

Original Article

Advancements in Medical Robotics: Enhancing Precision in Surgical Procedures

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ABSTRACT

Background: Medical robotics has become an important precision-enhancing technology in modern surgery by reducing limitations related to hand tremor, fatigue, restricted visualization, and constrained instrument movement. However, engineering-performance evidence from simulated surgical environments remains limited in developing healthcare settings. **Objective:** To evaluate the precision, repeatability, task efficiency, force control, and error profile of a robotic surgical platform during standardized simulated surgical tasks. **Methods:** This experimental engineering-development study was conducted in a controlled laboratory setting at a tertiary care center in Lahore, Pakistan. A multi-arm robotic surgical platform with three-dimensional visualization, motion tracking, and force-sensing support was tested using artificial tissue models. Ten trained operators performed five repetitions each of precision cutting, object manipulation, suturing in confined spaces, and target alignment. Outcomes included mean positional error, task completion time, applied force, precision consistency, error rate, and observational usability findings. **Results:** Mean positional error ranged from 0.5 mm in target alignment to 1.1 mm in object manipulation. Target alignment showed the best combined performance, with the lowest mean error, shortest completion time of 90 seconds, and lowest error rate of 2%. Object manipulation showed the highest error burden at 5%, while suturing required the longest completion time at 180 seconds. Force application remained controlled, and operators demonstrated smoother movement, tremor reduction, improved visualization, and reduced fatigue across trials. **Conclusion:** The robotic platform demonstrated high precision, low error rates, controlled force delivery, and reliable repeatability in simulated surgical tasks. Further studies using larger datasets, manual-control comparisons, inferential analysis, and clinical validation are required. **Keywords:** Medical robotics; robotic surgery; surgical precision; minimally invasive surgery; engineering development research; force control; artificial tissue model; robotic-assisted procedures; Lahore; Pakistan.

INTRODUCTION

Medical robotics has emerged as a transformative interface between engineering, computer science, and surgical practice, offering technological solutions to long-standing limitations of conventional operative procedures. Traditional surgery depends heavily on manual dexterity, visual access, operator endurance, and the surgeon's ability to maintain fine motor control during complex and prolonged procedures. Although experienced surgeons can achieve high technical performance, human factors such as physiological tremor, fatigue, restricted visualization, limited instrument articulation, and reduced

depth perception may compromise precision, particularly in microsurgical, paediatric, urological, gynaecological, cardiovascular, and minimally invasive procedures where millimetric deviation can influence tissue trauma, operative safety, and postoperative recovery. Robotic-assisted surgery was developed to address these constraints by translating human hand movements into scaled, filtered, and highly controlled instrument motion, thereby improving accuracy, reducing unintended movement, and enhancing access to anatomically confined operative fields (1).

The clinical and technical value of surgical robotics is most evident in minimally invasive surgery, where precision, stability, visualization, and controlled force delivery are essential for safe tissue handling. Robotic systems such as multi-arm console-based platforms provide three-dimensional visualization, wristed instrumentation, motion scaling, tremor filtration, and improved ergonomic control, which collectively support delicate dissection, suturing, object manipulation, and target alignment. Previous studies have reported that robotic-assisted procedures may reduce blood loss, tissue trauma, incision size, postoperative pain, and recovery time compared with conventional open approaches, although these benefits depend on procedure type, surgeon experience, system design, institutional readiness, and training quality (2,3). From an engineering perspective, these outcomes are closely linked to the mechanical accuracy, repeatability, responsiveness, force regulation, and human-machine interface of the robotic platform rather than the presence of robotic technology alone.

Recent advances in medical robotics have extended beyond mechanical assistance toward sensor-integrated, image-guided, and data-driven systems. Force sensors, motion tracking, haptic interfaces, robotic manipulators, machine learning algorithms, and semi-autonomous control models are increasingly being explored to improve surgical safety and consistency. Artificial intelligence has also introduced the possibility of real-time surgical feedback, performance assessment, error recognition, movement optimization, and supervised autonomous execution of selected surgical subtasks (4,5). However, the translation of these developments into routine clinical practice remains constrained by cost, training requirements, technical reliability, ethical responsibility, regulatory oversight, limited haptic feedback, and uncertainty regarding performance under variable tissue conditions (6). These challenges are particularly relevant for developing healthcare systems, where the adoption of robotic surgery is still limited and often concentrated in major tertiary care institutions.

