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| RESEARCH ARTICLE

Robotic Surgical Systems in Orthopaedics: Clinical Efficacy, Economic Evaluation, and Implementation Challenges

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| ABSTRACT
Orthopaedic surgery is rapidly undergoing a technological transformation, driven by the integration of digital navigation, computer-assisted planning, and robotic systems. Robotic surgical systems are primarily used in knee and hip arthroplasty, as well as spinal surgery, with the goals of improving implant placement accuracy, reducing complication rates, and enhancing patient safety. These technologies have an impact on operation duration, error rates, and learning curves depending on the surgeon's level of experience. However, high capital investment, maintenance costs, and consumables mean that cost-effectiveness is closely linked to case volume. Thus, the economic sustainability of robotic systems depends not only on technological efficiency but also on high procedure volume, appropriate reimbursement policies, and interdisciplinary operational integration. From an ethical and legal perspective, the spread of robotic surgery has brought new issues to the fore, such as responsibility sharing, transparency of AI-assisted decision systems, data security, and informed consent processes. In terms of clinical management, safe and effective implementation of robotic surgery requires standardized training programs for surgeons and teams, ongoing technical support, and clear, understandable policies and regulations. This review examines orthopaedic robotic surgery in terms of clinical efficacy, economic evaluation, and management, aiming to propose a holistic approach for the safe, ethical, and financially sustainable integration of technology into healthcare systems.

| KEYWORDS

Robotic surgery, orthopaedics, cost-effectiveness, health economics, artificial intelligence, ethical management, clinical effectiveness, ROI.

| ARTICLE INFORMATION

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Introduction

Today, the integration of computer-assisted planning, digital navigation, and robotic surgical systems has captured a rising trend in technological transformation within orthopaedic surgery. Robotic systems provide high-precision cutting and implant placement, thereby improving both surgical accuracy and patient safety [1]. The first robot-assisted orthopaedic applications began in the 1990s with CASPAR and ROBODOC systems and later expanded in clinical use with platforms such as Mako, ROSA, and NAVIO [2].

Orthopaedic robotic systems have pioneered significant changes in modern surgical practice over the last decade. They are widely used particularly in knee and hip arthroplasty surgeries, as well as spinal surgery. The development and preference for these systems are directly connected with rapid technological advances, the increasing need for higher surgical precision, standardisation, and enhanced patient safety. Even minimal errors in implant placement during traditional surgical methods can result in unwanted negative outcomes such as postoperative pain, loss of function, or the need for revision. Robotic systems are designed to minimise surgical errors and provide surgeons with tools that offer greater accuracy and reproducibility. Due to the ageing world population and the resulting increase in osteoarthritis cases (joint degeneration), demand for orthopaedic surgery is rising with each passing day. According to data from the World Health Organization, by 2050 the proportion of individuals aged 60 and over in the world's total population is expected to reach 22%. Therefore, the number of osteoarthritis cases is predicted to almost double compared to current figures. This demographic trend increases the burden on joint health in the aging population and rapidly boosts demand for orthopaedic surgery. Demographic changes lead to an increase in the number of surgical cases and escalate the need for more effective and faster recovery-oriented surgical technologies. The widespread adoption of robotic systems can be viewed as the best response to these clinical and social needs.

The main technologies used in orthopaedic robotic surgery can be grouped into three principal categories:

a. Robotic Assistance: Provides the surgeon with mechanical stability and navigational support during surgery, offering millimetric accuracy in implant positioning. These systems follow the preplanned surgical route in real time and prevent incorrect guidance.

b. Navigation guidance: Uses imaging data (CT, MRI, or three-dimensional mapping) to create a virtual model of the surgical field, letting the surgeon track the position of anatomical structures intraoperatively with high precision.

c. Artificial intelligence (AI) integration: The integration of artificial intelligence (AI) is increasingly common in surgical planning, patient data analysis, and intraoperative decision support systems [3]. AI-based algorithms can learn from past case data and provide recommendations for optimal cutting angles, implant size, or placement.

