Enhanced performance and efficiency of robotic autonomous procedures through path planning algorithm

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ABSTRACT

To optimize surgical routes for better patient outcomes and more efficient operations, we want to test how well these algorithms work. Finding the best algorithms for different types of surgeries and seeing how they affect things like time spent in surgery, precision, and patient safety is the goal of this exhaustive study. By shedding light on the effectiveness of route planning algorithms, this work aspires to aid in the development of autonomous robotic surgery. To find out how well various algorithms work in actual surgical settings; this study compares them. The results of this work have the potential to enhance robotic surgery efficiency and improve surgical outcomes by informing the creation of more efficient route planning algorithms. The overarching goal of this study is to provide evidence that autonomous robotic surgery can benefit from using sophisticated route planning algorithms, which might lead to more accurate, faster, and safer procedures. The surgical patient dataset exhibits a wide variety of medical variables, including ages 38–62, weight 65–85 kg, height 160–180 cm, blood pressure 110–140/90 mm Hg, heart rate 70–85 bpm, hemoglobin 12–14 g/DL, and body mass index (BMI) 25.4–29.4.

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1. INTRODUCTION

With the potential for greater accuracy and better patient outcomes, robotics incorporation into surgical operations has sparked a healthcare revolution. Particularly promising for the improvement of surgical practice is the use of autonomous robotic systems. Autonomous robotic surgery relies heavily on route planning algorithms to guide the movement of surgical instruments within the patient's body. Surgeons may improve patient outcomes by increasing accuracy and decreasing stress to neighboring tissues by optimizing these pathways. This research aims to assess the efficacy of route planning algorithms within the framework of autonomous robotic surgery, particularly in relation to their capacity to enhance efficiency and results. The purpose of this study is to examine the effects of current algorithms on different surgical parameters and to determine their strengths and weaknesses via a thorough examination. In real-world surgical settings, we want to evaluate several route planning algorithms' performances in terms of accuracy, speed, and adaptation to changing circumstances. This research aims to compare and evaluate various algorithms in order to shed light on their efficacy and find ways to make them better. Ultimately, we hope that our evidence-based suggestions for route planning algorithm selection and optimization will help propel autonomous robotic surgery forward. Minimizing surgery timelines, improving patient outcomes, and increasing overall efficiency are just a few of the many advantages that this study hopes to bring to light.

This work aims to survey the current literature on robotic surgical route planning algorithms and analyze empirical data from simulated and clinical settings. In addition to discussing possible future research and development areas, the paper delves into the difficulties and limits of existing algorithms. To summarize, the study's overarching objective is to improve patient care and surgical results by illuminating the function of route planning algorithms in autonomous robotic surgery. The study aims to contribute to the continuous development of surgical practice and provide the groundwork for improvements in surgical robots. Using path planning algorithms, the development of autonomous robotic surgery is given in section 2. Section 3 discusses the path planning algorithms role in autonomous robotic surgery and the findings are obtained from the surgical patient dataset in bioinformatics and autonomous robotic surgery in section 4. The conclusion is discussed in section 5.

2. LITERATURE SURVEY

To optimize the surgical route while still satisfying all of the criteria of the procedure and avoiding any potentially dangerous locations, many automated surgical path planning approaches have been suggested. The surgical course of hard devices, such as puncture needles, flexible instruments, such as catheters and needles, or medical robots may be planned to use these approaches [1]. When deployed as autonomous systems in unfamiliar areas, path planning becomes even more important for continuum robots. In such cases, while plotting a route, it's important to think about more than just the beginning and ending points; you also need to think about the current environmental circumstances and the system's status [2]. Having a robot lead the probe is another add-on that lets you automate the whole process. Even though no fully autonomous system is now accessible, there are several robotic ultrasound systems detailed in the literature for use in various soft tissue diagnostic applications [3]. One definition of path planning is the process by which a mobile agent finds a method to get from one location to another in the state space. The mobile agent's volume and location pose are important factors to consider in engineering applications. As an example of a workplace, we may think of the state space where the mobile agent's volume and position pose are relevant factors [4].

