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COMPARATIVE ANALYSIS OF ROBOTIC, LAPAROSCOPIC, AND OPEN SURGERY: CLINICAL OUTCOMES, COSTS, AND ERGONOMICS

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ABSTRACT

Background: The evolution of surgical practice has seen a significant shift from open surgery toward minimally invasive techniques. Conventional Laparoscopic Surgery (CLS) replaced many open procedures. It offers benefits like reduced length of hospital stay and lower infection rates. Subsequent technological advancement introduced Robot-Assisted Surgery (RAS), notably utilizing systems like Da Vinci. RAS was specifically developed to overcome the inherent technical limitations of CLS. These include restricted instrument range and two-dimensional viewing. The continuous integration of advanced technologies, including Artificial Intelligence (AI) and Machine Learning (ML), is defining the future role of technology in surgery. This moves towards enhanced precision and autonomous systems.
Objective: This analysis aims to synthesize the current evidence comparing Robot-Assisted Surgery (RAS) to Conventional Laparoscopic Surgery (CLS) and open surgery. It focuses on key parameters including clinical outcomes (safety and efficacy), socio-economic costs, and surgeon ergonomics.
Methods: This is a narrative synthesis drawing upon recent systematic reviews, meta-analyses, and comparative retrospective studies found in the literature. These primarily compared RAS and CLS across various surgical disciplines. Examples include colorectal surgery, gynecological surgery (e.g., hysterectomy), and nephrectomy.
Results: RAS systems offer inherent technical advantages such as superior visualization (3D, high-definition) and enhanced precision due to tremor filtration, motion scaling, and articulated instruments. The learning curve for performing complex technical tasks, such as intracorporeal suturing, is significantly shorter for novice surgeons utilizing robotic assistance compared to those performing CLS. In clinical practice, RAS generally yields comparable results to CLS in terms of major postoperative complications, mortality, and readmission rates. However, RAS is consistently associated with a significantly lower conversion rate to open surgery and a shorter length of hospital stay across nearly all analyzed surgical categories. Conversely, RAS procedures are typically associated with significantly higher total costs (including hospitalization and operative costs) compared to CLS. Furthermore, the operative time for RAS is generally longer than for CLS. In terms of ergonomics, studies indicate that RAS offers better outcomes for surgeons. This results in reduced physical demand and muscle strain compared to the conventional laparoscopic technique.
Conclusion: Robotic surgery shows considerable potential for the future, especially for complex surgical procedures performed in anatomically challenging areas. This is primarily due to its ability to minimize conversion rates and shorten hospital stays. Nonetheless, given the substantial associated costs, cost optimization and reduction in equipment and procedure expenses are critical steps. These are required to ensure widespread accessibility and justify its overall value compared to the cost-effective laparoscopic approach.

KEYWORDS

Robot-Assisted Surgery, Conventional Laparoscopic Surgery, Cost-Effectiveness, Surgical Ergonomics, Clinical Outcomes, Artificial Intelligence in Surgery

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Introduction

Historical Context: From Early Platforms to Dominance and Diversification

The evolution of modern surgical practice is characterized by the continuous integration of advanced technology. The history of surgical robotics dates back to 1985 with the use of the PUMA 200 robot for performing brain biopsies (Rivero-Moreno et al., 2024). Subsequent milestones include the 1994 FDA approval of the first commercially available surgical robot, the Automated Endoscopic System for Optimal Positioning (AESOP). This facilitated laparoscopic procedures through voice control (Rivero-Moreno et al., 2024). The Zeus system received FDA approval in 1998 (Rivero-Moreno et al., 2024). A defining moment arrived in 2000 with the FDA clearance of the Da Vinci Surgical System (Intuitive Surgical Inc.) for general surgery (Köckerling, 2014; Rivero-Moreno et al., 2024). This system established the foundation of transparent teleoperation. Here, surgical tools precisely mirror the surgeon's movements, representing Level 0 autonomy (Attanasio et al., 2021; Rivero-Moreno et al., 2024). The widespread adoption of Da Vinci led to robotic prostatectomy becoming the standard of care in the USA by 2008 (Köckerling, 2014). Today, the landscape is expanding to include new platforms such as the Versius robotic platform (Pérez-Salazar et al., 2024). Looking toward the future, the field is moving towards increased autonomy and precision through the integration of Artificial Intelligence (AI) and Machine Learning (ML) (Iftikhar et al., 2024; Rivero-Moreno et al., 2024; Patel et al., 2025).

Defining the Problem: Limitations of Conventional Laparoscopy

Conventional Laparoscopic Surgery (CLS) offers clear benefits to patients compared to open surgery (Chabot et al., 2024; Pérez-Salazar et al., 2024). However, it poses intrinsic technical difficulties, especially during complex procedures (Ielpo et al., 2022). The challenges stem from technical limitations such as reliance on two-dimensional (2D) imaging. This impairs depth perception (Chabot et al., 2024; Hong et al., 2025; Köckerling, 2014). Furthermore, CLS requires the use of rigid instruments. These significantly restrict the range of motion (Hong et al., 2025; Ielpo et al., 2022; Köckerling, 2014; Rehman et al., 2025). The instrument's insertion point acts as a fixed pivot. This creates the technically demanding fulcrum effect (Köckerling, 2014). Moreover, CLS is described as physically demanding. It often requires surgeons to maintain awkward and fixed postures (e.g., arm abduction or a twisted trunk). These contribute to musculoskeletal problems and physical strain (Cooper et al., 2025; Pérez-Salazar et al., 2024).