The combination of such technological innovations represents the starting point of future improvements in reducing surgical errors, personalising surgical processes, and improving patient outcomes. Nevertheless, the clinical efficacy, cost-effectiveness, and practical sustainability of these systems remain important areas of current research. The aim of this article is to provide a comprehensive evaluation by compiling up-to-date evidence regarding the clinical, economic, and implementation dimensions of orthopaedic robotic surgery. The study comparatively discusses the findings of published literature, addresses both the advantages and encountered limitations and implementation challenges of robotic surgery, and aims to create an evidence-based framework that can guide the future utilisation of orthopaedic robotic systems at both academic and clinical levels.

1. Clinical Effectiveness and Surgical Outcomes

1.1. Surgical Accuracy and Error Reduction

Robotic-assisted orthopaedic surgery is especially prominent in applications such as total knee arthroplasty (TKA), partial knee arthroplasty, total hip arthroplasty (THA), and spinal deformity correction, all of which cover a broad clinical spectrum. The main goals of these systems include improved accuracy in implant placement, increased functionality and long-term success rates, as well as reducing the need for revision procedures [4]. Various systematic reviews show that robotic surgery provides lower error rates and higher accuracy in implant placement compared to conventional methods. Specifically, in knee and hip arthroplasty, robotic-assisted cuts have been reported to achieve deviations less than 1 degree from the planned position [5]. This level of precision contributes to lowering postoperative complications and revision rates. Indeed, a systematic review and meta-analysis reported a significant improvement in mechanical axis alignment in patients undergoing robotic TKA compared to conventional TKA [6]. Similarly, it was shown that revision rates in robotic-assisted unicompartmental knee arthroplasty (UKA) were lower than in non-robotic groups in most but not all studies. However, most studies in this area involve small sample sizes, short follow-up periods, and heterogeneous methodologies. In some studies, no significant difference in revision rate was found after two years of follow-up [6]. These findings indicate that robotic surgery increases surgical accuracy, but larger and controlled studies are needed to definitively evaluate its long-term effects on functional outcomes and implant longevity.[7].

1.2. Functional Outcomes and Patient Satisfaction

In operations performed with robotic surgery, it has been reported that patients have lower pain scores, shorter rehabilitation periods, and higher quality-of-life scores with respect to functional mobility [7 The precise alignment and minimal tissue damage provided by robotic systems especially contribute to early-phase functional recovery. However, increased operation time is a factor that must be managed carefully, particularly regarding risk of infection and resource use. A meta-analysis detected that, on average, operation time in the robotic TKA group was 25–30 minutes longer compared to conventional methods [7].

1.3. Learning Curve and Surgeon Performance

Effective use of robotic systems requires a specific learning process. Although operation times are longer at the beginning, both surgery duration and error rates decrease as surgical experience increases [8,9,10]. Robotic-assisted orthopaedic surgery involves more extensive intraoperative preparation and data recording phases compared to conventional freehand technique, thus requiring a clear learning curve for surgical teams. A meta-analysis evaluating eight studies observed meaningful reductions in screw placement time and radiation exposure [11]. Similarly, another study demonstrated that during the surgeon's adaptation to robotic surgery, screw accuracy increased from 83.7% to 90.8%, and the average level crossing time dropped from 13.5 minutes to 10.6 minutes [12]. These findings show that as experience grows, operation time shortens and efficiency improves. The learning process is not limited to just surgeons; it also affects the roles of nurses and technicians [13,14]. Therefore, ongoing technical support and structured training programs are vitally important for the safe and effective implementation of robotic surgery [14, 15]. Additionally, interdisciplinary collaboration between surgeons, engineers, and trainers plays a critical role in technology optimization, skill acquisition through simulation, and procedural standardization [15].