There are three main types of path-planning algorithms for flexible needle puncture: numerical, inverse solution, and search method. One drawback of these algorithms is that they are not very real-time and only aim to reduce the path length or time, without guaranteeing that the paths obtained are optimal [5]. Planning a robot's route in such a way that it efficiently and methodically covers all its target area is known as coverage path planning. When complete covering of an area is required, such as in environmental monitoring or cleaning, this is often used [6]. Complete coverage path planning (CCPP) is crucial for an autonomous underwater helicopter (AUH) in the near-bottom region sweep in unknown conditions, which is a common application situation. We provide a comprehensive coverage route planning method for AUH using a single beam echo sounder [7]. This method incorporates both the initial path planning and an online local collision avoidance mechanism. Robot route planning and control during minimally invasive procedures (MIPs) is very demanding. Obstacles and dangerous locations, including areas of cardiac calcification, must be avoided, and unexpected contact with lumen walls must be reduced [8]. Researchers in the field of multi-robot cooperation have focused on investigating various route planning strategies to let many robots interact cohesively and avoid crashes [9]. One innovative area of study is autonomous robotic surgery, which seeks to eliminate the need for human surgeons by developing and implementing robotic devices that can carry out surgical operations independently. Surgical robotic devices with autonomous control have the potential to minimize tissue injury, perform clever moves, and increase accuracy [10]. Interventional surgical robots have been the subject of many attempts to manipulate those using reinforcement learning (RL) approaches. These include route planning, surgical training systems, and surgeries involving surrogate surgeons. In contrast to human doctors, who often need multimodal input to execute their procedures, these techniques usually depend on single-modal surgical data [11]. It is usual practice to use basic route planning algorithms or approaches for avoiding obstacles. Although they work well in controlled environments, they aren't adaptable enough to deal with different and unforeseen situations. A potential substitute that has arisen in recent times is machine learning (ML) [12].

When sending items to distribution hubs, certain major online retailers may group similar-sized containers together. Planning techniques, such a height-first selection approach or a selection method with established stack patterns, make it easy to modify the automation in these situations [13]. Within a given space or chamber, path planning is the process of figuring out how a robot will get from one point to another. In many cases, especially in confined, complicated, and interior spaces, more optimization and refinement of the robot's generated route is required [14]. Computing a series of valid configurations that connects two points, one at the beginning and one at the end, without collisions is the task at hand in the route planning issue for mobile robots. Wheeled mobile robots need obstacle avoidance and navigation capabilities for many practical uses [15]. The framework is like a beacon in the dark human-robot interaction (HRI) world, showing the way to interactions that are both successful and painless. Careful tuning of control strategies, algorithms for route planning, and methods for avoiding obstacles has been carried out [16].

To avoid impediments and robot collisions, the primary goal of route planning is to discover the optimal path. Safer and quicker navigation is achieved by splitting the continuous route into optimum sub-path edges. The route planning algorithms may be broadly classified into two types: indoor and outdoor. Indoor algorithms are used when the size and complexity of the arena or workplace are known in advance, whereas outdoor algorithms are used when these details are unknown [17]. The most common local route planning algorithms now in use are behavior decomposition (BD), cased learning (CL), and DWA, or dynamic window approach. To complete the whole moving job, BD-based algorithms break down the route planning into separate parts, called behavioral primitives [18]. To make sample-based procedures more effective, many ways have been suggested, such as multi-directional search sampling and bi-directional search sampling. In real-world scenarios, it is difficult to connect trees while yet adhering to the differential limitations of robot dynamics [19]. To overcome the shortcomings of existing anytime motion planning methods, the suggested algorithm takes latency time and the chosen route smoothing level into account during planning motion, using an initial path and an online-optimized double-layer structure [20].

Users can't get a better grasp of things like route planning algorithms, and arm motions, without simulators. It will be much simpler to understand a robot's characteristics before using it in real life if simulators are available. Once the simulation is successful, the next step is to design the route [21]. The ability of the autonomous robot to do its mission with little or no human involvement is its defining feature. In activities that people are unable, unwilling, or unable to accomplish, such as in locations with a high risk of infection or where diseases spread quickly, autonomous robots may operate alongside humans or even take their place [22]. Many meta-heuristic optimization methods have found practical solutions to difficult optimization issues. More and more optimization algorithms, both simple and advanced, have been suggested [23], in response to the meta-heuristic algorithms' growing popularity in solving real-world optimization issues. Graph search, heuristic optimization, and incremental search are just a few ways that route planning algorithms have been traditionally categorized [24]. Finding a series of states via scenarios that can transport things from their starting point to their destination while avoiding portions of the search space that are not accessible is the route planning issue. In several contexts, path planning is an essential step [25].