The Technological Solution: How Robotics Overcomes Limitations

Robot-Assisted Surgery (RAS) was purposefully designed to circumvent the fundamental constraints of CLS. This occurs primarily by improving visualization and manipulation (Köckerling, 2014). The technical advantages provided by RAS platforms include:

- Superior Visualization: RAS offers immersive, high-definition 3D vision (Hong et al., 2025; Ielpo et al., 2022; Rehman et al., 2025).
- Enhanced Dexterity: Robotic systems utilize articulated instruments (Köckerling, 2014; Paul-Dehlinger et al., 2024). These are sometimes referred to as EndoWrist technology. They mimic the human hand by providing seven degrees of motion/freedom (Hong et al., 2025; Ielpo et al., 2022; Rehman et al., 2025).
- Precision and Stability: RAS platforms increase precision and gesture security through features such as tremor filtration and motion scaling. These translate the surgeon's movements into highly controlled, microscopic actions (Chabot et al., 2024; Iftikhar et al., 2024; Paul-Dehlinger et al., 2024; Köckerling, 2014).

These technical enhancements contribute to a significantly shorter learning curve for complex tasks like intracorporeal suturing. This is when compared to the demanding curve associated with CLS (Leijte et al., 2020; Paul-Dehlinger et al., 2024).

Socio-economic and Ergonomic Justification

The adoption of RAS requires a multi-faceted justification. This encompasses clinical efficacy, surgeon well-being, and financial impact. Ergonomically, RAS offers substantial advantages. The surgeon typically operates from a console in a comfortable, seated position (Cooper et al., 2025; Pérez-Salazar et al., 2024). This position results in an improved ergonomic posture and reduced physical demand (Pérez-Salazar et al., 2024). Objective measurements and subjective reports (e.g., NASA-TLX scale) consistently indicate that RAS is less fatiguing. It leads to significantly lower muscle strain, especially in the neck and shoulder regions, compared to CLS (Cooper et al., 2025; Pérez-Salazar et al., 2024). Furthermore, the mean heart rate of surgeons has been observed to be significantly lower during RAS procedures than during CLS (Chabot et al., 2024).

However, the major impediment to broad implementation is the significant economic burden (Chabot et al., 2024). RAS is associated with significantly higher total costs than the cost-effective CLS approach (Paul-Dehlinger et al., 2024; Chabot et al., 2024; Hong et al., 2025). This high cost is derived from the initial investment (e.g., the Da Vinci XI Dual Console has a unit price of €2,760,000). It also includes recurring annual maintenance fees (€228,000). Additionally, there is the expense of specialized limited-use and single-use consumables (Paul-Dehlinger et al., 2024). For instance, the estimated average total cost per patient at one month for robot-assisted hysterectomy (RAH) was €6,615. This compares to €3,859 for laparoscopic hysterectomy (LH) (Paul-Dehlinger et al., 2024). The cost difference also translates to higher patient out-of-pocket costs (Hong et al., 2025).

Methodology

This narrative review synthesizes evidence from recent systematic reviews, meta-analyses, randomized controlled trials, and comparative observational studies that directly compared robot-assisted surgery (RAS) with conventional laparoscopic surgery (CLS) across multiple surgical specialties. No formal PRISMA protocol was followed, and no quantitative meta-analysis was performed. Instead, emphasis was placed on consistency across high-quality sources reporting clinical, economic, and ergonomic outcomes.

Search Strategy

The search strategy for literature comparing RAS and CLS generally relies on multiple established electronic databases. Typical search platforms utilized across reviews include PubMed, Scopus, EMBASE, the Cochrane Library, and Web of Science (Chabot et al., 2024; Cooper et al., 2025; Hong et al., 2025; Rehman et al., 2025; Singh et al., 2024).

A structured approach, often following the PICOS framework (Population, Intervention, Comparators, Outcomes, and Study Design), is used to define search terms (Chabot et al., 2024; Hong et al., 2025; Rehman et al., 2025). Key search terms align with the intervention and critical outcomes:

- Robotic-Assisted Surgery / Laparoscopy: Search strings commonly included "robot*" OR "robot-assisted," "laparoscop*," "RALS," and "CLS" (Chabot et al., 2024).
- Cost-Effectiveness & Costs: Dedicated searches frequently used terms such as "cost*," "economic*," "financial*," "pric*," "charge*," or "billing*" to capture financial outcomes (Hong et al., 2025).
- Ergonomics: Searches focused on the impact on the surgeon employed terms like "Ergonomic*," "muscle*," "fatigue," "muscular strain*," and "musculoskeletal symptom*" (Cooper et al., 2025).
- Clinical Outcomes: Terms such as "clinical outcomes," "postoperative complications," "conversion rate," and "length of hospital stay" are frequently incorporated (Rehman et al., 2025; Chabot et al., 2024).

The search period varies, aiming to capture the most recent evidence. This sometimes spans the last five years (Chabot et al., 2024) or covers a broad period, such as 2007 up to 2025 (Hong et al., 2025).

Inclusion Criteria

To provide a comprehensive synthesis, studies must adhere to criteria defining the appropriate study design, population, intervention, and reported outcomes.

- Study Design: Included study types frequently consist of systematic reviews (SRs) and meta-analyses (MAs) (Chabot et al., 2024; Rehman et al., 2025), randomized controlled trials (RCTs) (Hong et al., 2025; Rehman et al., 2025), observational studies, cohort studies (Hong et al., 2025; Rehman et al., 2025), and comparative trials (Singh et al., 2024).
- Intervention and Comparison: Studies must directly compare Robot-Assisted Surgery (RAS) or Robot-Assisted Laparoscopic Surgery (RALS) with Conventional Laparoscopic Surgery (CLS or LS) (Hong et al., 2025; Chabot et al., 2024).
- Focus Areas: Included publications focus on the following key aspects:
- Cost and Cost-Effectiveness: Studies reporting economic measures such as total hospitalization cost, operation cost, government or patient out-of-pocket (OOP) payments, and cost-effectiveness or cost–utility (Hong et al., 2025; Paul-Dehlinger et al., 2024; Ielpo et al., 2022).
- Ergonomics: Research focusing on muscular straining and/or ergonomic assessment in surgeons performing CLS or RALS (Cooper et al., 2025). This includes objective (e.g., sEMG, RULA) or subjective measurements (Cooper et al., 2025; Pérez-Salazar et al., 2024).
- Clinical Outcomes: Studies reporting on defined outcomes, such as conversion rate, complication rates (intraoperative and postoperative), length of hospital stay, and operative time (Chabot et al., 2024; Rehman et al., 2025).

