



Modern robotic surgery: Evaluation of accuracy, surgical performance and clinical outcomes

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Abstract

Robotic surgery has undergone substantial development over recent decades, evolving from systems primarily designed to improve visualization and instrument control into advanced platforms that combine precise motion, three-dimensional visualization, data analysis, sensory feedback, and artificial intelligence technologies. This evolution has expanded the use of robotic surgery across multiple specialties, including colorectal, gastric, pancreatic, urologic, and cardiac surgery.

This paper aims to evaluate the impact of modern robotic surgery on accuracy, surgical performance, and clinical outcomes, while examining its advantages compared with laparoscopic and conventional surgery. It also discusses recent technological developments in robotic systems, with the da Vinci 5 system presented as an example of a modern platform incorporating technologies such as force measurement and surgical data analysis.

The study is based on a review of original studies, systematic reviews, and meta-analyses published in the scientific and medical literature. Evidence indicates that robotic surgery provides important technical advantages, including improved instrument control, greater range of motion, enhanced visualization, and the ability to perform precise movements in confined anatomical spaces. Some studies have also demonstrated clinical benefits in selected procedures, such as lower conversion rates to open surgery or shorter hospital stays. However, robotic surgery does not demonstrate universal superiority over laparoscopy across all procedures, while cost, training, and technical safety remain important challenges.

Recent developments suggest that the future of robotic surgery may increasingly depend on integrating robotics with artificial intelligence, data analysis, and sensory feedback, potentially enabling systems with greater capacity to measure performance, support surgeons, and improve clinical outcomes.

Keywords: Robotic surgery, robot-assisted surgery, da Vinci, surgical accuracy, surgical performance, artificial intelligence, minimally invasive surgery, clinical outcomes, force feedback

Introduction

Robotic surgery has evolved from a limited technological concept intended to assist surgeons with instrument control into an advanced field of minimally invasive surgery combining mechanical systems, electronics, software, and data analysis. This development has increased the use of surgical robots across a broad range of medical specialties, including colorectal, gastric, pancreatic, urologic, and cardiac surgery [1-5].

One of the major characteristics of robotic surgery is its ability to provide greater instrument mobility than conventional laparoscopic instruments, together with three-dimensional visualization, magnification, and precise control of instrument movement. These characteristics are particularly important during procedures requiring meticulous dissection in narrow or complex anatomical regions [1, 3].

These technologies have made some complex surgical procedures more feasible through minimally invasive approaches. However, the presence of a robotic system does not necessarily guarantee better clinical outcomes in every situation. Outcomes depend on the type of procedure, disease characteristics, surgeon experience, technical implementation, and other factors associated with perioperative care.

In recent years, robotic systems have undergone additional development through the introduction of technologies for force measurement and operative data analysis. Modern da

Vinci platforms, including da Vinci 5, provide advanced capabilities in force measurement and surgical data analysis [8-10].

These technologies should not be considered goals in themselves, but rather part of a broader movement toward data-driven and quantitatively measured robotic surgery.

Research Objective

This study aims to:

1. Examine the development of modern robotic surgery.
2. Evaluate its effects on surgical accuracy, control, and performance.
3. Compare robotic surgery with laparoscopic surgery in terms of clinical outcomes.
4. Examine the benefits of robotic surgery across different specialties and procedures.
5. Evaluate economic considerations and technical safety.
6. Examine the role of modern technologies such as force measurement and data analysis.
7. Evaluate the role of artificial intelligence in robotic surgery.
8. Discuss the future transition toward more autonomous robotic systems.

Research Question

To what extent can modern robotic surgery improve surgical accuracy, performance, and clinical outcomes compared

with laparoscopic and conventional surgical approaches, and what role may emerging technologies such as data analysis, sensory feedback, and artificial intelligence play in the development of these systems?

Methods

1. Research Design

An analytical literature review was conducted on scientific studies addressing modern robotic surgery, with emphasis on accuracy, surgical performance, clinical outcomes, safety, cost, and recent technological developments. The review was not limited to a single robotic system. Instead, it considered evidence concerning robotic surgery broadly, using da Vinci systems, including da Vinci 5, as examples of technological development.

2. Sources of Information

The review relied on studies published in medical and scientific databases, particularly studies indexed in PubMed, together with systematic reviews and meta-analyses published in specialized scientific journals.

