Current Perspective on Different Bionic Robots in Medical Field

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Abstract. Bionic robots provide new avenues and possibilities for solving various engineering and scientific problems by mimicking the structure and functionality of biological organisms. Today's bionic robots can not only mimic the movement patterns of animals but also achieve more complex functions, such as entering the human body to diagnose symptoms.This paper introduces the importance of bionic robots in the field of medicine and their related applications. Firstly, the paper defines bionic robots and emphasizes their interdisciplinary nature, highlighting their role in driving innovation and development in medicine. It then analyzes the applications of two main types of bionic robots in medicine: multi-joint rigid-body bionic robots and soft-bodied bionic robots. Using examples such as the Da Vinci surgical robot and soft-bodied bionic robots, it details their principles, design characteristics, and application cases in medicine. The paper also discusses the advantages and limitations of these robots, such as the high precision and minimally invasive advantages of the Da Vinci surgical robot, but also the issues of high learning costs and expensive equipment. Finally, it introduces the frontier of rehabilitation robots, emphasizing their important role in helping patients recover. In conclusion, this review comprehensively elaborates on the basic theories and specific application cases of biomimetic robots in the medical field, providing important references for further research and application in this field.

Keywords: Bionic robotics; surgery robot; rehabilitation devices.

1. Introduction

Bionic robots are a type of robot that takes the natural biological organisms as prototypes and is designed by simulating the behaviors, structures, and movement modes of biological organisms. The design and manufacture of bionic robots require the integration of knowledge from multiple fields such as biology, mechanical engineering, electronic engineering, computer science, and artificial intelligence, making it a highly interdisciplinary subject. The development of bionic robotics technology also promotes the innovation and development in fields such as robotics, bionic medicine, search and rescue, etc. Bionic robots have wide application prospects in the medical field. They can simulate the structure and function of the human body, providing valuable tools for medical personnel, and can simulate and practice high-precision operations. In addition, bionic robots can be used in many fields such as medical assistance, surgery, rehabilitation, etc.

The research on bionics has always been multifaceted, that is, it has been necessary to develop both robots imitating humans and machinery imitating other living beings. Robots that mimic the human body mainly imitate the human torso as well as behaviour, giving them the ability to perform human tasks. And there have been many successful cases of application in the field of medicine. For example, in 1996, the first generation of Da Vinci surgical robots was introduced [1]. Its main achievement is to achieve the implementation of the operation without direct contact between the surgeon and the patient, through the three-dimensional vision system and action calibration system operation control, by the robotic arm as well as surgical instruments to simulate the completion of the doctor's technical movements and surgical operations. On the other hand, in bionic medical robots, research on miniaturized simulation of insects, worms [2], jellyfish [3], and other small organisms is also receiving increasing attention with its development. In particular, soft robotic systems, a relatively recent development, consist of pliable materials capable of undergoing significant deformation with minimal pressure, tension or even damage, particularly when navigating confined spaces. Today, there are many successful cases of bionic robots used in the human body as transluminal endoscopic and interventional robots, widely adopted by medical staff for their high intelligence, less trauma, postoperative pain and lack of side effects for patience. And other than just equipped with a endoscopy and diagnose disease through human natural orifices the soft robots are also able to plug in an electric hook, knife, forceps, and other micro surgery tools to carry out minimally invasive operations.

This article will elaborate on the basic theory and specific application cases of bionic robots in the medical field.