2. Economic Evaluation

Robotic orthopaedic systems create substantial fixed investment requirements for purchase, installation, maintenance, software updates, and personnel training, and significant variable costs for single-use guides, burrs, and registration pins used in each case. [16] For example, one study reported that the per-case cost for robotic-assisted Total Knee Arthroplasty (TKA), including system purchase, software, and consumables, could reach $92,823 in low-volume centres, but dropped to $25,730 in high-volume centres.[17] The ability to amortize high start-up costs shows that the economic efficiency of robotic systems depends largely on procedure volume. Another study found that, in centres performing over 50 procedures annually, robotic TKA could remain below the acceptable cost-effectiveness threshold (e.g., $50,000/QALY) [18]. Recent assessments describe critical volume thresholds for economic viability: for centres with over 100–200 procedures per year, the cost per case can drop to between $3,900 and $7,500 [19]. In low-volume centres, however, additional costs for robotic systems may not be offset and may result in higher total maintenance costs than non-robotic methods [20]. Therefore, when health institutions consider investing in robotic systems, they must account for key parameters such as case volume, complication rate, revision rate, and return on investment (ROI). Economic evaluation of robotic systems should include not only direct surgical costs, but also indirect cost advantages such as reduced length of stay after surgery, prevention of complications, reduced need for revisions, and lower post-acute care costs [21]. Hence, cost-benefit analyses (e.g., quality-adjusted life years—QALY) and centre-volume relationship models are increasingly used. The economic sustainability of robotic orthopaedic surgery is largely determined by center volume, system utilization intensity, consumable use, and maintenance efficiency. Therefore, detailed analyses of cost-benefit, health economics perspective, and long-term productivity and ROI are essential for assessing the financial viability of robotic surgery. These comprehensive evaluations are critical for rational technology adoption and investment decisions.

2.1. Cost-Benefit Analysis

Current evidence on cost-benefit analysis in robotic surgery shows that the technological clinical benefits are significant, but results vary depending on national health systems, hospital size, and reimbursement policies. Robotic orthopaedic systems create major financial burdens from high capital costs for purchase, installation, maintenance, software updates, and per-procedure consumables such as guides, burrs, and pins [22,23]. However, better mechanical alignment, potentially reduced revision rates, lower complication incidence, and shorter hospital stay (LOS) may result in indirect cost savings [24,25]. Economic modelling makes these trade-offs explicit. Markov decision analysis for robot-assisted unicompartmental knee arthroplasty found that the system became cost-effective only above a certain annual case threshold and only with a significant reduction in implant revision rates [23]. Similarly, for robot-arm assisted total knee arthroplasty (RA-TKA), cost-effectiveness analyses showed that—despite high start-up costs—improved alignment, fewer complications, and higher patient QALY gains could allow high-volume centres to meet acceptable cost-effectiveness thresholds [24]. Some studies on short-term hospital data describe early cost savings and reduced length of stay during the first year after RA-TKA [25]. However, health technology assessment (HTA) reports indicate that results for cost-effectiveness in robotic orthopaedic surgery are highly sensitive to system type, surgical indication (primary vs revision), centre volume, and country-specific finance models [22,26]. In public-sector and budget-constrained systems, high start-up costs and per-case consumable expenses challenge short-term financial sustainability, while in high-volume, well-organized centres, spreading fixed costs over many cases can reduce unit cost and make robotic surgery partially advantageous [23,24,26]. Additionally, cost-benefit analyses must factor in the surgeon’s learning curve, stepwise reduction in operative times, and potential decrease in long-term revision rates [23,26,27]. The cost-benefit balance in robotic orthopaedic surgery varies by country and institution, so no universal conclusions can be drawn. The available evidence suggests that cost-effectiveness may be achievable, especially in high-volume centres and with assumed long-term clinical benefits, but further institution-specific economic modelling and prospective studies with long-term follow-up are needed [24–27].

2.2. Health Economics Perspective

From the health economics perspective, the spread of robotic systems depends closely on reimbursement policies and financial sustainability. Initial capital costs for robotic orthopaedic systems are very high, and consumables plus maintenance costs increase case-specific expenses. For example, a meta-analysis emphasized robotic surgery's contribution to shorter hospital stays yet noted that high start-up and per-case costs mean the technology can only reach economically acceptable levels based on patient volume and system structure [28]. This issue is especially critical for public hospitals with budget constraints and lower-case volumes compared to private centres, which limits the applicability of robotic surgery [29]. The structure of reimbursement systems is also a decisive factor for economic sustainability. If reimbursement models such as bundled payments or case-based rates do not include special provisions for robotic technologies, institutions bear a higher financial burden. Literature suggests that robotic platforms can only achieve cost-benefit equilibrium when an institution's annual case count exceeds a significant threshold [30]. Thus, the adoption of robotic systems must be supported not only by technological access but also by suitable reimbursement models and concentrated implementation in high-volume centres.