3. Study Selection

Priority was given to studies that:

- Compared robotic surgery with laparoscopic surgery.
- Evaluated postoperative clinical outcomes.
- Examined accuracy, control, and surgical performance.
- Addressed robotic applications across different surgical specialties.
- Investigated technical safety and reliability.
- Evaluated the economic cost of robotic surgery.
- Addressed modern technologies such as force measurement and sensory feedback.
- Investigated artificial intelligence and data analysis in surgery.
- Examined advanced robotic applications in highly complex procedures, including cardiac surgery.

4. Data Analysis

Studies were analyzed according to major domains including accuracy and control, instrument range of motion, surgical performance, operative time, hospital stay, complications, conversion to open surgery, cost, safety and reliability, data and sensory feedback, and artificial intelligence and the future of robotic surgery.

Results

1. Accuracy and Surgical Control

Evidence indicates that robotic surgery provides several technical advantages that can improve a surgeon's ability to control instruments, particularly during procedures requiring precise movements in confined anatomical regions.

Robotic systems typically provide magnified three-dimensional visualization and instruments with multiple degrees of freedom, allowing them to reproduce some movements of the human hand inside the body. These characteristics may facilitate precise procedures that can be more difficult with conventional laparoscopic instruments [1, 3].

Robotic systems may also reduce some limitations associated with laparoscopic instrument movement, such as the transmission of external hand movement to the

instrument inside the body. This can allow the surgeon to perform more controlled and precise movements.

Nevertheless, technical accuracy must be distinguished from clinical improvement. Greater motion precision or improved visualization does not necessarily translate into lower complication rates or better final outcomes for every patient.

2. Surgical Performance

Surgical performance can be evaluated using indicators such as operative time, unnecessary movements, instrument motion, forces applied to tissues, and rates of error or conversion to open surgery.

Surgical Performance (continued)

Modern robotic systems can collect large quantities of intraoperative data, creating opportunities to evaluate surgical performance more objectively. Rather than relying primarily on direct observation or years of experience, future assessment may use quantitative indicators derived from instrument motion, operative time, and applied forces.

This transition represents an important step toward developing more objective methods for evaluating and training surgeons.

3. Technological Development and Force Feedback

Modern robotic surgery has gradually moved from systems focused mainly on visual and motor control toward systems capable of collecting additional quantitative information during surgery.

Measurement of forces applied to tissues is an important example of this direction. Sensors incorporated into instruments or robotic systems can record forces during interaction between instruments and tissues.

This development is demonstrated by modern platforms, including da Vinci 5, which provides advanced capabilities for force measurement and operative data analysis [8–10].

Early studies suggest that increased force-feedback capability may be associated with reduced force use during selected surgical procedures [8–10]. The importance of this technology extends beyond reducing force itself, because these data may eventually be used to assess surgical performance, improve training, and connect instrument use with clinical outcomes.

Evidence regarding the long-term clinical effects of this technology remains limited, requiring larger and more comprehensive studies.

4. Clinical Outcomes

Comparative studies indicate that the clinical impact of robotic surgery varies according to the type of procedure.

In colorectal surgery, a systematic review and meta-analysis of 13 randomized trials found no statistically significant difference in postoperative complications between robotic and laparoscopic surgery. However, operative time was shorter with laparoscopy, while conversion rates to open surgery were lower with robotic surgery [1].

Other analyses in patients with colon cancer have shown that robotic surgery may be associated with longer operative times but may provide advantages such as shorter hospital stays and lower conversion rates in some analyses [2, 4].

These findings suggest that the value of robotic surgery may be more apparent in selected complex procedures, while differences may be limited in other operations.

5. Robotic Surgery in Different Surgical Specialties

Robotic surgery is no longer limited to a single specialty and is now used across a broad range of surgical fields.

Robotic Surgery in Different Surgical Specialties (continued)

In colorectal surgery, robotic systems have been extensively studied, particularly for colorectal resection and treatment of colorectal cancer^[1-5].

In gastric surgery, comparative analyses suggest that robotic surgery may provide selected perioperative advantages, while differences in operative time and cost remain^[16].

In pancreatic surgery, several analyses indicate that robotic surgery can be an effective option for complex procedures such as pancreaticoduodenectomy, with some studies reporting short-term benefits^[17-19].