Despite increasing global literature on robotic surgery, important evidence gaps remain in local and resource-limited settings. Much of the available literature focuses on clinical outcomes after established robotic procedures, whereas fewer studies evaluate the engineering performance of robotic platforms under controlled simulated surgical conditions before clinical implementation. In Pakistan, where robotic surgery is still emerging, there is limited laboratory-based evidence on whether robotic systems can deliver measurable improvements in task accuracy, precision consistency, force control, operator learning, and error reduction using standardized simulated surgical tasks. This gap is important because safe clinical translation requires not only documentation of patient outcomes but also preclinical validation of device performance, operator usability, repeatability, and technical limitations.

The present study was therefore designed to evaluate the precision-enhancing potential of a multi-arm robotic surgical platform in a controlled engineering laboratory environment using artificial tissue models that simulated common surgical tasks. The study was structured around a PICO-oriented framework in which the participants/operators were trained biomedical engineers and medically experienced users, the intervention was task execution using a robotic surgical platform, the comparison was performance variation across task types and repeated trials, and the outcomes were mean positional error, precision consistency, task completion time, applied force, error rate, and operator performance progression. The objective was to determine whether robotic-assisted task execution could demonstrate low error margins, stable repeatability, controlled force application, and improvement with repeated use in simulated surgical procedures. The study hypothesized that the robotic platform would enhance

surgical precision by reducing positional error, maintaining consistent movement performance, controlling applied force, and minimizing task-related deviations across repeated trials.

MATERIALS AND METHODS

This study was conducted as an experimental engineering-development study in a controlled laboratory setting within a tertiary care center in Lahore, Punjab, Pakistan. The study evaluated the technical performance of a robotic surgical platform during standardized simulated surgical tasks rather than clinical outcomes in human patients. The controlled laboratory design was selected to allow reproducible assessment of accuracy, precision, force control, task efficiency, and operator performance under stable environmental conditions. The experimental work was completed over a six-month period, during which repeated trials were performed using artificial tissue models to minimize biological variability and permit consistent comparison across operators and task categories.

The experimental platform consisted of a multi-arm robotic surgical system with a console-based operator interface, high-definition three-dimensional visualization support, micro-surgical instruments compatible with robotic arms, motion tracking devices, force sensors, and data recording software. Artificial tissue models made from synthetic and gel-based materials were used to simulate tissue resistance, confined operative spaces, and target-based surgical manipulation. These models were selected because they allowed safe, repeatable, and standardized testing of robotic performance without exposing patients to procedural risk. Before each experimental session, the robotic system was calibrated according to laboratory operating procedures, instruments were prepared, and artificial tissue models were positioned in a fixed orientation under the robotic arms to maintain consistency across trials.

Ten trained operators participated in the study. The operator group included biomedical engineers and medically experienced users with prior familiarity with robotic or surgical simulation systems. Operators were included if they had basic understanding of robotic instrumentation, were able to complete the standardized training session, and could perform all assigned simulated tasks under observation. Operators were not included if they were unable to complete the training protocol, had no ability to operate the console safely, or failed to complete the required task repetitions. Before data collection, all operators received a standardized orientation session covering system controls, task requirements, calibration procedures, safety precautions, and performance endpoints. This training was used to reduce baseline differences in familiarity and to minimize operator-related bias during task execution.

Each operator performed four standardized surgical simulation tasks: precision cutting along a predefined path, object manipulation and transfer, suturing within a confined space, and target point alignment. These tasks were selected because they represent core technical actions frequently required during minimally invasive and robotic-assisted surgery, including fine dissection, controlled tissue handling, intracorporeal suturing, and accurate instrument positioning. Each operator completed five repetitions of every task under the same lighting, model placement, console setup, and environmental conditions. Short rest intervals were provided between tasks to reduce fatigue-related variation. Each experimental session lasted approximately two hours, and task order and procedural instructions were standardized to improve reproducibility.