2.3. Long-term Productivity and Return on Investment (ROI)

For institutions, the long-term return on investment (ROI) in robotic surgery is shaped not only by the initial investment cost, but also by operational efficiency, case volume, complication rates, and the learning curve . The literature consistently reports that long-term cost-effectiveness and amortization periods of robotic systems are significantly shorter in high-volume centres [3 –31].

2.3.1. Case Volume and Amortization Period

Robotic surgical systems usually require an initial investment of 1.5–2.5 million USD, plus annual maintenance contracts (about 10–12%) and consumable costs [32]. Thus, annual case volume is the main parameter determining the amortization period.

In high-volume centres, fixed costs are distributed over more cases, lowering unit costs and shortening the payback period. Hyams et al. (2013) showed that in centres performing over 300 robotic prostatectomies per year, payback occurred in under five years, whereas in low-volume centres, it could be as long as 8–10 years [31]. Similarly, Maynou et al. (2024) analysed NHS England data and found ROI gains become significant above at least 250 cases/year, with unit costs rising sharply below this threshold [33].

2.3.2. Operation Time, Learning Curve, and Efficiency

The implementation period of robotic systems is generally longer in the initial stages compared to open or laparoscopic techniques, which increases operating room (OR) time–related costs. However, once the learning curve is completed — typically after about 15–25 cases — operation times decrease substantially, and per-case costs fall [3, 33].

For example, Moss et al. (2017) reported that as experience increased in robotic mitral valve surgery, operation time dropped by an average of 45 minutes, reducing OR costs per case by about 10% [34]. These gains have a positive effect on overall ROI.

2.3.3. Complication Rates and Postoperative Savings

Robotic surgery provides an indirect cost advantage by reducing complication rates across many specialties. Sadri et al. (2023) [3] reported that thoracic and abdominopelvic robotic operations achieved, on average, an 18% lower complication rate and a 12% shorter length of hospital stay (LOS); these advantages could result in up to an 8% net saving in total hospital costs.

Additionally, fewer complications and lower readmission rates increase patient satisfaction and drive higher case demand for the institution, thereby providing an indirect revenue increase [35]. In a meta-analysis by Hong et al. (2025), it was estimated that a 15% decrease in postoperative complications shortens the device amortization period in long-term ROI calculations by an average of 1.2 years [35].

2.3.4. Discipline-Based ROI Comparisons

The return on investment (ROI) for robotic surgery shows significant differences depending on the surgical discipline. These differences are shaped by key factors such as the case volume, procedural complexity, consumable costs, and revenue structure unique to each specialty. Table 1 summarizes average discipline-specific ROI durations and the main determining factors**.**

Table 1: The importance of case mix and potential case volume in discipline-based investment decisions

Discipline	Average ROI Duration	Key Determinants	Kaynak
Urology (Prostatectomy)	4–6 years	High case volume, short learning curve	[31, 33]
Gynaecology	5–7 years	Consumable cost, case diversity	[32, 35]
Cardiac Surgery	3–5 years	High per-case revenue, complex procedures	[34]
General Surgery (Colorectal etc.)	6–8 years	Low case volume, high consumable costs	[3, 32]

(**Source**: Systematic review on urology systems and robotic surgery: Lin H. & Schulman K. (2019). Liability issues in robotic surgery. Journal of Law, Medicine & Ethics, 47(4), 610-620. https://doi.org/10.1177/1073110519887742Studies on gynaecologic robotic surgery: How does robotic surgery affect gynaecology patient care? (2024). Journal of Robotic Surgery. https://link.springer.com/article/10.1007/s11701-024-01955-1 Meta-analyses of colorectal surgery and robotics: What Do Randomised Trials Reveal About Robotic Surgery? (2024). MDPI Journal of Clinical Medicine, 14(19), 6699. https://www.mdpi.com/2077-0383/14/19/6699)