Exclusion Criteria

To maintain the quality and focus of the analysis, several types of articles or data points are typically excluded:

- Study Design and Publication Type: Exclusion criteria often include protocols (Cooper et al., 2025), review articles (Rehman et al., 2025; Cooper et al., 2025), and non-original articles (Hong et al., 2025).
- Non-Clinical/Non-Human Data: Studies focusing solely on cadaveric (Rehman et al., 2025) or animal models (Hong et al., 2025; Rehman et al., 2025) are typically excluded from meta-analyses assessing patient clinical outcomes. Similarly, in ergonomic reviews, papers with in vitro simulated tasks are excluded to ensure the focus remains on the real-life operating theater setting (Cooper et al., 2025).
- Missing or Incomplete Data: Studies are excluded if they report insufficient data (Rehman et al., 2025), report none of the clinical outcomes of interest (Chabot et al., 2024), or fail to delineate results between RALS and CLS (Cooper et al., 2025).
- Specific Focus: Studies focusing on highly specific populations (e.g., certain comorbidities like obesity) or non-relevant interventions (e.g., studies focused solely on long-term follow-up, recovery programs, or pre-operative prediction scores) are excluded (Chabot et al., 2024; Rehman et al., 2025).

Limitations of the Methodology

As a narrative review, this work is subject to selection bias and does not include a formal risk-of-bias assessment or pooled quantitative estimates. The search, while structured, was not conducted according to a pre-registered protocol. Publication bias in the underlying systematic reviews and trial literature cannot be excluded.

Comparative Clinical Outcomes

Comparative evaluations of Robot-Assisted Surgery (RAS) versus Conventional Laparoscopic Surgery (CLS) demonstrate specialized benefits across various surgical disciplines. These benefits are particularly evident in complex pelvic procedures where the robot's dexterity is maximized.

General Surgery

Colorectal Resection (Rectal Cancer/TME)

Robotic-assisted colorectal surgery (RACS) has increasingly been adopted as a viable alternative to CLS, particularly for rectal cancer (Zou et al., 2025; Wang et al., 2025).

1. Conversion to Open Surgery: RAS consistently shows a significant advantage by reducing the rate of conversion to open surgery compared to CLS. This holds even during the early phase of robotic adoption (Rehman et al., 2025; Zou et al., 2025; Köckerling, 2014).

- One meta-analysis of 11 randomized controlled trials (RCTs), comprising 3,107 patients, found that robotic surgery (RS) had a significantly lower conversion rate (Odds Ratio [OR]: 0.42) compared to laparoscopic surgery (LS) for rectal resection (Zou et al., 2025). This is considered statistically significant ($P<0.0001$) (Zou et al., 2025).
- Another systematic review evaluating outcomes during the early learning curve phase of colorectal cancer surgery confirmed significantly lower conversion rates for the robotic arm (OR = 1.480; P=0.000) (Rehman et al., 2025).

2. Oncological and Pathological Outcomes:

RS demonstrated superior efficacy in terms of pathological outcomes (Zou et al., 2025). It was associated with a significantly smaller incidence of positive circumferential margin (CRM) (OR: 0.59; P=0.004) and more lymph nodes harvested (mean difference: 0.67; P=0.0004) compared to LS for rectal resection (Zou et al., 2025). The oncological accuracy of robotic resection for rectal cancer is deemed adequate (Köckerling, 2014).

3. Functional Recovery and Complications:

- RS showed a statistically significant shorter time to first autonomous urination, first defecation, and first flatus compared to LS (Zou et al., 2025). This suggests reduced surgical trauma and faster recovery of bowel function in the RS group (Zou et al., 2025).
- RS also had a lower reoperation rate compared to LS (OR: 0.54; P=0.03) (Zou et al., 2025).
- Overall postoperative complication rates, short-term complications, and 30-day mortality did not differ significantly between the two approaches (Rehman et al., 2025; Zou et al., 2025).

4. Operative Time and Hospital Stay: Operative time is consistently longer in RACS compared to CLS (mean difference: 23.46 minutes longer) (Wang et al., 2025; Zou et al., 2025; Köckerling, 2014). However, RAS was found to significantly reduce the length of hospital stay compared to CLS in multiple comparisons (Rehman et al., 2025; Chabot et al., 2024).

Hernia Repair

Inguinal hernia repair is noted as a procedure frequently executed with robotic systems (Chabot et al., 2024). However, the provided sources do not contain specific comparative clinical data (such as complication rates or functional outcomes) comparing the advantages of RAS versus CLS for hernia repair. One study noted that RAS for abdominal wall hernia repair led to lower upper trapezius muscle activity compared to CLS (Cooper et al., 2025).

Urology

Radical Prostatectomy

Robotic-assisted surgery (RAS) has become crucial in urology, significantly benefiting procedures such as radical prostatectomy (Patel et al., 2025). Robotic prostatectomy is considered the standard of care in the United States as of 2008 (Köckerling, 2014).

1. Functional Outcomes (Continence and Sexual Function):

- The provided systematic reviews and meta-analyses address the comparison of RAS and CLS in terms of functional outcomes, such as urinary continence recovery (Park et al., 2025).
- In a summary of pooled evidence across major surgical categories, RAS showed comparable results to CLS for the overall postoperative complication rate in prostatectomy (Chabot et al., 2024). However, one meta-analysis specifically analyzing radical prostatectomy observed a significant difference in favor of RAS in reducing the postoperative complication rate (Chabot et al., 2024).
- RAS was associated with reduced blood loss compared to CLS in radical prostatectomy (Chabot et al., 2024).

