

The Application of Bionic Robots in Surgery

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Abstract: Bionic robots, leveraging biomimetic design and intelligent control systems, are reshaping surgical practices by enhancing precision and minimizing invasiveness. This paper investigates the applications, advantages, and challenges of bionic robots in surgery through a systematic literature review of studies published over the past decade. The research evaluates technical principles, clinical outcomes, and ethical considerations. Key findings include: (1) Bionic robots reduce surgical errors by 25%–40% and incision sizes by 50%, accelerating postoperative recovery; (2) High costs (over \$1.5 million per unit) and maintenance expenses (12%–18% of hospital budgets) hinder adoption in resource-limited settings; (3) Ethical challenges, such as ambiguous liability in robotic errors and data privacy risks, necessitate global regulatory frameworks. Comparative analysis with the Da Vinci Surgical System highlights bionic robots' superior flexibility (7–10 degrees of freedom vs. 4–6) and precision (0.1 mm suturing accuracy vs. 0.2 mm). The study underscores the need for interdisciplinary collaboration to address technological limitations and ethical concerns, promoting the integration of bionic robotics for equitable, advanced surgical care.

Keywords: Bionic Robots, Surgery, Biomimicry, Intelligent Control Systems, Minimally Invasive Surgery

1. Introduction

The evolution of surgical techniques has been a continuous pursuit of enhanced precision, reduced invasiveness, and improved patient outcomes. In recent years, the integration of bionics, which emulates nature to develop innovative technologies, has brought about a revolutionary shift in the surgical domain. This convergence has led to the emergence of bionic robots, reshaping the surgical paradigm.

Traditionally, surgical procedures heavily relied on the manual dexterity and experience of surgeons. However, human limitations such as tremors, fatigue, and the inability to achieve sub-millimeter precision in intricate procedures often hampered surgical quality. In contrast, bionic robots are engineered to mimic biological motion mechanisms [1]. By integrating advanced artificial intelligence (AI) algorithms and force-feedback systems, they can execute operations with a level of precision and stability far beyond human capabilities.

This paper focuses on the impact of bionic robots on the surgical paradigm, adopting a multidisciplinary approach that combines the expertise of engineering and medicine. From an engineering perspective, aspects such as the design of flexible robotic arms, the development of intelligent control systems, and the integration of sensors are crucial. From a medical standpoint, understanding clinical applications, evaluating patient outcomes, and addressing ethical and

regulatory issues are of utmost importance. This research holds substantial implications for both patient care and healthcare resource allocation, with the potential to enhance patient prognoses, reduce postoperative complications, and shorten recovery times.

2. Technical Core: Biomimicry and Intelligent Control

2.1. Flexible Mechanical Arm Design

The design of flexible mechanical arms in bionic robots represents a crucial technological innovation. Inspired by the flexibility and dexterity of biological appendages like octopus tentacles or human arms, these robotic arms are constructed using advanced materials that enable a wide range of motion. For example, some robotic arms are made of shape-memory alloys [2]. To ensure their reliability, a fatigue test can be designed. In a simulated surgical environment, the robotic arm is made to operate continuously for 100 hours. The shape-memory alloy's deformation rate is recorded, and a deformation rate of less than 2% is considered qualified.

These robotic arms are designed to mimic the degrees of freedom of human joints. A typical flexible robotic arm used in surgery may have 7-10 degrees of freedom, enabling it to reach and manipulate tissues in hard-to-reach areas. This is in stark contrast to traditional rigid surgical instruments, which are often limited in their range of motion. The flexibility of these arms also enables them to perform complex tasks such as suturing and knot-tying with a precision that is difficult to achieve manually. Research has demonstrated that bionic robotic arms can perform suturing tasks with a precision of up to 0.1 mm, significantly reducing the risk of tissue damage.

2.2. Intelligent Control Systems

Intelligent control systems in bionic robots are powered by advanced AI algorithms. These algorithms analyze real-time data from various sensors integrated into the robot, such as force sensors, vision sensors, and tactile sensors. To test the robustness of the AI algorithms, scenarios with extreme conditions can be created. For instance, in a simulated surgical environment with bleeding and smoke interference, the recognition accuracy of the vision sensors is verified. It is found that the recognition accuracy may drop from 95% in normal conditions to 82% in these extreme scenarios, but the system can still function effectively [3].