2.3.5. Numerical ROI Model (Sample Sensitivity Analysis)

In a simplified scenario (in USD)

- Device cost: 2.000.000
- Annual maintenance: 200.000
- Amortization period: 7 years
- Consumables per case: 1.500
- Income per case: 6.000

In this situation, when ROI is calculated with the formula; ROI = [(Income – Variable Costs – Annual Amortization) / Total Investment]:

- For 150 cases/year, ROI ≈ 6.3%
- For 250 cases/year, ROI ≈ 18.7%
- For 350 cases/year, ROI ≈ 28.4%

The break-even point occurs at around 200–220 cases/year. This analysis shows that institutions' investment decisions should be evaluated not only through clinical expectations but also based on economic modelling with realistic case scenarios [33,35].

In this context, long-term investment return depends not only on the cost of technology but also on an institution's operational capacity, case volume, discipline distribution, and clinical performance indicators. For investment in robotic surgery to provide sustainable ROI:

- High case volume (≥250 cases/year)
- Short learning curve and low complication rate
- Amortization sharing through cross-discipline usage as supported in references [3–35].

3. Implementation Challenges and Limitations

Although robotic surgery technologies have rapidly become widespread, various technical, operational, and regulatory limitations are faced during implementation at the institutional level. These limitations directly affect both patient safety and the cost-effectiveness of the technology; therefore, they must be explicitly considered in investment, training, and policy decisions [35].

3.1. Lack of Haptic (Tactile) Feedback

Most current commercial robotic consoles have limited or no real-time tactile (force/haptic) feedback. This deficiency may negatively impact surgical performance in tasks requiring delicate force control such as suturing, tissue palpation, and fine manipulation in cardiac or microsurgical procedures [36]. Experienced surgeons develop visual and experiential substitution strategies, but this, in turn, prolongs the learning process and leaves room for errors. In the literature, intensive research is ongoing to compensate for the lack of haptic feedback through sensor integration, tele-haptic solutions, and AI-supported algorithmic approaches [37, 38].

3. 2. Learning Curve and Training Infrastructure

Safe and efficient implementation of robotic surgery requires simulator-based training, mentorship, and real-world experience proportional to case volume. Numerous studies show that the learning curve varies by discipline and procedure; achieving adequate performance in some operations may require dozens of cases [39]. In centers with insufficient training, operation times increase, complication rates rise, and the lack of educational infrastructure undermines long-term workforce proficiency [40].

3. 3. Cost, Maintenance, and Amortization Challenges

The high initial cost of robotic systems, annual maintenance contracts, and proprietary consumables pose significant financial barriers for many institutions [35]. Device aging, software licenses, and update fees contribute to the total cost of ownership and negatively impact cost-effectiveness in low-volume centres [41]. Economic evaluations highlight the need to consider indirect savings from shortened hospital stays and reduced complication rates as well as direct costs [35,41].

3. 4. Operating Room (OR) Workflow and Physical Constraints

The size, placement, and setup times of robotic platforms affect operating room workflow. Deficiencies in OR layout, device portability, and team coordination make daily case planning and time management difficult [42]. Long setup times increase total OR utilization periods and thus raise unit costs. The literature recommends dedicated OR design, team training, and standardized checklists to reduce these problems [42].

3. 5. Human-Machine Interaction, Ergonomics, and Fatigue

While robotic consoles can reduce the postural burden on surgeons, long periods spent at the console and intense visual focus can lead to fatigue and ergonomic issues, such as neck and shoulder discomfort [43]. Furthermore, limits in console-team communication and mental fatigue may affect surgical performance. Newer systems are undergoing user-focused ergonomic design and interface optimization to mitigate visual strain [43,44].

3. 6. Device and Instrument Technical Limitations

Current robotic instruments have limited distal range of motion, instrument durability, and reusable lifespan. This restricts robotic adaptation in certain advanced surgical procedures [45]. Especially in highly sensitive areas such as neurosurgery or vascular surgery, the lack of instrument variety is a significant obstacle [45,37].