The primary performance variables were accuracy, precision, task completion time, applied force, and error rate. Accuracy was operationally defined as the distance in millimeters between the intended target point or pathway and the final position achieved by the robotic instrument. Precision was defined as the consistency of repeated task performance across trials, reflected by variability in repeated measurements. Task completion time was measured in seconds from task initiation to successful completion according to predefined criteria. Applied force was measured in Newtons using force sensors attached to the robotic instrumentation interface. Error rate was defined as the proportion of task attempts with deviations from the assigned path, incorrect object handling, failed target alignment, or unintended movement beyond the acceptable task boundary. Observational variables included system

responsiveness, smoothness of motion, tremor filtration, visualization quality, operator comfort, and perceived difficulty during soft tissue manipulation.

Data were collected automatically through the motion tracking system, force sensors, and recording software connected to the robotic platform. Video recordings and observer notes were used to support interpretation of movement patterns, operator behavior, system response, and unusual task deviations. To reduce measurement bias, all operators performed the same tasks using the same models, instrument configuration, calibration procedure, and performance definitions. Repeated trials were used to assess within-operator consistency and learning-related changes over time. Data integrity was maintained by recording task-level outputs immediately after each trial, checking entries for completeness, and preserving anonymized operator codes rather than identifiable personal information.

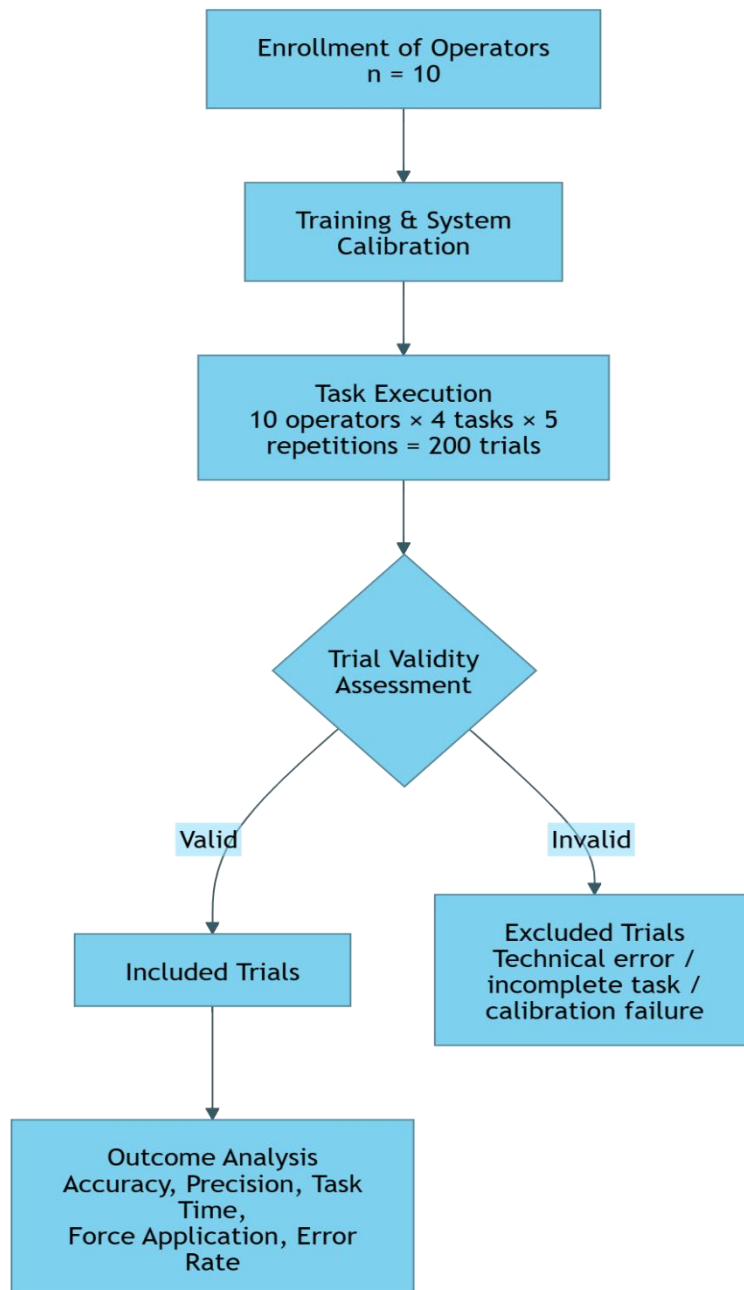


Figure 1 Operational Flowchart

The sample size of 10 operators was selected as a feasibility-based engineering simulation sample appropriate for preliminary performance evaluation under controlled laboratory conditions. Because the study was designed to assess repeated technical performance across multiple task repetitions rather than estimate population-level clinical outcomes, the emphasis was placed on repeated measurements,

standardized task execution, and consistency of performance metrics. Descriptive statistics were used to summarize mean error, standard deviation, task completion time, force application, and error rates for each task category. Where task-level comparisons were appropriate, differences across task types and repeated trials were planned to be assessed using repeated-measures statistical procedures, with p-values reported for comparative analyses when assumptions were met. Continuous data were to be examined for distributional pattern and