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Overview of Design and Control Technologies for Bionic Prosthetic Hands

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Abstract. The human hand is one of the body's most dexterous organs, profoundly influencing activities of daily living and social participation. Bionic prosthetic hands are a major focus in rehabilitation robotics and can help people with upper-limb disabilities restore hand movement and sensory function. To clarify the development status of bionic prosthetic hand technology, this paper primarily focuses on mechanical design and provides a review of bionic hand design, control, and grasping performance. In terms of structural design, the paper summarizes the design principles of bionic hands based on human anatomical structures and movement mechanisms, along with various methods for driving hand movements; in control, it reviews the application of various sensors and multi-degree-of-freedom controls; regarding grasping, it introduces grasping techniques and adaptive grasping methods. On this basis, the paper analyzes existing shortcomings of bionic hands in dexterity, control stability, sensory feedback, cost management, and durability, and discusses future prospects for lightweight, intelligent, and human-robot integrated development.

Keywords: prosthetic hand, structural design, sensors, grasping, degrees of freedom

1. Introduction

The human hand is essential for precise manipulation and daily activities. Many people worldwide with upper-limb disabilities have lost hand function because of congenital or acquired causes, such as accidents or disease [1]. The loss of hand function directly impacts their work and daily life to varying degrees [1]. Globally, approximately 11.3 million individuals with unilateral upper limb traumatic amputations face significant challenges in performing activities of daily living (ADLs) [2]. Bionic prosthetic hands have become one of the most effective solutions for restoring hand functionality.

The human hand has a sophisticated structure, consisting of 27 bones, 34 muscles, and 22 degrees of freedom, enabling high-precision movements and dexterous operations. In recent years, the development and interdisciplinary integration of robotics, sensing technologies, materials science, and artificial intelligence have propelled bionic hands toward lightweight, intelligent, and multi-degree-of-freedom designs.

This paper reviews the key technologies of bionic prosthetic hands from the perspectives of design, control, grasping, limitations, and future prospects, aiming to provide a reference for related

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research and study.

2. Design of bionic prosthetic hands

2.1. Principles of prosthetic hand design

The human hand is often modeled as an open-chain structure comprising the palm, wrist, and fingers. Each finger except the thumb has three joints: the metacarpophalangeal, proximal interphalangeal, and distal interphalangeal joints. The thumb, on the other hand, moves toward the palm through the carpometacarpal joint. The degrees of freedom of the whole hand determine its movement capabilities and dexterity.

The design of bionic prosthetic hands draws on principles of mechanical, functional, and structural bionics. The core of the design is to recreate the anatomy and movement mechanisms of the human hand in an engineering sense. Structurally, bionic hands arrange the fingers, joints, palm, and wrist according to human proportions to achieve a more realistic shape, and sizes and weight closer to that of a real hand. In terms of movement, reproducing finger coupling and finger-to-palm motions helps make grasping more natural. Functionally, it aims to meet the needs of daily life while balancing dexterity, strength, and speed.

Since the human hand has a lot of degrees of freedom, it's impossible to place enough actuators to achieve the desired flexibility in a bionic hand. This is why underactuated designs have become a key theoretical foundation. Underactuation means using fewer actuators than degrees of freedom, allowing fewer motors to drive multiple joints. By using passive elements like springs, tendons, and differential mechanisms, joints can move in a coupled way and adapt their shape naturally. Underactuation reduces the weight of the hand, simplifies the control system, and—with passive compliance—helps the hand grasp objects flexibly and robustly.

In specific designs, finger lengths, range of motion for each degree of freedom, and the user's grasping needs must be considered to improve realism while meeting market demands. Additionally, the weight distribution should be closer to the forearm or proximal area to reduce inertia when worn, enhancing comfort and stability during use.

2.2. Design methods of simulated hands

The primary driving methods for bionic prosthetic hands include micro servo motors, shape memory alloys (SMAs), and pneumatic artificial muscles. Motor-driven systems offer high stability and well-established control, making them a common solution in commercial prosthetic hands. SMA-driven systems provide high output per unit mass, are easily highly integrated, and facilitate the realization of multi-degree-of-freedom dexterous hands. Micro SMAs combined with tendon-driven passive mechanisms are used to construct multi-degree-of-freedom dexterous hands [3-5].