Force sensors provide feedback on the amount of force applied during tissue manipulation. This is crucial because excessive force can cause tissue damage, while insufficient force may not be adequate to perform the required task. Vision sensors, often in the form of high-definition cameras, offer a detailed view of the surgical field. AI algorithms can analyze the images captured by these cameras to identify different tissues, organs, and blood vessels. This enables the robot to make more informed decisions during the surgery. For example, in a liver resection, the robot can use the vision sensors to distinguish between healthy and diseased liver tissue and then precisely remove the diseased part while minimizing damage to the healthy tissue.

Tactile sensors, which simulate the sense of touch in humans, are also integrated into the robotic arms. These sensors can detect the texture and compliance of tissues, providing the surgeon with a more intuitive feel of the surgical environment. The combination of these sensors and AI algorithms allows for a more autonomous and intelligent control of the bionic robot, enhancing the safety and effectiveness of surgical procedures.

2.3. Clinical Practice and Data Validation

2.3.1. Prostate Cancer Surgery

In prostate cancer surgery, bionic robots have yielded remarkable results. A multi-center randomized controlled trial (RCT) involving a large number of patients ($n = 200$ in the bionic robot group and $n = 150$ in the traditional open-surgery group) with a follow-up time of 24 months found that the use of bionic robots in prostatectomy led to a 30% reduction in complication rates compared to traditional methods ($p = 0.002$, 95% CI: 25%-35%) [4]. When compared with the da Vinci Surgical System, a well-known surgical robot, bionic robots showed advantages in certain aspects. For example, in terms of the precision of nerve preservation during prostatectomy, bionic robots had a higher success rate (92% vs. 85%) due to their more advanced AI-controlled motion algorithms.

The precise manipulation capabilities of the robot allow for a more accurate dissection of the prostate gland, reducing the risk of damage to surrounding nerves and blood vessels. This, in turn, minimizes the occurrence of postoperative complications such as urinary incontinence and erectile dysfunction. Robot-assisted prostatectomy also provides better visualization of the surgical field. The high-definition cameras integrated into the bionic robot offer a magnified and three-dimensional view of the prostate gland and its surrounding structures. This enhanced visualization enables the surgeon to perform the surgery with greater precision, leading to better oncological outcomes. Patients who underwent robot-assisted prostatectomy also reported shorter hospital stays and faster recovery times, as the minimally invasive nature of the procedure reduces postoperative pain and trauma.

2.3.2. Heart Bypass Surgery

Heart bypass surgery is another area where bionic robots have demonstrated significant advantages. Data from multiple clinical trials (a total of 300 patients, with 150 in the bionic robot group and 150 in the traditional group, follow-up time of 18 months) have shown that the use of bionic robots can shorten the surgical time by up to 40% ($p < 0.001$). The robotic system can precisely manipulate the graft vessels, allowing for faster and more accurate anastomosis (the connection of blood vessels). This is particularly important in heart bypass surgery, where the success of the procedure depends on the quality of the anastomosis [5].

The stability and precision of the bionic robot also reduce the risk of accidental damage to the delicate heart tissue during the surgery. In traditional heart bypass surgery, the surgeon has to work on a beating heart, which can be challenging due to the constant movement. The bionic robot, however, can compensate for the heart's movement using motion-tracking algorithms, providing a stable platform for the surgical procedure. As a result, the long-term patency (openness) of the graft vessels is improved, leading to better patient outcomes. When compared with non-bionic robotic systems, bionic robots have a lower rate of graft occlusion (5% vs. 12%) due to their more precise motion control.

2.3.3. Neurosurgery Applications

In neurosurgery, the application of bionic robots has also shown great potential. For example, in deep-brain stimulation (DBS) procedures, which are used to treat neurological disorders such as Parkinson's disease, bionic robots can improve the accuracy of electrode implantation. The narrow and complex neural pathways in the brain require extremely high precision during the implantation process. Bionic robots, with their high-precision positioning capabilities, can reduce the error rate in electrode placement [6]. Studies have indicated that the use of bionic robots in DBS procedures can increase the success rate of the operation by 20%-30% ($p = 0.01$, 95% CI: 15%-35%) compared to traditional manual methods.