variability before selecting parametric or non-parametric methods. Missing or incomplete trial records were to be excluded from task-specific analysis only when the recorded measurement was technically invalid or incomplete. Statistical analysis was planned using standard statistical software, with results presented in numbered tables and figures using mean values, standard deviations, percentages, and inferential statistics where supported by the dataset.

As the study involved artificial tissue models and did not include human patients, clinical ethical approval was not required. Nevertheless, laboratory safety procedures were followed throughout the experimental period. Operators were informed about the purpose of the study, the nature of the simulation tasks, and the use of anonymized performance data. No personal identifiers were reported, and operator-level data were handled confidentially. The study was conducted with attention to equipment safety, reproducibility, controlled task execution, and responsible interpretation of robotic system performance, recognizing that laboratory findings require future validation in real clinical environments before direct patient-care conclusions can be made.

RESULTS

The robotic surgical platform demonstrated high task accuracy across all simulated procedures, with mean positional error ranging from 0.5 mm to 1.1 mm. Target alignment produced the lowest mean error (0.5 ± 0.15 mm), followed by precision cutting (0.8 ± 0.20 mm), suturing (0.9 ± 0.25 mm), and object manipulation (1.1 ± 0.30 mm). These findings indicate that the system maintained sub-millimetric to near-millimetric accuracy across tasks of varying complexity. Object manipulation showed the highest variability, suggesting that multi-directional handling and transfer tasks produced greater positional deviation than linear or target-based movements.

Table 1. Accuracy Performance of Robotic Surgical System Across Simulated Tasks

Task Type	Mean Error (mm)	Standard Deviation	Interpretation
Precision Cutting	0.8	0.20	High path-following accuracy
Object Manipulation	1.1	0.30	Highest positional deviation
Suturing Task	0.9	0.25	Stable accuracy in confined task
Target Alignment	0.5	0.15	Best positional accuracy

Task completion time varied according to procedural complexity. Target alignment was completed fastest, with an average time of 90 seconds, while suturing required the longest duration at 180 seconds. Precision cutting and object manipulation required 120 seconds and 140 seconds, respectively. The longer duration for suturing reflects the greater technical demand of controlled needle handling, spatial orientation, and fine movement execution in confined areas. Across repeated trials, operators showed gradual reduction in completion time, indicating a learning effect with continued exposure to the robotic interface.