Regarding transmission mechanisms, tendon-driven transmission mimics human tendons, placing the actuators in the palm or forearm to achieve remote actuation and reduce finger mass, which is the most common driving method for bionic hands [6, 7]. Linkage transmission directly transfers the rotational motion of a motor to the finger joints through rigid rods and link chains. Gear transmission relies on various meshing structures to transmit kinetic energy. Gears, linkages, and four-bar mechanisms offer high rigidity, enabling precise motion trajectories and angular control. These are often combined with tendon drives to form hybrid transmission solutions. For example, the BiDexHand, a tendon-driven bionic hand, uses innovative joint designs to achieve 16

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independent degrees of freedom along with mechanically coupled joints, balancing anthropomorphic dexterity with structural simplicity [6].

In terms of design approaches, four paradigms have emerged in the past five years: integrated additive manufacturing, underactuated simplification, modular open-source, and rigid-soft coupling. The integrated additive manufacturing approach primarily employs multi-material 3D printing, forming structures such as the skeleton, transmission system, actuators, and sensors in a single print, rather than manufacturing them separately. The underactuated approach replaces active adaptation with passive adaptation, enabling a few actuators to drive the entire hand. The modular open-source approach prioritizes reproducibility, iterability, and low cost. The rigid-soft coupling method seeks to combine the advantages of rigid skeletons with those of soft contact surfaces.

Regarding construction materials and manufacturing processes, 3D printing and lightweight plastics are commonly used to accelerate iteration and reduce costs. To enhance strength and rigidity, load-bearing parts of bionic hands often employ nylon-aluminum alloys or carbon fiber, forming rigid-soft composite structures. Modular design separates the fingers, palm, and wrist into independent modules, facilitating repair, replacement, and customized designs, while supporting mass production for cost control and broader application.

The arrangement of actuators in simulated hands affects overall performance; therefore, larger actuators are often placed in the palm or forearm to reduce finger inertia and improve controllability. Micro motors combined with reducers are directly embedded into the fingers, enabling compact and independent actuation for each part.

3. Control methods

3.1. Sensors and their use

In the control system of a bionic hand, sensors play a crucial role in acquiring information about the external environment and the motion of the device itself. According to the type of measured object, they can be classified as: position sensors, force sensors, tactile sensors, attitude sensors, and electromyography (EMG) sensors.

Position sensors are mainly used to detect joint angles and finger movement ranges. Force sensors are primarily used to measure gripping force. Tactile sensors can detect contact location, contact area, and pressure distribution on the contact surface. Attitude sensors are generally part of an inertial measurement unit (IMU), integrating accelerometers and gyroscopes, and are used to detect the overall spatial posture and tilt angles of the prosthetic hand. In dynamic grasping scenarios, they help the control system correct actions when the hand shakes. EMG sensors belong to the category of biosignal sensors and collect surface muscle electrical signals from the residual limb, converting human muscle movement intentions into control commands, serving as the higher-level input source for the prosthetic hand and enabling the user to actively operate it. The coordinated use of various sensors constitutes the prosthetic hand's perception system, providing complete information support for multi-degree-of-freedom coordination.

In prosthetic hands, the role of sensors has evolved from simple signal acquisition to being a key part of the "perception–feedback" closed-loop. Multiple types are used in coordination. They can provide feedback on the contact state of the prosthetic hand to the user or manufacturer, enabling more convenient and natural operation and helping manufacturers produce bionic prosthetic hands better suited to users.

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3.2. Multi-degree-of-freedom control

Multi-degree-of-freedom (DOF) control is the core for achieving coordinated multi-finger movements and human-like grasping in bionic prosthetic hands. Prosthetic hands rely on coordination among multiple joints to perform pinching, enveloping, opposition, and other complex actions. The goal of multi-DOF control is to generate multiple joint movements stably and intuitively from limited input signals. Mechanical structure and control strategies are deeply coupled at this stage, reducing the control burden, which is also why underactuated bionic hands are widely adopted.