2. Related Works

2.1. Several Types of Bionic Robots Applied in Medical Field

2.1.1 Da Vinci robotic surgical system

Surgical robots can accurately perform a variety of surgical operations, such as suturing, cutting, drilling, etc. They can overcome the physiological limitations of human hands and improve surgical accuracy and efficiency. For example, the Da Vinci surgical robot system is widely used in urology, oncology, cardiovascular surgery, and other fields. The Da Vinci surgical robot, which completes surgery with the help of the Da Vinci surgical system, is a typical case of the application of bionic robots in the medical field. The Da Vinci surgical system includes a surgically designed console for the surgeon, a patient-side cart with four interactive robotic arms, a high-performance on-site visual system as Figure 1 shows, and proprietary EndoWrist® instruments as Figure 2 shows [4]. The surgeon can scale, filter, and convert the movement of their hands captured by the console's motion capture system into actual surgical operations on the EndoWrist instruments on the three robotic arms to complete the surgery. The fourth robotic arm, on the other hand, is used to control the camera and adjust the viewing angle to provide real-time, low-latency, high-definition video of the surgeon's operations. Additionally, the 3D endoscope and image processing equipment in the Da Vinci surgical system can magnify images tenfold for the surgeon to view.

Fig. 1 High-performance on-site visual system of Da Vinci surgical system [5]

Fig. 2 The Patient-side cart Da Vinci surgical system [5]

Da Vinci robotic surgery has the following prominent advantages: First, with its ability to control the number and size of incisions to extremely low levels, surgeries can be minimally invasive or even non-invasive, greatly reducing the time needed for wound healing and reducing the hospital stay of patients by about 33%. Furthermore, da Vinci surgery can also reduce the probability of wound infection. Obviously, replacing the surgeon's arms and wrists with robotic arms to control the surgical knife can eliminate hand tremors, accurately and without delay reproduce the movements of the surgeon's hands, and reduce the possibility of surgical accidents. The design of the EndoWrist surgical instruments aims to provide surgeons with flexible and natural operations, as well as a wider range of movements than human hands, enabling surgeons to better perform surgical operations. Moreover, for many invasive surgeries, such as those for treating prostate cancer, most patients choose conservative treatment due to their high risk. The application of da Vinci robots can significantly reduce the risks of such surgeries and provide safer and more reliable surgical options for more patients [4, 6].

Despite the many advantages of Da Vinci surgical robots, their popularity is still hindered by the following disadvantages. First, doctors need time to master this technology and require continuous practice to operate it proficiently. In addition, due to the technological and market monopoly of current manufacturers of surgical robots, the high cost of purchasing, operating, and maintaining surgical robots, with prices exceeding $1 million, makes many small and medium-sized hospitals hesitate. Moreover, the robotic arms are high-value consumables that are temporarily installed on the robot and cannot be used after 10 uses, urgently needing to increase production capacity to reduce prices and promote popularization. Many surgeons find it difficult to operate comfortably because they indirectly operate the surgery through joysticks instead of directly contacting the patient, making it difficult for them to grasp surgical techniques through touch and vision. Finally, there is still a certain number of patients who doubt the reliability of this new technology and have resistance to robots and this indirect form of surgery [6].

While da Vinci surgical robots bring many advantages to humans, they also face some obstacles to promotion and risks of use. With the continuous progress of this technology and its application, it is believed that these challenges and risks will gradually be overcome and resolved.

2.1.2 Soft Bionic Robots

Soft robots are currently a significant focus in the field of biorobotics research. By mimicking numerous soft-bodied animals found in nature, soft robots have achieved remarkable feats. Inspired by octopuses, Laschi C designed artificial muscle actuators based on SMA springs and developed a prototype of a robotic arm [7], Figure 3 shows their design of the muscular hydrostats, in which L represents the longitudinal muscles and the layer where actuators radially arranged, and T locates is representing the transverse muscles. Similarly, inspired by starfish, Mao S designed a starfish-like soft robot using shape memory alloy (SMA) actuators [8], mainly mimicking the pneumatic characteristics of starfish. Compared to traditional hard robots, soft robots are made of soft materials. The deformable properties of these materials, along with their nearly infinite degrees of freedom in deformation motion, make it easy to achieve changes such as stretching, bending, and twisting, as well as adapt well to complex physical environments. For soft-bodied animals, after long-term evolution and natural selection, their nervous system's motor control functions and the skeletal muscle system's motion execution functions are cleverly coordinated to produce flexible, diverse, and agile movements with excellent environmental adaptability [9]. People can utilize these characteristics for tasks such as medical diagnostics within human body fluids or as prosthetic limbs to assist disabled individuals in daily life.