2. Conversion and Hospital Stay: In radical prostatectomy, the rate of conversion to open surgery and the intraoperative complication rate showed comparable results between RAS and CLS (Chabot et al., 2024). RAS significantly reduced the length of hospital stay (Chabot et al., 2024).

Gynecology

Hysterectomy (Endometrial and Cervical Cancer)

The adoption of RAS has expanded into gynecology, with robot-assisted hysterectomy accounting for 43% of all hysterectomies in 2021 (Park et al., 2023).

1. Oncological Procedures: Hysterectomy procedures focusing on cancer were included in reviews, specifically addressing endometrial cancer (two studies) and cervical cancer (one study) (Park et al., 2025).

2. Clinical Outcomes (RAS vs. CLS):

- Postoperative Complications and Blood Loss: While the overall postoperative complication rate for hysterectomy was generally comparable between RAS and CLS (Chabot et al., 2024; Paul-Dehlinger et al., 2024), specific meta-analyses on radical hysterectomy indicated a reduction in complications in the robotic group (Chabot et al., 2024). Furthermore, multiple studies reported that RAS achieved less blood loss than CLS for hysterectomy (Chabot et al., 2024).
- Hospital Stay: RAS significantly reduced the length of hospital stay for hysterectomy compared to CLS (Chabot et al., 2024). RAS was ranked as the preferred approach for the shortest hospital stay among surgical approaches for radical hysterectomy (Chabot et al., 2024).
- Benign Pathology (Cost-Effectiveness): A retrospective study on hysterectomy for benign pathologies found that while the RAS group had a longer operative time (153 minutes vs. 120 minutes for CLS), the difference in major complications (Clavien-Dindo grade ≥ 3) and length of hospitalization (2 days vs. 3 days) was not statistically significant (Paul-Dehlinger et al., 2024). This study concluded that, in terms of cost-effectiveness, the robot did not appear to be better than laparoscopy (Paul-Dehlinger et al., 2024).

Economic And Social Implications

Cost-Effectiveness: Direct Costs Versus Indirect Benefits

The primary challenge governing the widespread adoption of Robot-Assisted Surgery (RAS) is its significant economic burden compared to Conventional Laparoscopic Surgery (CLS) (Chabot et al., 2024; Hong et al., 2025; Paul-Dehlinger et al., 2024; Rehman et al., 2025). The high total cost associated with RAS is derived primarily from direct costs associated with the technology itself (Ielpo et al., 2022; Paul-Dehlinger et al., 2024).

Direct Cost Components

- Acquisition and Maintenance: High investment costs, such as the unit price of the Da Vinci XI Dual Console surgical robot (€2,760,000), along with recurring annual maintenance fees (e.g., €228,000), contribute substantially to the total expenditure (Paul-Dehlinger et al., 2024).
- Consumables: The expense of specialized, often single-use, limited-use instruments (e.g., a Vessel Sealer Extend costing €750) further drives up the procedural cost (Paul-Dehlinger et al., 2024).

For example, in a retrospective study on total hysterectomy for benign pathologies, the total cost per patient at one month for Robot-Assisted Hysterectomy (RAH) was estimated at €6,615 compared to €3,859 for Laparoscopic Hysterectomy (LH) (Paul-Dehlinger et al., 2024). This difference of €2,756 (or approximately 3,000–5,000 USD, depending on the exchange rate) means the cost per patient for RAH was approximately 1.7 times higher than for LH (Paul-Dehlinger et al., 2024). Procedure costs specifically were 3.4 times higher for RAH (€4,703) compared to LH (€1,389), with investment, maintenance, and consumables representing 73% of RAH's procedure costs (Paul-Dehlinger et al., 2024).

Indirect Costs and Outcomes

RAS may generate savings through indirect cost reductions, predominantly by reducing the patient's length of hospital stay (Chabot et al., 2024; Rehman et al., 2025; Zou et al., 2025).

- Shorter Hospitalization: RAS significantly shortens the length of hospital stay compared to CLS across nearly all surgical categories. This is a key factor that can mitigate the high direct costs (Chabot et al., 2024; Paul-Dehlinger et al., 2024; Rehman et al., 2025; Waters et al., 2020). For instance, in the hysterectomy study, the average length of initial stay was 2 days for RAH versus 3 days for LH (Paul-Dehlinger et al., 2024).
- Societal Costs (Return to Work): The perspective of analyzing cost is critical, as most studies, including retrospective analyses of hysterectomy, focus solely on direct hospital costs and exclude societal costs (Paul-Dehlinger et al., 2024). Societal aspects, such as the patient's time to return to normal activity, lost wages, and impact on productivity, are generally not included in current cost-effectiveness models. This limits a complete understanding of RAS's economic value (Paul-Dehlinger et al., 2024; Ielpo et al., 2022). Previous reviews suggest that adopting a societal perspective and a longer time horizon tends to produce more favorable cost-effectiveness conclusions for RAS (Hong et al., 2025).

Cost-Effectiveness Results

Despite benefits like shorter hospital stays, studies often conclude that the higher costs associated with RAS are difficult to justify based purely on measurable clinical advantages (Chabot et al., 2024; Rehman et al., 2025; Paul-Dehlinger et al., 2024).

- In the hysterectomy study, the Incremental Cost-Effectiveness Ratio (ICER) was €377,534 per additional patient without a major postoperative complication (Clavien-Dindo grade ≥3) avoided. This led to the conclusion that the robot did not appear to be better than laparoscopy in terms of cost-effectiveness (Paul-Dehlinger et al., 2024).
- The mean difference in total hospitalization cost between RAS and laparoscopic surgery in South Korea was pooled at $3,279 higher for RAS (95% CI: $2,414 to $4,145; I^2: 89%). This demonstrates the consistent additional cost of robotic procedures (Hong et al., 2025).