In recent years, deep learning has been introduced into electromyography (EMG) decoding and grasping force estimation. For example, improved temporal convolutional networks can map eight-channel EMG signals to finger grasping forces, enabling adaptive grasping of soft objects [8]; convolutional neural networks have also been used for object shape recognition to select grasping modes accordingly [9]. For multi-DOF coordination, researchers have proposed force-position alternating control and impedance control strategies to achieve adaptive grasping of objects with different stiffnesses and shapes [10]; shared control combines human intention with machine autonomous decision-making, allowing embedded proximity and pressure sensors to autonomously achieve minimal-force grasping, significantly reducing the user's burden [11]. Multimodal control further integrates tactile, motion, and EMG information, allowing rapid adjustment of grasping force based on contact states, approaching human-level manipulation [12].

In multi-DOF control, the number of gesture classifications and the switching efficiency are key indicators. A larger number of gesture classes enables richer grasping modes but increases classifier complexity and recognition difficulty, requiring a trade-off between dexterity and reliability [9]. To enhance natural control, studies have also focused on multi-DOF synchronous control mapping—meaning that instead of using discrete gesture switching, EMG features continuously drive multiple joint degrees of freedom, resulting in smooth transitions and movements closer to those of a human hand [9]. The complexity of multi-DOF mechanical systems makes precise movement difficult to maintain. Therefore, DH parameters and URDF models are commonly used for calculation and calibration with the current-torque mechanical structure.

4. Grasping with a bionic prosthetic hand

Grasping is a core function of prosthetic hands and a key criterion for evaluating the performance of bionic prosthetic hands. Based on the shape, size, weight of the object, and task requirements, grasping can be categorized by force application into power grasp, intermediate grasp, and precision grasp. A power grasp primarily involves the palm and multiple fingers enveloping the object; it emphasizes grip strength and stability and is suitable for large and heavy objects. Precision grasp relies on the fingertips and thumb for manipulative movements, focusing on fine dexterous control, suitable for small and delicate objects. Intermediate grasp lies between the other two types. In practical products, various preset grasping modes are generally used to cover daily scenarios. For instance, the commercial OHAND bionic hand features 11 joints and 6 degrees of freedom, enabling it to perform 27 daily grasping actions, ranging from holding a cup or a pen to operating tools, suitable for most everyday situations [8].

Adaptive grasping is a current research focus. Through passive compliance of underactuated structures or active adjustment via sensor feedback, prosthetic hands can automatically conform to the contours of target objects without first recognizing the objects' shape, size, or orientation. This

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enables stable, reliable, and highly fault-tolerant enveloping grasps, significantly enhancing the practical capabilities of prosthetic hands in unstructured environments.

Furthermore, grasping performance is typically evaluated from the perspectives of grasp success rate, force control accuracy, and daily functional assessment. Grasping experimental evaluation indicators can be categorized into four types: motion indicators, mechanical indicators, task success rate indicators, and robustness indicators. Each type of indicator reflects different aspects of the comprehensive operational capability of prosthetic hands.

A prosthetic hand capable of dexterously manipulating various objects integrates cutting-edge advances from engineering, materials science, and biomedical technology into its design and fabrication [13]. Today, as prosthetic hands increasingly replicate the movement characteristics of human fingers, their motion trajectories can more perfectly reproduce the kinematic paths of the users [14]. They can also simulate a variety of actions such as grasping, pinching, and lifting, and exhibit superior dexterity and controllability, enabling users to accomplish various daily tasks and significantly improving their quality of life [13]. Clinically, researchers can now conduct virtual clinical trials, simulate various scenarios, and test the performance of prosthetic hands under multiple conditions [15]. The design of prosthetic hands based on shape memory alloys offers strong scalability, allowing the development of fully functional prosthetic hands [16]. Lightweight and durable materials ensure the comfort and affordability of prosthetic hands while supporting comprehensive functional use. Moreover, the utilization of 3D printing technology reduces the cost of prosthetic hands, promoting their development toward more personalized and customized solutions.

5. Current drawbacks and challenges of bionic hands

Despite significant advances in bionic hand development, bionic hands still differ considerably from natural human hands.

At the mechanical structure level, a fundamental trade-off exists between weight, output force, and size. For sensor systems, integrating high-performance miniaturized sensors is challenging. On the control side, issues mainly revolve around motion intention recognition and multi-degree-of-freedom coordinated control. At the engineering and clinical application level, high-performance prosthetic hands are expensive, and core components like miniature motors and sensors often rely on imports, making widespread adoption difficult.