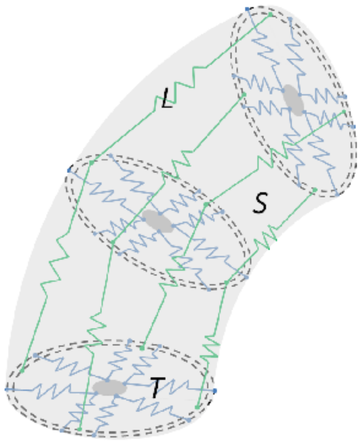

Fig. 3 The design of the artificial muscular hydrostats [7]

Nowadays, soft bionic robots mainly mimic organisms with unique swimming or grasping methods, such as starfish [8], octopuses, and nematodes. In 2011, a jellyfish-imitating robot developed by Virginia Tech in 2011, is very similar to a real jellyfish in both shape and structure [10]. The robojelly uses a BISMAC drive structure, internally consisting of eight strips of shape memory alloy (SMA) and elastic steel plates arranged radially along the umbrella surface, filled and covered with silicone to form an umbrella-shaped structure as shown in Figure 4, with flaps added to the outer edge of the umbrella surface to enhance propulsion. Controlled by the contraction amplitude under the coordination of thermal resistance of SMA, when the contraction amplitude is maximized, it returns to its initial state, completing one cycle. By continuing this process, propulsion is achieved, controlling the bionic jellyfish robot to move forward. Its model simplifies the physical structure of jellyfish into some shape memory alloys, completing the jellyfish's vortex propulsion [11]. Octopuses, as unique soft-bodied animals, have also received favor from many scientists and engineers. The fiber-reinforced actuator (FRA) optimized and designed by Nanjing University of Aeronautics and Astronautics is expected to be applied to bionic flexible limb robots (SRL) [12], inspired by the biological characteristics of octopus tentacles. Octopus tentacles can achieve various forms of movement such as bending, stretching, and twisting, which perfectly meet the driving requirements expected by the bionic limb robot to provide the wearer with expandable extra legs or arms. The team used fiber-reinforced actuators to simulate muscle fiber function and developed a new type of fiber-reinforced actuator to simulate the motion characteristics of octopus tentacles [12]. The actuator is a hollow silicone body surrounded by fiber-reinforced material, which deforms once compressed gas is input. By changing the direction of the fibers, the actuator can achieve different types of deformation, including axial elongation, radial expansion, bending, and twisting, similar to the effects of octopus tentacle muscle fibers.

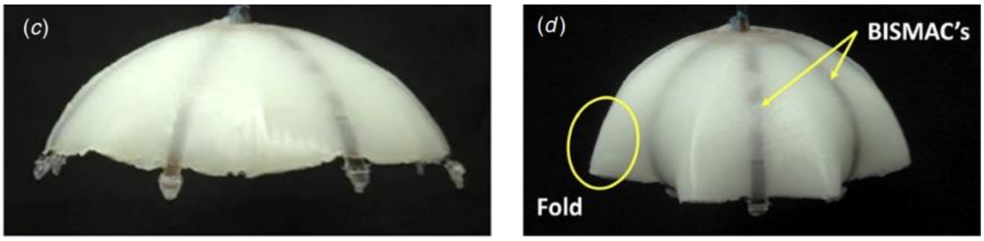

Fig 4. The folding effect and location of BISMAC actuators of the robojelly [10]