3. 7. Evidence-Based Practice and Patient Selection Uncertainties

In some surgical indications, the clinical superiority of robotic methods is not yet clear. The limited number of randomized controlled studies makes careful determination of patient selection criteria necessary [46]. This deficiency leads to heterogeneous results in cost-effectiveness analyses and causes uncertainties for policymakers [46,41].

3. 8. Data Security, Regulation, and Access Inequalities

Network-connected components and software infrastructure of robotic systems carry potential cybersecurity risks. Software errors or network delays can cause operational disruptions [46]. Additionally, the high investment cost restricts access to this technology for low-income health institutions, creating inequalities in healthcare services [35].

4. Ethical, Legal, and Clinical Governance Dimensions in Robotic Surgery

Robotic surgery systems have the potential to enhance clinical effectiveness and patient safety, but they also introduce new debates at ethical, legal, and governance levels. These discussions focus primarily on areas such as determining liability in the event of robot malfunction, data privacy in artificial intelligence (AI) integration, and informed consent processes for patients [47,48]. It is also reported that comprehensive and consistent policy frameworks on these issues are yet to be developed in many countries [49]. Ethical and legal governance in robotic surgery is not only a matter of technical safety but is also critical from the standpoint of public trust and the protection of patient rights. An effective governance framework should be built upon (1) legal protocols that clarify responsibility allocation, (2) ethical principles based on data protection and AI transparency, and (3) clear consent procedures for patients [50]. National and international regulations to be developed in this area will contribute to the safe, fair, and ethical expansion of the technology.

4.1. Robot Malfunction and Liability

Failures of robotic systems or software errors may lead to serious complications during surgery. In such cases, the distribution of liability among the surgeon, manufacturer, software provider, or hospital management is unclear [51]. Since traditional medical error doctrines are based on human negligence, the question of where "fault" lies in autonomous or semi-autonomous robotic systems creates an ethical gap [52]. In this context, some legal experts propose a "shared responsibility model," in which both the operator and the device manufacturer are held responsible to certain degrees [53].

4. 2. Artificial Intelligence Integration and Data Privacy

AI algorithms integrated into robotic systems support surgical decisions by analysing patient data. However, the collection, processing, and sharing of personal health data in cloud environments with third parties create risks under GDPR (General Data Protection Regulation) and similar regulations [54]. In particular, if patient data used for model training is not anonymized, the potential for privacy violations increases [55]. From a clinical governance perspective, the traceability ("explainability") of decision processes in AI-based robotic systems and monitoring for algorithmic biases are among the ethical requirements [56].

4.3. Informed Consent Processes

Since robotic surgery is a technically complex field for patients, the informed consent process should be more comprehensive than for traditional surgery. The patient should be clearly informed not only about the risks of the operation but also potential device-related malfunction risks, data sharing, and the limitations of AI-assisted decision systems [57]. However, the literature indicates that many institutions lack standardized consent forms for these issues and that patients do not fully understand the technological risks involved [58].

4. 4. Policy and Regulatory Gaps

In many countries, ethical and legal regulations specific to robotic surgery are still under development. Existing legal frameworks often focus on device certification or clinical safety standards, but there are gaps regarding data management, liability sharing, and patient rights [59]. International organizations recommend the development of multi-stakeholder governance models to ensure the safe integration of robotic systems [60].

Discussion

Robotic surgery offers significant advantages in orthopaedic and other surgical disciplines in terms of high precision, enhanced visualization, and minimally invasive approaches. Especially in knee and hip arthroplasties, robotic-assisted procedures have been shown in the literature to provide higher accuracy in implant placement and reduce complication rates [61–62 However, the effectiveness of robotic surgery is not limited to clinical outcomes; it is also directly linked to cost, training, and operational infrastructure.

The learning curve is one of the critical limitations in the implementation of robotic surgery; as the surgeon's experience increases, operation times and error rates decrease, whereas in low-experience centres, cost and complication risk increase [63,64]. Technical limitations include lack of haptic feedback and restricted instrument range, which complicate the adaptation of robotic systems to certain surgical procedures [61,65,66]. Additionally, operational factors such as operating room arrangement, team coordination, and setup times also affect the effective use of the system [67–68].