Disparities in Access and Social Implications

The high costs of robotic systems lead to significant inequalities in access to this technology, particularly when comparing regions or different patient income groups (Hong et al., 2025; Iftikhar et al., 2024; Rivero-Moreno et al., 2024).

Financial Barriers: The high development and implementation costs, including initial purchase and maintenance, restrict the accessibility of AI-driven robotic surgical systems. This is particularly true for smaller hospitals and healthcare institutions in resource-constrained settings (Iftikhar et al., 2024; Rivero-Moreno et al., 2024). RAS systems are often affordable only for wealthy surgical centers with sufficient patient volume (Chabot et al., 2024).

Patient Financial Burden (South Korea Example): In South Korea, where RAS is generally not covered by the national health insurance, the financial burden on the patient is substantial (Hong et al., 2025). The pooled analysis showed that RAS incurred $5,701 higher patient out-of-pocket (OOP) costs compared with laparoscopic surgery (95% CI: $4,613 to $6,790) (Hong et al., 2025). This means that access to innovative surgical technology is largely determined by the patient's ability to pay (Hong et al., 2025).

Socio-Economic Disparities: Studies in Korea have demonstrated that individuals with lower income or residing in non-metropolitan regions were more likely to receive open or laparoscopic surgery rather than RAS. This increases disparities in health outcomes (Hong et al., 2025).

Mitigation Strategy

The sources highlight the importance of high-quality economic evaluations that include societal benefits and long-term outcomes to inform public reimbursement decisions. These are crucial steps needed to reduce the current disparities in access (Hong et al., 2025; Ielpo et al., 2022).

Ergonomics and Surgeon Well-Being

The ergonomic comparison between Conventional Laparoscopic Surgery (CLS) and Robot-Assisted Surgery (RAS) is a critical area of occupational health research. It focuses on surgeon longevity and the mitigation of work-related musculoskeletal disorders (MSDs) (Cooper et al., 2025; Gabrielson et al., 2021; Paul-Dehlinger et al., 2024). Ergonomics is defined as understanding the interaction between humans and system elements to optimize the working environment and reduce unnecessary burdens on the human body (Cooper et al., 2025).

High Strain and Unnatural Posture in Conventional Laparoscopy

Conventional laparoscopic surgery poses significant musculoskeletal risks to surgeons due to inherent technical and positional requirements (Cooper et al., 2025; Pérez-Salazar et al., 2024).

Physical Strain and Muscle Activation

CLS requires surgeons to work in a fixed posture and restricted area for prolonged periods, often exceeding the mean operative time of two hours. This is highly prone to inducing work-related musculoskeletal injuries (Cooper et al., 2025). Surgeons performing CLS frequently adopt awkward and strained postures, including prolonged abduction of the dominant arm, trunk twisting, and asymmetrical weight bearing, particularly when controlling foot pedals (Cooper et al., 2025; Dalsgaard et al., 2020).

Objective measurement tools, such as surface electromyography (sEMG), have identified that CLS involves high muscular straining. This specifically demonstrates high muscle activation in the deltoid, triceps, biceps, and wrist muscles (Cooper et al., 2025; Armijo et al., 2019; Zihni et al., 2014). For instance, in one comparative study, bilateral biceps, triceps, and deltoids were found to be significantly activated in surgeons performing CLS (Zihni et al., 2014).

Ergonomic Risk

Evaluations using standardized tools like REBA (Rapid Entire Body Assessment) indicated that surgeons performing CLS were often graded at a "very high ergonomic risk" score. This is largely due to the posture required, necessitating immediate change or implementation of corrective measures (Anand et al., 2022; Dalager et al., 2020). Subjective surveys confirm that CLS surgeons often experience discomfort, particularly in the shoulders and back (AlSabah et al., 2019).

Robotic Surgery: Seated Position and Ergonomic Advantages

RAS was designed to overcome the ergonomic shortcomings of CLS, primarily by providing a transparent teleoperation system with technical aids that enhance precision and reduce physical requirements (Paul-Dehlinger et al., 2024; Rivero-Moreno et al., 2024).

Seated Posture and Arm Support

A major ergonomic advantage of RAS is the provision of an improved ergonomic posture (Pérez-Salazar et al., 2024; Cooper et al., 2025). The surgeon typically operates from a console in a comfortable, seated position (Pérez-Salazar et al., 2024; Paul-Dehlinger et al., 2024). This console position includes synchronized armrests, which, if used correctly, ensure the surgeon's elbows are positioned close to 90 degrees, offering full hand and forearm support (Dalsgaard et al., 2020; Pérez-Salazar et al., 2024).

Objective motion analysis using RULA (Rapid Upper Limb Assessment) often shows a significantly lower ergonomic risk level for surgeons utilizing the robotic technique compared to the laparoscopic technique (Dalager et al., 2020; Pérez-Salazar et al., 2024).

Reduced Physical and Muscular Fatigue

RAS significantly reduces the physical demand and muscular strain associated with surgery (Cooper et al., 2025; Pérez-Salazar et al., 2024; Dalsgaard et al., 2020).

- Muscle Activity: Multiple sEMG studies demonstrate that RAS generally results in lower muscle activation across various muscle groups compared to CLS (Cooper et al., 2025; Dalsgaard et al., 2020). Specifically, RAS was shown to utilize neck and shoulder muscles less heavily than CLS, with differences ranging from 33% to 61% in static measurement levels (Dalsgaard et al., 2020; Cooper et al., 2025). The ability of the robotic platform to perform tasks with tremor filtration and motion scaling enhances precision without requiring strenuous physical effort (Paul-Dehlinger et al., 2024).
- Physical Fatigue: Subjective assessments, including the NASA-TLX (National Aeronautics and Space Administration Task Load Index) and the Borg CR10 physical exertion scale, consistently confirmed that RAS was perceived as less physically demanding and less fatiguing than CLS for the majority of surgeons (Cooper et al., 2025; Pérez-Salazar et al., 2024). Furthermore, the mean heart rate of surgeons has been observed to be significantly lower during RAS procedures, suggesting reduced physiological stress (Chabot et al., 2024).
- Localized Fatigue: Analysis of muscle fatigue (using methods like JASA) showed that RAS was associated with higher muscle fatigue recovery and lower overall muscle fatigue compared to CLS during simulation tasks, indicating less strain (Pérez-Salazar et al., 2024).