2.2. Differences between Different Bionic Robots in Medical Applications

2.2.1 Multi-jointed Hard Body Bionic Robots

Multi-joint rigid body robots, such as bionic mechanical arms, are mainly used in the medical field for the operation end of surgical robots and the external limbs of rehabilitation robots, with the main body undergoing treatment outside the body. Surgical robots assist doctors in completing complex surgeries through minimally invasive surgical procedures using high-definition imaging systems and multi-degree-of-freedom bionic mechanical arms. In 1985, robotics was used for the first time in the United States for surgical procedures, when Los Angeles hospital doctors completed a robot-assisted positioning of a neurosurgical brain biopsy using an industrial robotic arm, the Puma 560 [13]. In the late 1980s, the Stanford Research Institute (SRI) began research and development on surgical robots for field surgery [13]. In 1995, Dr. Frederic Moll, who had worked at SRI, founded Intuitive Surgical with the goal of commercializing surgical robots, and in 1999, the da Vinci surgical robot was launched. In 1998, Computer Motion introduced the Zeus robotic system, and the company merged with Intuitive Surgical in 2003. Da Vinci, as the only surgical robot certified by the FDA, has almost monopolized the global market [4]. Surgical robots perform surgeries for various conditions using a single incision, further reducing patient trauma, with smooth surgeries, precise movements, and good postoperative patient recovery.

2.2.2 Soft-bodied Bionic Robots

Soft robots are applied in medical fluid inspection robots due to their excellent adaptability to complex environments and their deformability [9]. Nematodes and earthworms can move freely in soft, unstructured environments with minimal environmental damage, which is essentially consistent with the medical environment and purpose. In the process of mimicking the traction methods of these types of creatures, researchers have studied different types of actuators, with the main goal of finding a safe, reliable, easy-to-control, and compact actuator. The earliest application of nematode bionic structures was in industrial pipeline robots, which was successful. Although there are some similarities between industrial pipelines and human body cavities, directly applying nematode robots from industrial pipelines to clinical digestive tract detection is impossible. The characteristic of the nematode bionic structure is that there is always one motion unit that is supported on the moving object's surface in some way, and the other units may elongate or shorten along the body longitudinally. Nematode movement is based on the ability to anchor to the surface of the moving object, and without this ability, they cannot move forward. Therefore, the anchoring ability of nematode bionic motion is crucial. In the human body cavity, the intestinal tissue is a soft, easily deformable, and low-friction coefficient viscoelastic biological tissue. If the robot deforms too little, the friction generated is small, and it will slip during movement. If the robot deforms too much, it may exceed the physiological tolerance limit of the digestive tract tissue, potentially causing medical accidents [14]. Researchers have used three methods of supporting anchoring: pneumatic, mechanical, and adsorption. Pneumatic and mechanical methods support the robot on the intestinal wall through changes in the bionic robot structure, which may cause some damage to the intestinal tissue. The adsorption method fixes the robot on the intestinal wall by vacuuming, but due to the influence of intestinal villi, the adsorption force is small and unstable [2]. The special movement environment of the human digestive tract imposes strict restrictions on the size of the driver, with the design goal being small diameter and length. The development of a specific movement mode is still needed for intestinal inspection robots to achieve non-invasive intervention in gastrointestinal examinations, which will facilitate the detection and treatment of intestinal and gastric cancer. Table 1 showed the different bionic robots in medical applications.

Table 1. Different bionic robots in medical applications

Category	**Multi-jointed hard body bionic robots**	**Soft-bodied bionic robots**
Main Application	Surgical robots and rehabilitation robots	Transluminal endoscopic and interventional robots
Challenges	Surgical precision and minimizing trauma	Safe anchoring in soft, low-friction biological tissue
Specific Focus	Minimally invasive surgeries	Safe movement in soft, unstructured environments (like rectum)
Future Goals	Improved surgical precision and patient outcomes	Non-invasive intervention in gastrointestinal examinations

2.3. Introduction to The Frontiers of Bionic Robotic Rehabilitation

In order to help people with paralysis, muscle weakness, and stroke to perform normal daily activities, researchers have designed and developed a number of robotics-based rehabilitation devices, such as orthotics and exoskeletons, to provide motor assistance and aid in rehabilitation. Bionic exoskeletons have seen a number of R&D advances in the field of rehabilitation, such as the Sarcos exoskeleton [15], the MIT exoskeleton [16], used to enhance the strength of healthy people carrying heavy objects. The LOPES exoskeleton [17], which carries the patient's own weight to perform muscle rehabilitation, is used by physical therapists for rehabilitation purposes. The exoskeleton developed by Park integrates four McKibben artificial muscles at the ankle joint and reinforces the foot and calf structure with textiles and carbon fiber [18]. The maximum dorsiflexion at the ankle joint can reach 110 Nm, with a weight of 0.95 kg. The exoskeleton proposed by Wehner et al [19]. uses eight pneumatic actuators and a soft structure with multiple fabrics. The design of the soft structure considers the concept of virtual anchor points. They designed the distribution and position of the fabric to maximize efficiency and comfort [20].