In urology, robot-assisted surgery is widely used, particularly for radical prostatectomy, where robotic systems permit precise movements around sensitive anatomical structures^[20].

These applications demonstrate that the value of robotic technology depends not only on the technology itself, but also on how well its capabilities match the requirements of the surgical procedure.

6. Robotic Surgery Versus Laparoscopic Surgery

Current evidence does not demonstrate absolute superiority of robotic surgery over laparoscopic surgery.

In some colorectal procedures, laparoscopy may be faster and less expensive, whereas robotic surgery may achieve lower conversion rates to open surgery^[1-4].

Robotic Surgery Versus Laparoscopic Surgery (continued)

Some studies also report benefits related to hospital stay or selected perioperative outcomes, but these benefits vary among procedures and studies.

Therefore, robotic surgery should not be viewed as a universally superior replacement for laparoscopy.

The choice of technique should depend on procedure type, case complexity, surgeon experience, hospital resources, cost, and expected outcomes.

7. Economic Considerations

Cost is one of the most important challenges to wider adoption of robotic surgery.

The cost of a robotic system includes acquisition, maintenance, surgical instruments, training, and operating expenses.

A systematic review and meta-analysis including 13 studies and 16,082 patients found that laparoscopic surgery was less costly than robotic surgery for colorectal resection, both in operating costs and overall costs^[7].

Consequently, any potential clinical benefit of robotic surgery must be considered against its additional cost.

This economic balance may differ among countries and hospitals and may change as the technology becomes more widespread, competition increases, and robotic systems evolve.

Advanced Robotic Applications in Cardiac Surgery

The use of robotics in cardiac surgery represents one of the most advanced and technically complex areas of robotic surgery.

A notable recent example is the first totally robotic human heart transplant, performed in 2024 at King Faisal Specialist Hospital and Research Centre in Riyadh, Saudi Arabia.

The surgical team was led by surgeon Firas Khaliel, and the procedure was performed on a 16-year-old patient with severe heart failure caused by non-ischemic dilated cardiomyopathy^[21].

The operation was preceded by intensive training using anatomical models and cadavers, with emphasis on reducing donor-heart ischemic time and ensuring procedural safety^[21].

This operation illustrates the possibility of expanding robotic surgery into highly complex procedures traditionally performed through open surgery.

Importantly, this example does not mean that all robotic heart transplantation procedures have become routine clinical practice. Rather, it represents a significant milestone requiring further experience and research before broader adoption can be evaluated.

Artificial Intelligence and Robotic Surgery

Artificial intelligence represents one of the most important future directions in robotic surgery.

Modern robotic systems generate large amounts of intraoperative data, including instrument movement, instrument-use time, procedural sequence, forces applied to tissues, and stages of the operation.

Artificial Intelligence and Robotic Surgery (continued)

These data can be used to train artificial intelligence algorithms to recognize surgical phases, analyze surgeon performance, and identify patterns associated with success or error^[12-14].

This could lead to more objective training systems capable of analyzing surgeon performance and providing quantitative indicators of movement, accuracy, and efficiency.

Artificial intelligence may also support surgeons during operations by recognizing anatomical structures, predicting subsequent steps, or alerting surgeons to potential risks.

These developments suggest that the future of robotic surgery will depend not only on improving instrument movement but also on the ability to understand and analyze the data generated during surgery.

Surgical Autonomy

The transition from systems fully controlled by surgeons to systems with partial autonomy is one of the most important future directions.

In current systems, surgeons remain primarily responsible for decision-making and operative control, while the robot functions as an advanced tool that assists with movement.

However, current research in artificial intelligence and robotics aims to develop systems capable of performing specific tasks with partial autonomy, such as moving instruments along planned trajectories or executing repetitive steps.

Increasing robotic autonomy nevertheless raises important challenges involving safety, legal responsibility, and ethics.

Surgical Autonomy (continued)

If an autonomous system makes an error during an operation, questions arise regarding responsibility among the surgeon, hospital, manufacturer, and software developer. Therefore, increasing system autonomy should be gradual and supported by strong evidence demonstrating safety and effectiveness.

Safety and Reliability

Technical safety is a fundamental element in evaluating robotic surgical systems because they depend on complex mechanical, electronic, and software components.