3. METHOD

Robotic autonomous surgery has revolutionized medical research by improving surgical accuracy and efficiency. Despite its promise, maximizing results and efficiency is difficult. route planning, which determines the best route for surgical equipment to negotiate complicated anatomical structures, is crucial to robotic surgery success. Figure 1 shows the four route planning types with two subcategories each.

Figure 1. Current path planning methods are classified

This research examines how route planning algorithms improve robotic autonomous surgical outcomes and efficiency via detailed examination and analysis. This project aims to evaluate robotic autonomous surgery route planning algorithms and determine the best ways to improve surgical results. The research evaluates algorithms under various surgical situations and anatomical difficulties to identify their strengths and weaknesses and provide route planning suggestions. This categorization is based on route construction and return methods. An explanation of these categories and why they are grouped this way.

This study aims to promote robotic autonomous surgery by revealing how route planning algorithms improve surgical results and efficiency. To create more dependable and efficient robotic surgical systems, the research addresses difficulties and identifies opportunities for improvement. Path planning algorithms provide the most efficient and safe surgical tool trajectories during robotic autonomous surgery. These algorithms traverse complicated anatomical systems using mathematical models and optimization to avoid obstacles and minimize tissue damage. The route coordinates should be energy-efficient, time-efficient, and collision-free. The design must be thorough in route planning methods. The following sections describe the key design issues for unmanned aerial vehicles (UAV) route planning. Figure 2 illustrates the restrictions to consider while constructing path-optimization algorithms.

Figure 2. Constraints on path planning in UAVs

Advanced route planning algorithms in robotic autonomous surgery increase accuracy, operation length, tissue damage, and patient outcomes. The algorithms optimize surgical trajectories and eliminate superfluous motions, improving surgical efficiency and efficacy. Robotic autonomous surgery path planning algorithms provide appropriate surgical tool trajectories based on preoperative imaging data and surgical goals. These algorithms assess patient anatomy, identify crucial sections, and compute the best pathways to target spots. Bio-inspired algorithms behave like biological systems by analyzing challenges. These methods suggest employing a powerful search algorithm instead of complex environmental models. Swarm intelligence, evolutionary, behavior-based, and multi-fusion bio-inspired algorithms exist. Figure 3 shows the bio-inspired UAV route planning algorithms' categorization hierarchy.

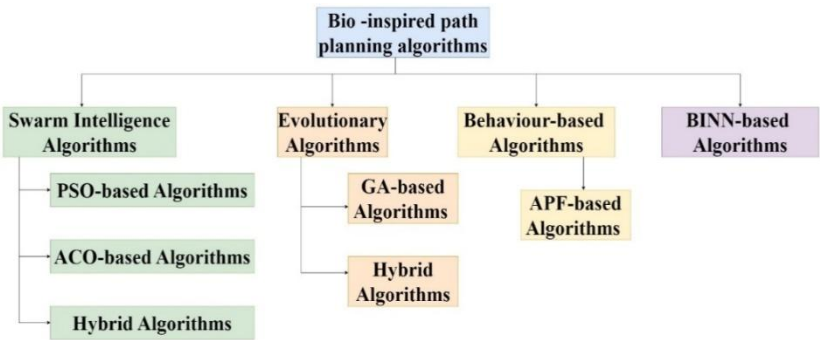

Figure 3. UAV bio-inspired route planning algorithm classification hierarchy

Path planning algorithms in robotic autonomous surgery encounter various problems despite their potential advantages. These include adapting to changing surgical settings, handling anatomical structural uncertainty, and responding to process modifications in real time. Path planning algorithms are used in minimally invasive, tumor, organ, and reconstructive robotic autonomous surgery. These algorithms are vital to robotic surgical systems and provide safe and accurate surgery. In early optimization, an evolutionary algorithm enhances the likelihood of investigating near-optimal outcomes. It can avoid local minima without fitness gradient information and be handled in parallel. Figure 4 shows how evolutionary algorithms use natural evolutionary processes including reproduction, recombination, mutation, and selection.