Additionally, because of the linkage between the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints, large objects may be hard to grasp. Theoretical kinematic models don't account for real-world constraints such as material thickness or extra mounting structures, leading to movement restrictions earlier than expected. Some robotic hands use small servo motors limited by weight and size, so the designed hand can't generate much gripping force. During design, issues such as tendon slack and resistance from elastic gloves still need to be addressed. Finding a balance between flexibility and actuation speed is also tricky. Without superelastic wires, prototypes undergo greater bending, but because shape memory alloys (SMAs) cool slowly by nature, SMA actuators can heat up rapidly during operation, shortening response times; however, the resulting heat accumulation can degrade materials and reduce system efficiency, remaining a significant challenge.

In clinical trials, several limitations remain, including small sample sizes, limited opportunities to evaluate performance over short clinical cycles, a lack of standardized evaluation protocols, and the tendency for trials to be conducted in highly controlled laboratory settings. These make it hard to compare studies and to accurately reflect real user experience. Furthermore, prosthetic hands are

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often abandoned due to comfort, limited functionality, and unattractive appearance, which hinders further improvements.

Although there are many shortcomings, the development and innovative breakthroughs in robotics-related technologies are driving bionic prosthetic hands toward becoming more intelligent and flexible. Future research should include larger and more diverse study populations, explore the scalability of prosthetic hand use, and ensure broader reliability [1]. Attention should also be focused on mechanical optimization, such as improving the range of motion and precision of mechanical fingers, and integrating sensor systems [17]. The design of prosthetic hands based on shape memory alloys can optimize the diameter of superelastic metal wires, achieving greater driving ranges while maintaining retraction efficiency and balancing flexibility and stability [16].

Regarding neural interfaces, brain-computer interface and peripheral nerve interface technologies hold promise for enabling intention-based control, directly decoding motor intentions from the nervous system and eliminating dependence on residual muscles. Reversible implanted electrodes, long-term signal stability, and biocompatibility remain critical challenges to be addressed [11, 18]. In terms of sensory feedback, pressure, temperature, and tactile information can be transmitted back to the nervous system through neural electrical stimulation or mechanical tactile stimulation, creating a perception-control closed loop that can significantly enhance operability and user integration. In intelligent control, artificial intelligence technologies such as reinforcement learning are expected to enable prosthetic hands to autonomously learn new tasks, adapt to different objects, and achieve more natural grasping with lower difficulty [11].

In mechanical design, lightweight dexterous hands driven by SMAs and flexible materials, as well as rigid-flexible coupling and soft structures, will continuously improve wearer comfort and adaptability; 3D printing and modular designs help reduce costs and promote the accessibility of prosthetic hands. Efforts to localize core components will enhance the industry's independent controllability [12]. Limited domestic production of core components such as high-energy-density micromotors and high-precision flexible sensors restricts autonomous control [19]. Engineering issues such as weight, volume, battery life, and durability also require ongoing optimization.

6. Conclusion

This article reviews and organizes the structural design, control methods, and grasping performance of bionic prosthetic hands. At present, design concepts such as under-actuation structures, rigid-flexible coupling, and integrated 3D printing can simplify the mechanical structure of prosthetic hands, reducing weight while improving dexterity. However, achieving an effective balance among balancing weight, output force, and overall dimensions remains challenging. Various sensors paired with multi-degree-of-freedom collaborative control are key to achieving human-like movements in prosthetic hands. By integrating signals such as electromyography, force, and touch, prosthetic hands can recognize users' movement intentions and achieve adaptive grasping. However, EMG signals are easily affected by factors like sweating and muscle fatigue, so real-time control of multiple degrees of freedom still presents many technical challenges.

In terms of grasping performance, adaptive grasping has greatly improved the prosthetic hand's ability to handle various real-world scenarios, yet no widely accepted standardized framework currently exists for evaluating such performance. Overall, bionic prosthetic hands still suffer from issues such as lack of tactile feedback, high cost of core components, insufficient domestic components, and unsatisfactory durability, all of which limit their widespread adoption in real life.

Going forward, relying on neural interfaces, artificial intelligence, flexible materials, and modular processing technologies, bionic prosthetic hands will continue to develop toward lightweight,

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intelligent, and highly integrated human-machine capabilities. Advancing key technologies such as the perception-control closed loop and domestic production of core components can help narrow the performance gap between prosthetic hands and human hands, thereby making high-performance bionic prostheses more accessible to a wider range of users.

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