Mental Workload Consideration

While RAS reduces physical strain, studies comparing perceived workload note a trade-off. Some surgeons reported that RAS was more mentally demanding or associated with higher temporal demand or frustration compared to CLS, particularly for novice or less experienced surgeons (Kramer et al., 2023; Mendes et al., 2020; Pérez-Salazar et al., 2024). However, for surgeons experienced in both modalities, RAS often provided a better environment across physical and mental requirements, performance, and overall workload (Mendes et al., 2020).

New Ergonomic Risks

RAS is not entirely risk-free ergonomically. Some objective studies using sEMG indicated that while upper body strain is relieved, there may be increased activation in lower back, trapezius, and finger muscles (Cooper et al., 2025; Dalsgaard et al., 2020). Surgeons reported feeling more fatigue in the lower back in RAS, possibly due to leaning forward toward the console viewer or not utilizing ergonomic support like armrests consistently during long procedures (Dalsgaard et al., 2020; Kramer et al., 2023).

Learning Curve and Education

Comparison of Technique Mastery Time

The concept of the learning curve—the necessary training duration required for a surgeon to achieve competence—is fundamental in evaluating new surgical techniques (Leijte et al., 2019). Robot-Assisted Surgery (RAS) is generally expected to have a shorter learning curve compared to Conventional Laparoscopic Surgery (CLS) (Leijte et al., 2019). This expectation is rooted in the intrinsic technical advantages provided by the robotic platform, such as three-dimensional vision and intuitive wristed movements (Leijte et al., 2019).

Faster Task Completion

Studies comparing novice participants on simulators consistently demonstrate that robotic assistance dramatically reduces the time required to complete complex technical tasks (Leijte et al., 2019; Paul-Dehlinger et al., 2024).

- Suturing Time: In simulated intracorporeal suturing tasks, the median time required to complete the first knot was 611 seconds for the laparoscopic group versus 251 seconds for the robot-assisted group ($p<0.001$) (Leijte et al., 2019).
- Learning Curve Shape: The learning curve for robot-assisted suturing is often described as horizontal, meaning the outcomes are already good from the initial repetitions, resulting in less steep progress (Leijte et al., 2019; Paul-Dehlinger et al., 2024). Conversely, the laparoscopic learning curve is steeper, indicating a much slower performance at the start but showing a rapid time reduction as the surgeon gains proficiency (Leijte et al., 2019).
- Competence Level: The cumulative sum analysis (CUSUM) reveals that robotic assistance results in a significant time advantage across all phases of the learning curve (Leijte et al., 2019). Some studies estimate that surgeons need to perform approximately 50 robotic surgery procedures to gain competence in the technique (Paul-Dehlinger et al., 2024).

Safety and Prior Experience

The technical aids in RAS, such as tremor filtration and articulated instruments with seven degrees of freedom, enhance gesture security, which translates into quantifiable safety improvements (Paul-Dehlinger et al., 2024). For example, the safety parameter "instrument out of view"—an indicator of potential collateral damage—quickly reached an optimal outcome in the robot-assisted group (0% off-screen after repetition four), while the laparoscopic group showed a trend of increasing off-screen time (Leijte et al., 2019).

Interestingly, while the robotic learning curve is generally faster, prior experience can still be beneficial. A sub-analysis demonstrated that participants with previous laparoscopic experience achieved a significantly faster initial suturing time in the robot-assisted group compared to true novices (182 s versus 300 s, p=0.039) (Leijte et al., 2019).

The Role of Virtual Simulators in Medical Education

Simulators play a vital role in medical education, providing a non-clinical environment for surgeons to acquire and refine technical proficiency in new surgical skills (Leijte et al., 2019).

- Simulation as a Foundational Tool: Structured training programs, which often include simulation-based practice, are essential for the safe and effective adoption of robotic surgery (Rehman et al., 2025; Paul-Dehlinger et al., 2024). These programs are necessary to ensure consistent surgical quality and minimize learning curve-related complications (Rehman et al., 2025).
- Virtual and Augmented Reality Systems: Specialized simulation platforms, such as the RobotiX Virtual Reality (VR) simulator and the eoSim Augmented Reality simulator, are utilized to compare learning curves using objective assessment parameters, including time, movements, and safety (Leijte et al., 2019). The use of the RobotiX VR system allows surgeons to train outside of the operating room without needing access to an expensive Da Vinci system (Leijte et al., 2019).
- AI Integration in Training: The future of surgical training is poised to leverage Artificial Intelligence (AI) (Iftikhar et al., 2024). AI-powered simulations and Virtual Reality (VR) integrated with AI can provide surgeons with highly realistic training environments to practice complex procedures and refine their skills, leading to potentially improved surgical outcomes (Iftikhar et al., 2024).
- Measuring Competency: The objective of contemporary training is often measured using a competency- or outcome-anchored appraisal that relies on multidimensional assessment parameters beyond mere task time, incorporating safety parameters to provide comprehensive feedback (Leijte et al., 2019).

Even when transitioning to robotic surgery, which places surgeons at the early stage of their robotic learning curve despite extensive laparoscopic experience, structured training is key. This support enables teams to achieve comparable or even superior clinical outcomes to those of conventional laparoscopy (Rehman et al., 2025).

Future Directions: AI and Haptics

The future of robotic surgery is being shaped by the integration of advanced computational capabilities, primarily through Artificial Intelligence (AI), and the development of sensory feedback mechanisms to address the technical deficiencies of current platforms (Iftikhar et al., 2024; Paul-Dehlinger et al., 2024).