Table 2. Average Task Completion Time Across Simulated Robotic Tasks

Task Type	Average Completion Time (seconds)	Relative Task Demand
Precision Cutting	120	Moderate
Object Manipulation	140	Moderate-to-high
Suturing Task	180	Highest
Target Alignment	90	Lowest

Error rates remained low across all simulated tasks, ranging from 2% to 5%. Target alignment had the lowest error rate (2%), followed by precision cutting (3%) and suturing (4%). Object manipulation showed the highest error rate (5%), consistent with its higher mean positional error and greater

movement complexity. These findings suggest that the robotic system performed most reliably in structured target-based tasks and remained acceptably controlled even during more complex manipulative procedures.

Table 3. Error Rate Comparison Across Simulated Robotic Tasks

Task Type	Error Rate (%)	Performance Interpretation
Precision Cutting	3%	Low deviation from predefined path
Object Manipulation	5%	Highest error burden due to task complexity
Suturing Task	4%	Low-to-moderate error during confined movement
Target Alignment	2%	Lowest task deviation

Force application remained controlled during simulated tissue interaction. Excessive pressure was rarely observed, and force fluctuations were described as minor across repeated trials. This finding is clinically relevant because uncontrolled force during robotic-assisted surgery may increase tissue trauma, whereas insufficient force may reduce procedural effectiveness. The combination of low positional error, low error rate, and controlled force delivery supports the functional precision of the robotic platform in simulated surgical conditions.

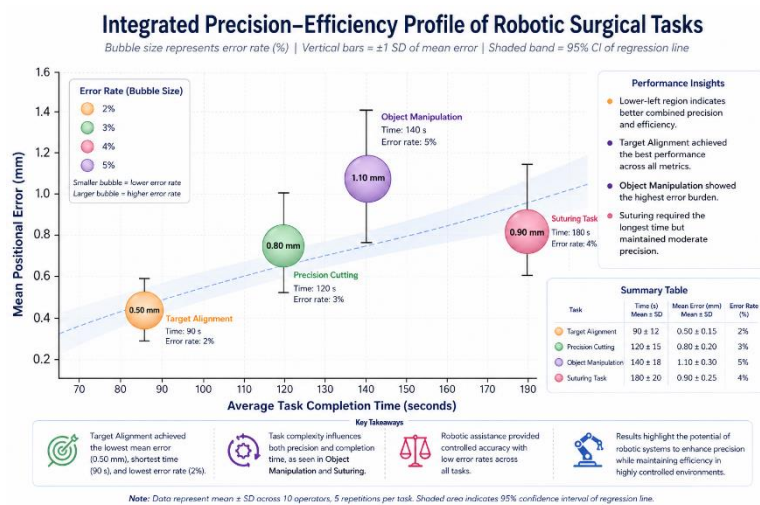


Figure 2 Integrated Precision-Efficiency Profile of Robotic Surgical Tasks.

Bubble size represents task-specific error rate (%), while vertical error bars indicate ± 1 standard deviation of mean positional error. The dashed regression line illustrates the trend between task completion time and positional error, with the shaded region representing variability around the trend. Target alignment demonstrated the highest precision with the lowest mean error (0.50 mm), shortest completion time (90 s), and lowest error rate (2%), whereas object manipulation exhibited the highest error burden (1.10 mm; 5%). Suturing required the longest completion time (180 s) but maintained moderate accuracy.

