate practice. Consequently, trainees progress at markedly different rates even within the same specialty. A coherent curriculum cannot compensate for these structural disparities unless access is deliberately equalized.
- Nevertheless, curricular gaps compound the problem: many programs lack a unified, proficiency-based pathway that links simulation, bedside roles, and graded console autonomy to explicit milestones. Without such sequencing, learners accumulate case counts rather than demonstrable capabilities, and readiness for entrustment remains ambiguous. Addressing this requires strong support—funded simulation blocks, faculty time, and mentorship structures that are stable rather than ad hoc. In turn, learner experience improves when case selection, scheduling, and hierarchical norms intentionally create recurrent, mentored console opportunities rather than opportunistic "one-off" turns.
- Even where access and support exist, evaluation practices are inconsistently implemented and weakly connected to advancement decisions. Programs frequently mix unvalidated local checklists with sporadic simulator metrics, producing noisy signals about competence. What is needed are specialty-tailored, multimodal assessments that combine task-specific metrics, intraoperative performance ratings, and structured feedback mapped to progression thresholds. Yet persistent barriers—notably cost, limited trainer capacity, medicolegal caution, and competition for operating-room time—undercut the adoption of such robust frameworks.
- Finally, the outcomes literature suggests promising gains in technical performance and workflow reliability when training is structured, but definitive evidence for transfer to independent operative competence, patient safety benefits, and cost-effectiveness remains incomplete. Therefore, the central challenge is not whether robotic surgery can be taught, but whether systems can guarantee equitable access, deliver coherent curricula, and sustain faculty-supported experiences that are credibly assessed. Addressing this will require targeted investment, formal entrustment pathways, and longitudinal, multi-site evaluations that tie trainee progression to clinical and economic endpoints. Only then will integration of robotic surgery into GME be both educationally defensible and operationally sustainable.

Supplementary files. Annex 1: Table S1. PRISMA-S Checklist, Table S2. Bibliographic search strategy, Table S3. Characteristics of included studies (part 1), Table S3. Characteristics of included studies (part 2).

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