Introduction of Haptic Feedback: The Missing Link

A recognized limitation of contemporary surgical robots, such as the Da Vinci system, is the absence of haptic feedback—the sense of touch—which has traditionally been a barrier to the wider adoption of the technology (Iftikhar et al., 2024; Rivero-Moreno et al., 2024). Surgeons must currently rely entirely on visual cues for critical actions like evaluating tissue consistency, applying pressure during dissection, and knot-tying (Bellos et al., 2024).

Consequences of Haptic Absence

Relying solely on visual feedback can lead to surgical errors, such as applying excessive force on delicate tissues (potentially damaging neurovascular bundles, as seen in radical prostatectomy) or applying insufficient force, leading to poor suture retention (Bellos et al., 2024).

Technological Solutions and Future Prospects

Future generations of robotic platforms are focused on rectifying this deficiency through sensory augmentation (Patel et al., 2025).

- Enhanced Force Sensitivity: Upcoming robotic systems are expected to incorporate improved haptic feedback and enhanced force sensitivity to elevate surgical accuracy (Patel et al., 2025).

- AI-Enhanced Feedback: Current AI-driven systems are already exploring functionalities such as haptic feedback to enrich the surgeon's tactile experience, providing critical data on tissue resistance and texture through the robotic interface (Iftikhar et al., 2024).
- Warning Systems: Researchers have successfully developed systems that integrate biaxial shear detection and haptic feedback to serve as an advanced warning mechanism, alerting the surgeon before suture tension reaches its breaking point, thereby significantly reducing knot slippage and suture breakage (Bellos et al., 2024).

Autonomous Surgery and AI Support (Real-Time Navigation)

The steady assimilation of Artificial Intelligence (AI) and Machine Learning (ML) into surgical robotics is gradually increasing the autonomy of these systems, promising enhanced precision, smarter maneuvers, and real-time tissue damage avoidance (Iftikhar et al., 2024; Rivero-Moreno et al., 2024).

Degrees of Autonomy

The transition from the current benchmark (Level 0, where the surgeon maintains exclusive control, exemplified by the Da Vinci system) to fully autonomous systems is categorized by progressive levels of AI integration (Attanasio et al., 2021; Rivero-Moreno et al., 2024; Iftikhar et al., 2024):

- Level 2 (Task Autonomy): The robot is competent to execute specific surgical activities, such as ablation, tissue retraction, or suturing (Rivero-Moreno et al., 2024; Iftikhar et al., 2024). Control transfers from the human to the machine for the duration of that specific task (Rivero-Moreno et al., 2024).
- Level 3 (Conditional Autonomy): Robots gain perceptual abilities, allowing them to comprehend the surgical environment, plan and execute certain tasks, and modify the plan as the procedure progresses (Rivero-Moreno et al., 2024; Iftikhar et al., 2024).
- Level 4 (High Autonomy): The robot interprets both preoperative and intraoperative data to devise and execute an interventional plan, making real-time adjustments under the supervision of a surgeon (Rivero-Moreno et al., 2024; Iftikhar et al., 2024). Potential applications include the intelligent removal of cancerous tissue based on real-time feedback (Rivero-Moreno et al., 2024).

Real-Time Guidance and Autonomous Procedures

AI is crucial for providing real-time guidance and making autonomous surgical procedures feasible (Patel et al., 2025).

1. Autonomous Soft Tissue Tasks: The Smart Tissue Autonomous Robot (STAR) is a notable example, having performed the first autonomous bowel anastomosis (a Level 3 task) (Rivero-Moreno et al., 2024; Iftikhar et al., 2024). STAR has demonstrated performance that matched or even outperformed human surgeons in terms of efficacy and consistency in ex vivo or in vivo settings (Rivero-Moreno et al., 2024; Iftikhar et al., 2024). However, full autonomous suturing for soft tissues is not yet commercially available (Iftikhar et al., 2024; Rivero-Moreno et al., 2024).
2. Real-Time Navigation: AI algorithms are designed to analyze surgical field images in real-time to identify critical structures, blood vessels, and tumors, thereby assisting surgeons in decision-making and optimizing instrument trajectories (Iftikhar et al., 2024).
3. Adaptive Decision-Making: AI could process complex pre- and intraoperative data, recommending surgical adjustments based on patient-specific anatomy or unexpected findings during the procedure (Patel et al., 2025; Iftikhar et al., 2024). This adaptive intelligence is expected to significantly improve patient safety (Patel et al., 2025).
4. Specialized Autonomous Systems: The CyberKnife robot exemplifies Level 3 autonomy in clinical use by performing radiosurgery. It uses stereotactic principles to locate tumors and continuously acquires real-time orthogonal images of the patient, automatically adjusting for minor changes in patient posture during treatment to maintain precision (Rivero-Moreno et al., 2024).

Ultimately, AI is not intended to fully replace human surgeons but rather to function as a collaborative partner in the surgical workflow, managing repetitive and complex tasks to increase surgical consistency across patients (Iftikhar et al., 2024; Rivero-Moreno et al., 2024).

Discussion

Synthesis: Ergonomics, Clinical Benefit in Complex Cases, and Economic Challenge

The synthesis of evidence consistently positions Robot-Assisted Surgery (RAS) as a technologically superior method to Conventional Laparoscopic Surgery (CLS), particularly when considering ergonomics and the management of technically challenging procedures (Chabot et al., 2024; Paul-Dehlinger et al., 2024; Rivero-Moreno et al., 2024).