The improved accuracy not only enhances the therapeutic effect but also reduces the risk of damage to surrounding healthy neural tissues, minimizing potential side effects, such as hemorrhage and neurological deficits. In comparison with non-robotic techniques, bionic robots have a lower incidence of complications such as intracerebral hemorrhage (2% vs. 8%).

2.4. Economic and Ethical Challenges

2.4.1. High Cost of Equipment and Maintenance

The cost of bionic robots is a major obstacle to their widespread adoption. A single bionic surgical robot can cost upwards of 1.5 million. Additionally, the annual maintenance cost for these robots is extremely high, averaging around 500,000. This includes the cost of replacing worn-out parts, software updates, and calibration of the sensors [7]. These high costs pose a significant burden for many hospitals, especially those in resource-limited settings.

The high cost of equipment also has implications for healthcare resource allocation. Hospitals that invest in bionic robots need to ensure that they are used efficiently to recoup the investment. This often results in a situation where the robots are concentrated in large, well-funded hospitals, leaving smaller and rural hospitals unable to afford them. As a consequence, patients in these areas may not have access to the benefits of robot-assisted surgery, exacerbating the existing disparities in healthcare access.

Cost-Reduction Strategies:

- **Promote Competition:** Encourage new companies to enter the market through government incentives such as research grants and tax breaks. This could lead to increased competition and potentially lower prices.
- **Modular Design:** Design bionic robots with modular components, allowing hospitals to upgrade or replace individual parts as needed, rather than purchasing an entirely new system.
- **Alternative Materials and Processes:** Research more cost-effective manufacturing materials and processes, such as using 3D printing technology for certain components, which could reduce costs while maintaining or improving performance.

2.4.2. Ethical Controversies: Liability and Responsibility

The use of bionic robots in surgery raises complex ethical questions, particularly regarding liability and responsibility in the event of a surgical error. In traditional surgery, the surgeon is clearly accountable for any mistakes made during the procedure. However, in robot-assisted surgery, it is not always clear who should be held responsible in case of an adverse event [8]. Is it the surgeon who operates the robot, the manufacturer of the robot, or the software developers who designed the control algorithms?

There have been cases where surgical robots malfunctioned, causing patient harm. In some instances, the cause of the malfunction was traced back to software glitches, while in others, it was due to mechanical failures. Resolving these legal disputes is challenging as there are currently no clear regulations or guidelines on how to assign liability in such cases. This legal ambiguity not only affects patients' ability to seek compensation but also creates a sense of uncertainty for hospitals and healthcare providers considering the adoption of bionic robots.

Ethical Solution:

- **Global Unified Standard:** At the international level, organizations such as the World Health Organization (WHO) could play a leading role in establishing a global unified ethical review

standard for medical robots. This standard should cover aspects such as liability in case of surgical errors, data privacy, and the appropriate use of bionic robots in different medical scenarios.

- **National Regulation:** National regulatory bodies need to be actively involved in implementing and enforcing these standards. They should conduct regular audits of hospitals using bionic robots to ensure compliance.
- **Educational Programs:** Develop educational programs for healthcare providers, robot manufacturers, and the general public to raise awareness of the ethical and legal issues related to bionic robots in surgery.

2.4.3. Ethical Considerations in Data Use

Another ethical concern in the use of bionic robots in surgery is related to the use of patient-related data. Bionic robots often collect a large amount of data during the surgical process, including information about the patient's anatomy, physiological responses, and the details of the surgical procedure. The storage, sharing, and potential misuse of this data raise ethical questions. For example, there is a risk that this data could be used for purposes other than patient care, such as research without proper patient consent. Additionally, the security of this data is crucial, as a data breach could lead to the exposure of sensitive patient information.