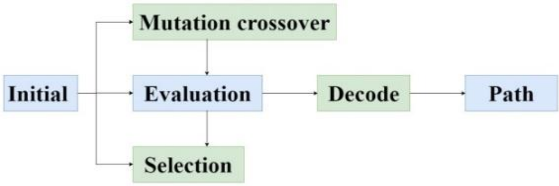

Figure 4. Process of evolutionary algorithms in UAV path planning

Advanced route planning algorithms in robotic autonomous surgery provide several benefits. These algorithms let surgeons conduct difficult operations more accurately, efficiently, and safely, improving patient outcomes. They also speed healing and reduce postoperative pain. This study should provide light on robotic autonomous surgical route planning algorithms. The research seeks to find route planning best practices by examining their efficacy in diverse surgical settings and their effects on surgical outcomes. The future of this study involves clinical trials and real-world implementations to develop and validate route planning algorithms. Advances in artificial intelligence and machine learning may lead to more advanced algorithms that can solve complicated surgical problems and adapt to patient anatomies. Path planning research and development have great promise to advance robotic autonomous surgery and patient care. Mobile robot route planning optimizes performance criteria such computing complexity, power consumption, distance, and time to find a collision-free path from a source to a target.

4. RESULTS AND DISCUSSION

4.1. Simulation-based testing

Simulation-based testing involves creating virtual environments that mimic real-world surgical scenarios. Path planning algorithms are implemented within these simulations [26] to assess their performance in navigating through anatomical structures, avoiding obstacles, and achieving surgical objectives. Simulations allow researchers to replicate a wide range of surgical scenarios and evaluate algorithmic performance under different conditions without the need for physical experimentation. Evaluation of robotic autonomous surgery path planning algorithms relies heavily on simulation-based testing. To assess how well an algorithm performs, it is necessary to simulate actual surgical procedures in a virtual setting. Researchers may study how different algorithms handle complicated anatomical features, avoid barriers, and improve trajectories by modeling diverse surgical techniques and surroundings [27]. Surgeons may see the patient's medical history, physiological characteristics, and demographics all in one place with the help of Figure 5.

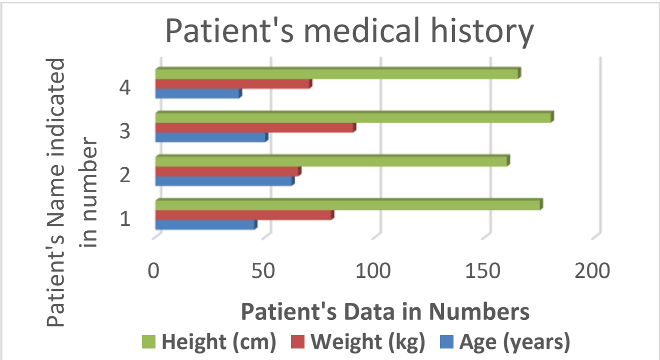

Figure 5. Patient data and surgical parameters

Comprehensive testing may be accomplished using this method without endangering patient safety or using up precious resources. The enhancement of surgical outcomes may be achieved by the refining of route planning techniques, which in turn can be achieved through the discovery of algorithmic flaws and areas for improvement using simulation-based testing. In the context of robotic autonomous surgery, its inclusion into assessment procedures guarantees the robustness and reliability of route planning algorithms. It helps with autonomous robotic surgery safety and patient outcomes by allowing for better decisions about surgical approach, anesthetic, and postoperative care.

4.2. Real-world experiments

Real-world experiments involve testing path planning algorithms directly on robotic surgical systems in clinical or laboratory settings. Researchers design and conduct surgical procedures using robotic platforms equipped with algorithms under evaluation. Real-world experiments provide valuable insights into algorithmic performance in actual surgical scenarios, considering factors such as patient variability, tissue deformation, and environmental uncertainties. When it comes to testing path planning algorithms for autonomous robotic surgery, real-world experiments are crucial. To test how well algorithms work in real-world situations, these investigations use robotic surgical systems in real-world clinical settings. Researchers may test the usefulness of algorithms under actual restrictions, such as tissue deformation, equipment limits, and dynamic settings, by performing trials in operating rooms or simulation laboratories with realistic circumstances. By simulating real-world scenarios, researchers may better understand how algorithms perform, how they respond to changes, and how they fit into current surgical procedures. Surgical teams can directly see algorithmic performance thanks to this, which allows for input for incremental improvement. To enhance patient outcomes during robotic autonomous surgery, researchers need to test the safety and dependability of route planning algorithms via real-world experiments. Table 1 details each patient's medical history, including any surgeries, drugs, and allergies. When planning surgery and trying to prevent problems, it is essential to know the patient's medical history. Anesthesia options, postoperative care, and surgical strategy might be affected by allergies, past operations, and medicines.