Studies of robotic surgical systems have shown that technical failures can occur, although they are not generally the main cause of procedural failure.

Robotic surgery requires contingency plans for potential technical failures, including the ability to convert to laparoscopic or open surgery when necessary.

Training of surgeons and medical teams is also important for reducing risk, particularly when using new systems or applying robotic surgery to highly complex procedures.

Safety depends not only on the system itself but also on team experience, infrastructure, training protocols, patient selection, and preparedness for emergencies.

Discussion

The findings demonstrate that modern robotic surgery represents an important technological development in minimally invasive surgery, but its evaluation requires a distinction between technological advancement and clinical improvement.

Robotic systems provide technical advantages including enhanced visualization, greater instrument mobility, precise control, and the ability to operate in narrow anatomical regions^[1-5].

These characteristics have contributed to expanded use of robotic surgery across multiple specialties, particularly for complex operations.

In recent years, development has moved beyond improving movement and visualization toward collecting and analyzing data. Force measurement and sensory feedback are examples of this direction, while da Vinci 5 represents a modern platform offering such capabilities^[8-10].

However, reduced applied force or greater instrument precision does not necessarily mean improved clinical outcomes. Final outcomes are influenced by multiple factors, including disease characteristics, procedural complexity, surgeon experience, training, and postoperative care.

When robotic surgery is compared with laparoscopy, the picture is more complex. In some situations laparoscopy is faster and less expensive, while robotics may provide advantages in selected procedures, such as lower conversion rates to open surgery^[1-4].

For this reason, robotic surgery cannot be considered an absolutely superior replacement for laparoscopy. It is more accurately viewed as an advanced surgical tool whose benefits are greatest when its capabilities match the requirements of the procedure.

Discussion (continued)

Artificial intelligence represents the next potential stage of this development. If movement, force, time, and procedural-stage data can be effectively analyzed, systems may be

developed to help surgeons evaluate performance, detect errors, and support decision-making^[12-15].

In the future, some systems may progress from simply assisting surgeons to performing selected tasks with partial autonomy. However, this transition requires evidence of safety and effectiveness as well as clear frameworks for responsibility and ethics.

Limitations

Several limitations should be considered when interpreting the findings of this research.

First, studies differ in design, sample size, and procedure type, limiting direct comparison.

Second, surgeon experience varies across studies and can substantially influence surgical outcomes.

Third, some emerging technologies, including force feedback and surgical data analysis, remain relatively early in development; therefore, evidence regarding their long-term clinical effects remains limited.

Fourth, the cost of robotic systems varies between countries and hospitals, making economic findings difficult to generalize across health systems.

Fifth, rapid advances in robotics and artificial intelligence mean that some current findings may change as new generations of systems and clinical studies emerge.

Conclusion

The evidence analyzed in this paper indicates that modern robotic surgery represents an important development in minimally invasive surgery, particularly with regard to accuracy, control, visualization, and instrument range of motion.

Robotic systems have expanded across multiple surgical specialties, and studies demonstrate potential clinical benefits in selected procedures, such as lower conversion rates to open surgery or improvements in certain perioperative outcomes.

However, current evidence does not support considering robotic surgery universally superior to laparoscopic surgery. In some procedures, laparoscopy may be faster and less costly, whereas robotic systems may provide advantages in other procedures, particularly complex operations.

Technological development in robotic systems represents an important direction for the future of surgery. The addition of technologies such as force measurement and data analysis, as seen in modern systems such as da Vinci 5, indicates a transition from simple mechanical instrument control toward systems capable of collecting and analyzing quantitative information about surgical procedures.

Artificial intelligence is also a promising field that may change how surgical performance is evaluated, how surgeons are trained, and how intraoperative decisions are supported. In the longer term, combining robotics with artificial intelligence may enable systems capable of performing selected surgical tasks with partial autonomy.

Based on the available evidence, the research question can be answered as follows: modern robotic surgery can improve selected aspects of surgical accuracy, control, and performance and may provide clinical benefits in specific contexts and procedures. However, current evidence does not support universal superiority over laparoscopic or conventional surgery. The future of the field will likely depend increasingly on integration among robotics, data analysis, sensory feedback, and artificial intelligence,

together with continued large-scale clinical research to determine the true value of these technologies and their long-term effects on patient safety and clinical outcomes.

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