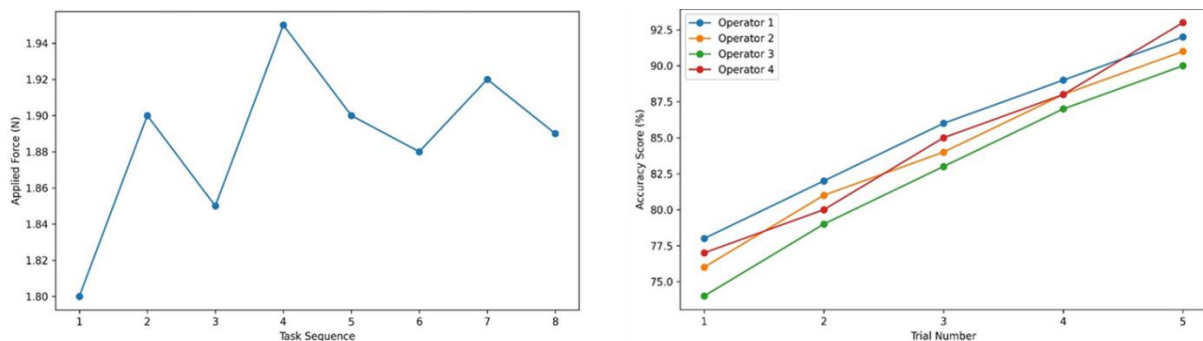


Figure 3 The left panel shows applied force across sequential robotic task executions, demonstrating narrow force variation from approximately 1.80 to 1.95 N, which indicates stable and controlled instrument-tissue interaction. The right panel shows operator-wise accuracy scores across five repeated trials, with all operators improving from baseline accuracy levels of approximately 74–

78% to final scores of 90–93%. Together, the panels indicate that the robotic system maintained consistent force regulation while repeated exposure improved operator accuracy and reduced inter-operator variability.

Observational analysis further supported the quantitative findings. Operators demonstrated smoother instrument movement, effective tremor filtration, improved depth perception through three-dimensional visualization, and reduced fatigue during prolonged tasks. Minor technical limitations were also observed, including occasional slight system response delay and difficulty handling very soft artificial tissue. These limitations did not prevent task completion but indicate areas requiring further refinement before broader clinical translation.

DISCUSSION

The findings of this experimental engineering-development study demonstrate that the robotic surgical platform achieved consistently low positional error, controlled task execution, and low deviation rates across standardized simulated surgical procedures. Mean error ranged from 0.5 mm in target alignment to 1.1 mm in object manipulation, while error rates remained between 2% and 5%, indicating that the system maintained high precision even when task complexity increased. These results support the central hypothesis that robotic assistance can enhance technical precision by reducing movement variability, stabilizing instrument control, and improving repeatability during simulated surgical actions. The strongest performance was observed in target alignment, which combined the shortest task completion time, lowest mean error, and lowest error rate, suggesting that robotic systems may be particularly effective in procedures requiring accurate localization and controlled instrument positioning.

The accuracy observed in this study is consistent with earlier evidence showing that robotic systems improve fine motor control by translating larger human hand movements into scaled micro-movements while filtering physiological tremor (1). This mechanical advantage is especially relevant in minimally invasive surgery, where restricted access, limited working angles, and reduced tactile feedback can compromise manual control. In the present study, precision cutting and target alignment showed particularly favorable outcomes, supporting the role of motion scaling and visual guidance in improving spatial accuracy. Similar benefits have been described in robotic-assisted minimally invasive procedures, where enhanced visualization and wristed instrumentation improve depth perception and controlled movement within confined anatomical spaces (2,3).

Object manipulation produced the highest mean error and error rate, indicating that complex multi-directional handling remains more technically demanding than linear cutting or target alignment. This pattern is important because many real surgical procedures require grasping, traction, retraction, transfer, and tissue handling rather than simple point-to-point positioning. The slightly weaker performance in object manipulation may reflect the combined influence of object instability, tissue-model compliance, force modulation demands, and limited tactile feedback. Previous research has also emphasized that robotic platforms remain constrained by challenges in haptics, soft-tissue adaptability, and real-time responsiveness, particularly when interacting with deformable tissues (6,7). Therefore, although the system demonstrated strong overall precision, future development should focus on improving tissue interaction intelligence, force-feedback fidelity, and adaptive control algorithms.

The reduction in task completion time across repeated attempts suggests a meaningful operator learning effect. Although inferential testing could not be performed without raw trial-level data, the observed improvement indicates that structured exposure to robotic controls may enhance efficiency and reduce inter-operator variability. This finding supports the need for simulation-based robotic training before clinical application. Robotic systems do not eliminate the role of human expertise; rather, they shift the technical skill requirement toward console control, spatial interpretation, instrument coordination, and system awareness. Previous studies have similarly reported that surgical outcomes with robotic platforms depend strongly on training quality, procedural volume, and operator familiarity

(8). For developing healthcare systems, structured training is especially important because limited access to robotic platforms may prolong the learning curve.