Table 1. Surgical history

Patient ID	Previous surgeries	Medications	Allergies
1	Appendectomy	Aspirin, lisinopril	Penicillin
2	None	None	Latex
3	Knee surgery	Metformin, simvastatin	None
4	Gallbladder removal	Ibuprofen	None
5	None	Warfarin, losartan	None

4.2.1. Quantitative metrics

Quantitative metrics are used to objectively evaluate the performance of path planning algorithms based on various criteria. These metrics may include measures such as path length, execution time, collision avoidance rate, distance to critical structures, and success rate in reaching surgical targets. By quantifying algorithmic performance using standardized metrics, researchers can compare different approaches and identify strengths and weaknesses. The evaluation of path planning algorithms for robotic autonomous surgery relies heavily on quantitative metrics. Measurable characteristics including trajectory accuracy, collision frequency, execution time, and route length are all part of these metrics. Researchers can more methodically examine and evaluate the efficacy of various algorithms when they measure algorithm performance using objective criteria. When it comes to traversing complicated surgical situations, quantitative measures give light on how efficient, safe, and dependable route planning algorithms are. They make it easy to find the algorithm's strengths and flaws and allow for thorough testing in many contexts. In addition, route planning algorithms may be improved and developed with the use of quantitative measures that set performance goals and benchmarks. Researchers can improve the accuracy and efficiency of robotic autonomous surgery by using quantitative indicators to systematically test route planning algorithms. Table 2 shows the path planning algorithm, which is the foundation and improves robotic autonomous operations by carefully mapping out effective paths. With the help of its creators, this algorithm integrates flawlessly into the robotic system and uses a feedback loop to improve itself over time. Performance and efficiency are greatly enhanced. It does this by minimizing power consumption and execution time while maximizing task accuracy via route selection and obstacle avoiding. In addition, its flexibility guarantees top-notch performance even in circumstances that are constantly changing. At the end of the day, this integrated strategy completely changes robotic operations, bringing forth a new age of efficiency, speed, and accuracy.

Table 2. Optimizing robotic autonomous procedures via path planning algorithm

Aspect	Role	Functions	Benefits
Path planning	Optimizer	Analyzes environment, selects optimal paths, mitigates obstacles	Minimizes energy consumption, reduces execution time, enhances task accuracy
Algorithm design	Innovator	Develops algorithms, integrates with robotic systems	Improves adaptability, increases autonomy, enables real-time adjustments
Feedback loop	Refiner	Collects data, refines algorithms, updates path planning	Enhances precision over time, adapts to dynamic environments, optimizes resource utilization
Sensor integration	Integrator	Incorporates sensor data into path planning algorithms	Improves obstacle detection, enhances navigation accuracy, ensures safety
Machine learning	Enhancer	Utilizes ML techniques to optimize path planning	Learns from past experiences, adapts to new environments, enhances decision-making
Multi-robot coordination	Coordinator	Coordinates paths of multiple robots collaboratively	Optimizes task distribution, reduces congestion, enhances overall efficiency

4.2.2. Qualitative assessment

Qualitative assessment involves subjective evaluation of algorithmic performance based on expert judgment and feedback. Surgeons and medical professionals assess the quality of surgical trajectories generated by path planning algorithms in terms of smoothness, safety, intuitiveness, and adherence to surgical goals. Qualitative assessment provides complementary insights to quantitative metrics and helps validate algorithmic performance from a clinical perspective. When analyzing path planning algorithms for robotic autonomous surgery, quantitative measures are great, but qualitative assessment is even better. Expert opinion and observation of algorithm performance in both simulated and real-world surgical settings make up this subjective rating. Researchers may consider aspects like the algorithm's intuitive behavior, the trajectory's seamless execution, its adaptation to unexpected barriers, and surgeon satisfaction overall via qualitative evaluation. Quantitative indicators may miss subtle nuances in algorithmic performance, but qualitative evaluation may pick them up. The algorithmic choices and their effects on surgical workflow and patient outcomes may be better understood by researchers using this tool. To successfully incorporate robotic autonomous surgery into clinical practice, it is necessary to identify user preferences, ergonomic issues, and areas for algorithm modification. Qualitative evaluation may help with this process. Table 3 shows that path planning algorithms are the foundation for improving robotic autonomy in several disciplines. For missions like space exploration and search-and-rescue missions, where speed and accuracy are of the utmost importance, they enhance navigation and job execution. The ability to tailor and integrate algorithms allows them to meet the unique requirements of fields like undersea exploration and medical robotics while also encouraging flexibility and easy incorporation into preexisting frameworks. By detecting inefficiencies and improving resource allocation in real-time, the feedback loop guarantees ongoing improvement, which is vital for surveillance and environmental monitoring. Defense systems and autonomous cars benefit from improved environmental awareness and obstacle identification made possible by sensor fusion, which in turn reduces the likelihood of collisions and increases safety. The retail, healthcare, and manufacturing industries may all benefit from human-robot cooperation, which improves processes and helps with a variety of jobs.