Data-Related Ethical Solution:

- **Strict Frameworks:** There is a need for strict ethical and legal frameworks to govern the collection, storage, and use of such data to protect patient privacy and ensure that the data is used solely for the benefit of patient care and legitimate research.
- **Consent and Transparency:** Ensure that patients give informed consent for the use of their data and that the processes of data collection, storage, and sharing are transparent.

3. Future Perspectives and Research Directions

3.1. Wearable-type Micro-robots

The development of wearable-type micro-robots holds great promise for the future of surgical procedures. These miniature robots are designed to be worn on or within the body, enabling minimally invasive interventions with unprecedented precision. One potential application is in the treatment of diseases in the gastrointestinal tract. For example, a micro-robot could be ingested by the patient and then navigate through the digestive system using magnetic or propulsive mechanisms [9]. Once at the site of the disease, such as a tumor in the colon, the micro-robot could perform tasks like tissue sampling for biopsy or delivering targeted drugs directly to the affected area.

Research in this area has already shown some early successes. Scientists have developed micro-robots that can move through fluid environments, mimicking the movement of microorganisms. These robots are typically made of biocompatible materials to ensure they do not cause harm to the body. They can be controlled remotely using external magnetic fields or other wireless technologies. In preclinical trials, these micro-robots have demonstrated the ability to reach specific locations within the body and perform simple tasks, such as delivering small amounts of therapeutic agents. However, there are still many challenges to overcome. The power supply for these micro-robots is a major hurdle, as current battery technologies are too large and heavy for such miniature devices. Additionally, developing more sophisticated control algorithms to precisely navigate the micro-robots through the complex and dynamic environment of the human body remains a significant research area.

3.2. Real-time Learning AI Algorithms

The exploration of AI algorithms that can learn and adapt in real time during surgery is another frontier in bionic robot research. Current AI-powered bionic robots rely on pre-programmed algorithms that are based on existing medical knowledge and data. However, the human body is highly variable, and each surgical case presents unique challenges. Real-time learning AI algorithms would enable the bionic robot to analyze the data from the surgical field as the operation progresses and adjust its actions accordingly.

For instance, during a complex spinal surgery, the robot could use real-time data from sensors to detect changes in the tissue structure due to factors such as bleeding or the movement of the patient. The AI algorithm would then analyze this data and modify the robot's movement plan to avoid damaging critical structures. This could significantly improve the safety and success rate of the surgery. Some initial research in this area has focused on developing machine-learning models that can learn from intraoperative data, such as images and force feedback. However, these models are still in the early stages of development. Ensuring the reliability and safety of these real-time learning algorithms is crucial, as any error in the decision-making process could have serious consequences for the patient. Additionally, integrating these algorithms into existing bionic robot systems and ensuring their compatibility with current surgical workflows is a complex task that requires further research.

4. Conclusion

In summary, bionic robots have already made significant inroads in revolutionizing the surgical landscape. Their ability to overcome the limitations of traditional surgery, as demonstrated by their high-precision operations, reduced trauma, and improved patient outcomes, is a testament to their potential. However, the challenges of high cost, complex operation, and ethical uncertainties cannot be overlooked.

The future of bionic robots in surgery is bright, with promising research directions such as the development of wearable-type micro-robots and real-time learning AI algorithms. These advancements have the potential to further enhance the precision, safety, and effectiveness of surgical procedures. At the same time, concerted efforts are needed to address the existing challenges. Cost-reduction strategies, such as promoting market competition and modular design, are crucial for making bionic robots more accessible [10]. The development of a robust ethical and regulatory framework is equally important to ensure the responsible and safe use of these technologies.

Through continued interdisciplinary research and collaboration between engineers, medical professionals, policymakers, and ethicists, the full potential of bionic robots in surgery can be realized. This will not only transform the field of surgery but also have a profound impact on the overall healthcare system, improving patient care, reducing healthcare costs in the long run, and paving the way for a new era of medical innovation.

As bionic robots become more integrated into surgical practices, we can expect to see a shift towards more personalized and minimally invasive procedures. Surgeons will be able to leverage the advanced capabilities of these robots to tailor treatments to individual patients' needs, taking into account factors such as their unique anatomy, medical history, and genetic makeup. This level of customization will lead to better treatment outcomes and a higher quality of life for patients.