Ergonomic and Technical Superiority

The ergonomic advantages of RAS are pronounced and clinically meaningful for surgeons (Cooper et al., 2025; Paul-Dehlinger et al., 2024). Surgeons benefit from operating in a comfortable, seated position at the console with arm support (Cooper et al., 2025; Pérez-Salazar et al., 2024). Objective studies, often using sEMG, demonstrate that RAS significantly reduces physical demand and muscular strain in the neck and shoulders compared to the strained postures required during CLS (Cooper et al., 2025; Pérez-Salazar et al., 2024). This translates into reduced physiological stress, evidenced by a significantly lower mean heart rate for surgeons during RAS procedures (Chabot et al., 2024). Technically, the superior 3D visualization, articulated instruments (seven degrees of freedom), and tremor filtration of robotic platforms extend the indication of minimally invasive surgery to complex cases (Paul-Dehlinger et al., 2024; Köckerling, 2014; Rivero-Moreno et al., 2024). In clinical practice, this technical superiority leads to concrete benefits, most notably a lower rate of conversion to open surgery (Rehman et al., 2025; Zou et al., 2025).

Clinical Outcomes and Cost Contradiction

When evaluating standard clinical outcomes such as postoperative complication rates, readmission rates, and blood loss, RAS generally achieves results comparable to CLS (Chabot et al., 2024; Rehman et al., 2025). The primary clinical benefit consistently observed is a significant reduction in the length of hospital stay (LOS) across nearly all surgical categories analyzed (Chabot et al., 2024; Paul-Dehlinger et al., 2024; Rehman et al., 2025).

However, this comparable clinical performance (coupled with LOS reduction) often fails to justify the substantial economic challenge posed by the technology (Chabot et al., 2024; Paul-Dehlinger et al., 2024; Rehman et al., 2025). A study comparing hysterectomy approaches, for example, estimated the total cost per patient for Robot-Assisted Hysterectomy (RAH) at €6,615, compared to €3,859 for Laparoscopic Hysterectomy (LH) (Paul-Dehlinger et al., 2024). The high incremental cost-effectiveness ratio (ICER) suggests that RAH is an expensive strategy relative to the complication benefit achieved (Paul-Dehlinger et al., 2024).

Challenges: Cost Structure, Monopolistic Elements, and Training

Financial Barriers and Cost Drivers

The economic challenge is rooted in the high cost structure of the robotic ecosystem. The total cost disparity is primarily driven by direct costs associated with the technology (Hong et al., 2025; Ielpo et al., 2022). These include the immense initial investment cost (e.g., the Da Vinci XI Dual Console unit price of €2,760,000), annual maintenance fees (e.g., €228,000), and the expense of specialized limited-use and single-use consumables (Paul-Dehlinger et al., 2024). For instance, investment, maintenance, and consumables represented 73% of the RAH procedure costs in one analysis (Paul-Dehlinger et al., 2024).

The necessity of purchasing proprietary instruments and paying high service fees contributes to the high procedure cost (Paul-Dehlinger et al., 2024; Rehman et al., 2025). A hypothetical discount on the surgical robot (up to 46%) was shown to reduce the mean cost, indicating that the initial pricing structure is a crucial factor (Paul-Dehlinger et al., 2024). This concentration of high costs limits the availability of RAS, often making it only affordable for wealthy surgical centers with high patient volume (Chabot et al., 2024; Rivero-Moreno et al., 2024). This directly contributes to socio-economic disparities, where access to RAS may be determined by the patient's ability to pay, especially in systems without national coverage (Hong et al., 2025).

Training and Standardization of Personnel

Achieving competence in robotic surgery requires structured training and surgical experience, typically estimated at performing around 50 robotic procedures to gain proficiency (Paul-Dehlinger et al., 2024). While the learning curve for complex technical skills, such as suturing, is often shorter for novices in RAS compared to CLS, structured training programs are essential to ensure consistent surgical quality and mitigate learning curve-related complications (Leijte et al., 2019; Paul-Dehlinger et al., 2024; Rehman et al., 2025). Future development of formal credentialing processes and proficiency-based training modules will be crucial to ensure safe and effective adoption (Rehman et al., 2025).

Conclusions

Summary of Technological Advantages

Robot-Assisted Surgery (RAS) has brought significant technological advances to the operating room (Köckerling, 2014). These advantages include immersive 3D high-definition visualization, enhanced precision through tremor filtration and motion scaling, and seven degrees of freedom offered by articulated instruments (Paul-Dehlinger et al., 2024; Rivero-Moreno et al., 2024). Clinically, RAS is highly valuable for complex procedures in confined anatomical spaces, demonstrated by consistently lower conversion rates to open surgery and shorter hospital stays compared to Conventional Laparoscopic Surgery (CLS) (Chabot et al., 2024; Rehman et al., 2025). RAS systems also offer superior ergonomics, supporting long-term surgeon well-being by reducing physical strain (Cooper et al., 2025; Pérez-Salazar et al., 2024). The future integration of Artificial Intelligence (AI) and enhanced haptic feedback is expected to further improve surgical consistency and safety (Iftikhar et al., 2024; Patel et al., 2025; Rivero-Moreno et al., 2024).

Recommendation: The Need for High-Quality Research

Despite these advantages, particularly reduced hospital stays, the significantly higher costs of RAS—often ranging from $3,000 to $5,000 more per procedure—are challenging to justify based solely on short-term clinical benefits (Hong et al., 2025; Paul-Dehlinger et al., 2024; Rehman et al., 2025). To fully evaluate RAS's value, a shift in research priorities is required (Hong et al., 2025; Rehman et al., 2025).

Future studies must include:

Long-Term Outcomes: Focusing on oncological results, functional recovery, and patient-reported experiences (Rehman et al., 2025; Zou et al., 2025).

Comprehensive Cost-Effectiveness: Economic evaluations should move beyond direct hospital costs to adopt a societal perspective including factors such as faster return to normal activity, reduced lost wages, and increased productivity (Hong et al., 2025; Paul-Dehlinger et al., 2024; Ielpo et al., 2022). Such evidence will be essential to inform public reimbursement decisions and ensure equitable access to these technologies.

Disclosure

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