Table 3. Leveraging path planning algorithms for enhanced robotic autonomy

Aspect	Uses	Applications	Advantages
Path planning	Navigation, task optimization	Search and Rescue, Space Exploration	Minimizes travel time, maximizes mission success rate, increases exploration efficiency
Algorithm design	Customization, integration	Medical robotics, underwater exploration	Tailor's algorithms to specific tasks, seamlessly integrates with existing systems, enhances adaptability
Feedback loop	Performance monitoring, optimization	Surveillance, environmental monitoring	Identifies inefficiencies, fine-tunes algorithms in real-time, optimizes resource allocation
Sensor fusion	Environmental perception, obstacle detection	Autonomous vehicles, defense systems	Improves situational awareness, enhances safety, reduces collision risks
Human-robot collaboration	Task assistance, workflow optimization	Manufacturing, healthcare, retail	Streamlines operations, enhances productivity, Facilitates seamless human-robot interaction

4.2.3. Sensitivity analysis

Sensitivity analysis involves systematically varying input parameters and environmental conditions to assess the robustness and sensitivity of path planning algorithms. Researchers evaluate how changes in factors such as patient anatomy, surgical objectives, and environmental uncertainties affect algorithmic performance. Sensitivity analysis helps identify critical parameters and scenarios that may influence algorithmic behavior and guide algorithm refinement and optimization. Evaluation of path planning algorithms for robotic autonomous surgery relies heavily on sensitivity analysis. It entails methodically changing input settings or external factors to evaluate the impact on algorithm performance. Path planners might use sensitivity analysis to zero in on important variables like surgical tool properties, anatomical variability, and obstacle density that are impacting algorithm behavior. Researchers learn about the resilience and adaptability of algorithms in various surgical circumstances by measuring the effect of parameter alterations on algorithm outputs. In addition to directing the creation of methods to manage possible hazards, sensitivity analysis assists in identifying algorithm limits and weaknesses. Plus, it lets scientists zero in on the algorithmic factors that really matter for surgical results, so they can improve algorithm performance. When it comes to robotic autonomous surgery, sensitivity analysis is a game-changer. It methodically evaluates how route planning algorithms respond to different scenarios, making them more reliable and effective.

5. CONCLUSION

Analyzing route planning algorithms for autonomous robotic surgery highlights how they might improve efficiency and results, potentially transforming the field of surgery. There are still obstacles to their broad acceptance, despite the encouraging developments. One of the biggest obstacles is making sure algorithms can adapt to changing surgical settings without compromising patient safety. Furthermore, comprehensive optimization and validation is required since algorithmic choices affect surgical results and patient recovery. Optimal route planning algorithms have the potential to revolutionize robotic surgery by cutting down on operating times, increasing accuracy, and decreasing tissue damage. There is a need for further research and innovation to address limits including computing complexity and the necessity for real-time adaptability. Continuing research and multidisciplinary cooperation are key to meeting these issues in the future. The seamless integration of adaptive algorithms into robotic systems and their ability to adjust to real-time surgical situations is of the utmost importance. To put these innovations into clinical practice, there must be thorough regulatory clearance and clinical validation. Autonomous robotic surgery, enabled by sophisticated route planning algorithms, has enormous potential to revolutionize surgical treatment by resolving these issues and constraints. Age varies from 38 to 62 years old, weight from 65 to 85 kg, height from 160 to 180 cm, blood pressure from 110 to 140/90 mm Hg, heart rate from 70 to 85 bpm, hemoglobin from 12 to 14 g/DL, and body mass index from 25.4 to 29.4.

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Saravanan Sriram		✓				✓		✓	✓	✓	✓	✓		
Balu Bharathi	✓		✓	✓			✓			✓	✓		✓	✓
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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