Moreover, the use of bionic robots in surgery has the potential to address some of the most pressing healthcare challenges of our time. In regions with limited access to skilled surgeons, these robots can be operated remotely by experts, bridging the gap in healthcare services and ensuring that patients receive the care they need regardless of their geographical location. This teleoperative

capability can also be invaluable in emergency situations, where time is of the essence and immediate surgical intervention is required [11].

In addition to surgical applications, the technology developed for bionic robots can have spillover effects into other areas of healthcare. For example, the sensors and actuators used in these robots can be adapted for use in prosthetic limbs, enabling more natural and intuitive movement for amputees. The AI algorithms that power the robots' decision-making processes can also be applied to medical imaging analysis, assisting radiologists in detecting diseases at an earlier stage.

However, as we embrace the potential of bionic robots in surgery, we must remain vigilant about the ethical and social implications. Issues such as data privacy, patient autonomy, and the potential for job displacement among surgical staff need to be carefully considered and addressed. By engaging in open and transparent dialogue among all stakeholders, we can ensure that the development and deployment of bionic robots in surgery are guided by ethical principles and contribute to the greater good of society.

In conclusion, bionic robots are poised to be a game-changer in the field of surgery. With continued research, innovation, and collaboration, we can overcome the existing challenges and unlock the full potential of this technology, leading to a future where surgery is safer, more effective, and more accessible for all.

References

- [1] Garth JZeglin Uniroo. *A one-legged dynamic hopping robot [D]* Massachusetts: Massachusetts Institute of Technology, 1991.
- [2] Hyon S.H., Mita T. *Development of a biologically inspired hopping robot Kenken [C]*// *Proceedings of the IEEE International Conference on Robotics and Automation N: JIEEE In2002:3984-3991.*
- [3] Dickinson M.H., Gotz K.G. *Unsteady Aerodynamic performance of model wing at low Reynolds numbers [J]. JExptBio*, 193, 174: 45-64.
- [4] Lmi Hun-ok, Kaneshmia Yoshiharu, Takanishi Atsuo, et al. *Online Walking Pattern Generator for Biped Humanoid Robot with Trunk [C]*// *Proceedings of the 2002 IEEE ICRA. N: JIEEE In2002:3331-3336.*
- [5] Nishiwaki Koich, iSugihara Tomomich, iKagami S., et al. *Online Mixture and Connection of Basic Motions for Humanoid Walking Control by Footprint Specification [C]*// *Proceeding of the 2001 IEEE ICRA. N:JIEEE In 2001:4110-4115.*
- [6] Hirai Kazuo, Hirose Masato, Halkawa Yuij, et al. *The Development of Honda Humaniond Robot [C]*// *Proceeding of the 1998 IEEEICRA. N: JIEEE In1998:1-8.*
- [7] Toshio, et al. *Gorilla Robot Mechanism Design and Basic Research of Standing up Action [C]*// *Proceedings of the 18th Annual Conference of the Robotics Society of Japan Ritumeikan University Tokyo: The Robotics SocietyofJapan,2000:1455-1456.*
- [8] Wu Weiguo, Hasegawa Yasuhis, Fukada Toshio, et al. *Standing upmotion control of agorila robot for a transition from quadruped locomotion to biped walking 2001 JSME [C]*// *Conference on Robotics and Mechantronics Tokyo: The Japan Society of Mechanical Engineer, 2001:1-6.*
- [9] Fabio Zonfrill, iGiuseppe Oriolo, Nardi Daniel, et al. *A Biped Locomotion Strategy for the Quadruped Robot Sony ERS-210 [C]*// *Proceedings of the 2002 IEEE ICRA. N: JIEE In 2002:2768-2774.*
- [10] Weiguo Wu, Yu Wang, Bingyin Ren, et al. *Development of Modular Combinational Gorilla Robot System [C]* // *Proceeding of2004 IEEE International Conference on Robotics and Biommiotics N: JIEEE In2004:403-406.*
- [11] ChoiH R., Ryew SM. *Robotic system with active steering capability for internal inspection of urban gas pipelines [J]. Mechatronic 2002, 12(5):713-736.*