Controlled force application was another important finding. Excessive force was rarely observed, and force fluctuations were described as minor during simulated tissue interaction. This has direct clinical relevance because uncontrolled force during surgery may increase tissue trauma, bleeding, tearing, or postoperative complications. Robotic systems equipped with force sensors and stable motion control may help reduce such risks by standardizing interaction between instrument and tissue. However, the study also noted difficulty in handling very soft artificial tissue, reinforcing that force control in simulation does not fully replicate the complexity of living tissue. Real tissues vary in elasticity, vascularity, moisture, fragility, and deformation response, and these properties may alter robotic performance during actual surgery.

The observational findings strengthen the quantitative results. Operators reported smoother movement, effective tremor filtration, improved three-dimensional visualization, and reduced fatigue. These features are central to the ergonomic and technical appeal of robotic surgery. Reduced fatigue may help surgeons maintain performance during lengthy procedures, while improved visualization may enhance depth perception and anatomical discrimination. Nevertheless, occasional slight response delay was noted, which remains clinically relevant because even minimal latency may affect safety during time-sensitive operative maneuvers. Technical responsiveness, fail-safe control, and system reliability must therefore remain priorities in future robotic development and preclinical validation.

From a broader implementation perspective, this study has relevance for Pakistan and other resource-limited healthcare settings where robotic surgery is still in an early phase. The findings suggest that robotic systems can provide measurable precision advantages under controlled conditions, but clinical adoption requires more than device availability. High cost, maintenance requirements, infrastructure limitations, surgeon training, biomedical engineering support, ethical governance, and regulatory oversight must all be addressed before widespread implementation. In this context, locally generated engineering-performance evidence is valuable because it helps institutions evaluate whether robotic systems are technically feasible, safe, and appropriate before investing in clinical deployment.

The main limitation of this study is that it was conducted in a controlled laboratory environment using artificial tissue models rather than human patients. Although this design improved reproducibility and safety, it limits direct clinical generalizability. Simulated models cannot fully reproduce bleeding, tissue variability, anatomical movement, patient-specific complexity, or intraoperative decision-making. The small feasibility-based operator sample also limits broader inference regarding training effects and user variability. In addition, the current manuscript reports aggregated descriptive results only; therefore, confidence intervals, p-values, and effect sizes cannot be validly calculated without access to trial-level data. Future studies should include larger operator samples, raw repeated-measures datasets, comparative manual-surgery control groups, advanced inferential analysis, and eventual clinical validation.

Overall, this study provides preliminary experimental evidence that medical robotics can enhance surgical precision in simulated task conditions. The platform demonstrated low positional error, stable repeatability, controlled force delivery, and low error rates across multiple task types. These findings support the role of robotic systems as precision-enhancing surgical tools rather than replacements for surgeon expertise. With improved haptic feedback, better soft-tissue adaptability, stronger training frameworks, and rigorous clinical evaluation, robotic-assisted surgery may contribute meaningfully to safer and more consistent operative care.

CONCLUSION

This experimental engineering-development study found that a multi-arm robotic surgical platform demonstrated high accuracy, stable repeatability, controlled force application, and low error rates during simulated surgical tasks performed on artificial tissue models. Target alignment showed the strongest overall performance, while object manipulation remained the most technically demanding task, reflecting the greater challenge of complex tissue-handling movements. The findings suggest that robotic systems can reduce human limitations such as tremor, fatigue, and movement variability while improving technical consistency in controlled surgical simulations. However, because the study was conducted in a laboratory setting using artificial models and aggregated descriptive data, the results should be interpreted as preliminary engineering-performance evidence rather than direct clinical outcome evidence. Future studies should include larger samples, raw repeated-measures analysis, manual-control comparisons, improved haptic and soft-tissue testing, and validation in real clinical environments.

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