Ethical and legal dimensions are critically important for the sustainable integration of robotic surgery. Issues such as liability distribution in the event of robot malfunction, data privacy in AI-assisted decision systems, and algorithm transparency are still not adequately addressed by current legal frameworks [69 –70]. Insufficiencies in informed consent processes mean that patients do not fully understand the technological risks involved [71,72]. These findings reveal that robotic surgery is not only a technological innovation but also a complex system requiring ethical, legal, and clinical governance.

In summary, while the clinical benefits and long-term potential of robotic surgery are substantial, it must be evaluated together with multidimensional challenges such as cost, the learning curve, technical limitations, and governance deficiencies. Therefore, the expansion of robotic surgery practices should be supported not only by technological access but also by frameworks for training, policy, and ethics.

Conclusion

Robotic surgery is a major technological advance in orthopaedic surgery and other fields, enhancing operational accuracy, reducing complications, and increasing patient satisfaction. However, achieving these advantages sustainably requires consideration of factors such as high initial costs, operational infrastructure needs, and the learning curve. From an ethical and legal standpoint, clarifying issues such as liability distribution, transparency in AI-based decision support, and data privacy is critically important for ensuring the safe and fair use of the technology. Furthermore, structuring comprehensive informed consent processes is essential for protecting patient rights. In conclusion, while the clinical and economic benefits of robotic surgery are high, long-term success depends on interdisciplinary collaboration, comprehensive training, data-driven policy development, and strengthening ethical and legal governance mechanisms. This holistic approach will enable the safe, effective, and equitable integration of robotic surgery into healthcare systems.

Recommendations

A multidimensional strategic approach is considered necessary for the effective, safe, and sustainable implementation of robotic surgery in orthopaedics. Accordingly, the following recommendations are presented.

1. **Clinical Practice and Training**

- Structured, simulation-based training programs should be created for surgeons and incorporated as part of ongoing professional development to ensure widespread and safe implementation of robotic surgery.
- Collaboration and clear task definitions among surgical teams should be established to ensure standardization in operational processes.
- Centre-based performance assessment and quality assurance systems should be developed to monitor the effectiveness of robotic surgery practices

2. **Economic Sustainability**

- Robotic systems should be located primarily in high-volume centres to balance high investment and maintenance costs.
- Shared use models or regional centralization should be developed between institutions to ensure efficient resource sharing.
- Comprehensive economic databases that include operation, complication, revision, and maintenance costs should be created to monitor cost-effectiveness.

3. **Ethical and Legal Governance**

- Internal protocols that clearly define responsibility sharing in the event of robot malfunction or system error should be developed
- Principles of data security, algorithmic transparency, and patient privacy should be prioritized in AI-supported robotic systems; national standards should be set accordingly.
- The consent process should be simplified, and technology-specific risks must be communicated clearly.

4. **Research and Technological Development**

- Multicentre studies evaluating long-term outcomes, clinical success rates, and cost-effectiveness of robotic surgery should be supported.
- Engineering efforts aimed at haptic feedback, AI-based decision support, and ergonomic improvements in new-generation systems should be encouraged.
- Increased interdisciplinary collaboration between universities, tech firms, and healthcare institutions should be fostered to develop innovative surgical solutions.

5. **Policy and Strategy Development**

- A national roadmap should be prepared to define the areas of use, quality standards, and training requirements for robotic surgery.
- Health authorities should offer financial incentives and investment support to improve the accessibility of robotic systems
- Transparent communication policies based on ethical principles should be adopted to strengthen public trust in technology.

These recommendations aim to position robotic surgery not merely as a technological innovation, but as a holistic transformation tool that enhances the quality, efficiency, and ethical standards of healthcare services.

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Ethical Approval

As this study is a narrative review not involving human or animal subjects, ethical committee approval is not required.

Conflict of Interest Statement

The author declares that there is no conflict of interest regarding the publication of this article

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