The team at Nanjing University of Aeronautics and Astronautics has designed a fiber-reinforced actuator based on the diverse movements and structural flexibility of octopus tentacles, which has the potential to be applied to flexible limb robots [12]. Traditional rigid limb robots lack flexibility and safety in operation and cannot assist operators in completing complex manipulation tasks. Octopus tentacles can achieve various forms of movement such as bending, expansion, and twisting, which perfectly meet the activity requirements of external limb rehabilitation robots. Therefore, the designed external limb robot will have higher load capacity and working range, helping patients recover better.

3. Discussion

The Da Vinci surgical robot can perform various surgical operations with precision, such as suturing, cutting, and drilling [4]. They can overcome the physiological limitations of human hands, improve surgical accuracy, and efficiency. However, there are several drawbacks to the Da Vinci surgical robot: the high time and cost for doctors to learn the technology, the high cost of the surgical robot and maintenance, the limited usage and high price of the robotic arms, the difficulty for doctors to grasp surgical skills through indirect manipulation, and the skepticism of some patients about the reliability of new technology [6]. The key to popularizing surgical robots is to first reduce costs, improve the safety of surgery, and demonstrate to the public the potential of future robotic surgery.

Soft bionic robots with their deformability and better adaptability to the environment are used by researchers to carry out medical work in the human body, which can do minimally invasive diagnosis or even non-invasive diagnosis, which greatly reduces the hospitalisation time of the patient, and at the same time provides a reliable means of in vivo observation for doctors [2]. At present, the main focus of the soft bionic robot research in their propulsion, visual sensors, force sensors, tactile sensors and other sensors loading method and how to improve the accuracy.

Rehabilitation robots can simulate the movement of human limbs and provide patients with personalised rehabilitation training programmes. These robots can monitor the patient's recovery progress, adjust the intensity of training, and improve the effect of rehabilitation. The assistive rehabilitation bionic robots can help patients with limited mobility to carry out daily activities, such as eating, turning over, moving, etc. These robots can improve patients' self-care and can improve patients' self-care ability and quality of life. The main drawbacks of existing exoskeleton rehabilitation robots are heavy weight, limited torque and power that can be provided to the patient, insufficient mechanical design, and sensors that cannot accurately and quickly collect all the user's intentions. It is not able to follow the correct gait pattern of a normal person.

4. Conclusion

So far, the development status of bionic robots and their applications in the medical field have been discussed for different types and purposes in this review. Regarding surgical robots, the focus has expanded beyond orthopedic and laparoscopic systems to include transluminal endoscopic and interventional robotic systems. These advancements allow for minimally invasive surgery through natural body openings. Additionally, research has led to developments in exoskeletons, prostheses, training robots, and mobile assistive robots. These technologies are particularly beneficial for patients with physical impairments, as they offer intelligent rehabilitation training and personalized assistance in daily activities. In this paper, the author introduced common and currently available bionic medical robots and exoskeleton rehabilitation robots found in the literature. The mechanical design of these devices has been classified based on bionic soft-bodied animals, bionic hard-bodied animals, and rehabilitation robots. According to various applications, various driving modes of the devices have been studied. In addition, some advanced strategies have been mentioned to design bionic robots to adapt to different applications in the medical field. The limitations and improvement scope of currently available bionic medical robots have been studied and discussed. The development stages of available medical robots have been introduced. To improve bionic robots in the medical field, researchers should pay attention to the materials used, driving modes, safety, and cost of the robots.

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