From Bionics to Precision Mechanical Design: A Study on the Structure and Function of Dexterous Hands in Humanoid Robots

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Abstract. With the rapid advancement of service robots, industrial collaborative robots, and intelligent prosthetic technologies, the dexterous hand of humanoid robots has become a focal point of research. As a key end-effector for humanoid robots to interact with the external environment, the dexterous hand embodies a profound integration of bionics and precision mechanical engineering. This paper begins with an analysis of the human hand's anatomical structure and its implications for dexterous hand design. It then systematically reviews mainstream mechanical design approaches and functional implementation strategies for robotic hands, concluding with a discussion on future development trends.

Keywords: Dexterous Hand, Humanoid Robot, Bionic Technology, Mechanical Engineering.

1. Introduction

Humanoid robots embody the integration of AI and mechanical engineering, with the dexterous hand as a key end-effector for human-robot collaboration, fine manipulation, and intelligent interaction. Unlike traditional grippers, dexterous hands emphasize biomimicry in structure, sensing, and control, inspired by the human hand's high DOF, compliance, and sensory capabilities. Recent advances in precision engineering, materials, and AI have driven their rapid development and application in fields such as rehabilitation, service robotics, rescue, and space. This paper reviews the evolution of dexterous hands, focusing on their bionic foundations, mechanical design, and functional strategies, to inform future end-effector development in humanoid robotics.

2. Anatomical Structure of the Human Hand and Foundations of Bionic Design

2.1. Structural and Functional Analysis of the Human Hand

The human hand is a highly evolved and multifunctional organ, characterized by a complex anatomical structure and refined motor control capabilities. Structurally, the hand consists of 27 bones, including 8 carpal bones, 5 metacarpal bones, and 14 phalanges, forming the wrist, palm, and fingers. In terms of articulation, the hand possesses approximately 29 joints, enabling a wide range of high degrees of freedom in motion—such as flexion, extension, adduction, abduction, and rotation.

A key feature of the human hand is the opposable thumb, which, due to its independent structure, enables precise grasping and enhances both grip strength and operational stability—making it central to dexterous manipulation. The tendon system comprises flexor and extensor muscles, which control finger bending and straightening, respectively. Tendons glide through sheaths and are guided by pulley systems to reduce friction and control movement paths.

The nervous system, primarily involving the median, ulnar, and radial nerves, integrates with tactile receptors to form a sophisticated feedback mechanism that ensures high-precision control and environmental perception.

The coordinated operation of these intricate systems allows the human hand to perform a wide range of complex and delicate tasks—such as writing, threading a needle, playing musical instruments, and manipulating tools.

2.2. Application of Bionics in the Design of Dexterous Hands

Bionics provides the theoretical foundation for dexterous hand design, enabling the evolution from basic grippers to advanced manipulators by mimicking the human hand's structure and function. Key design strategies include:

Structural Bionics: Mimics skeletal and joint configurations to achieve multi-DOF motion. Examples include the Shadow Hand (20 DOFs) and DLR-HIT Hand II with modular joints for flexibility and maintenance.

Actuation Bionics: Inspired by human tendons, tendon-driven systems (e.g., cables and pulleys) enable compact multi-DOF actuation. The Yale OpenHand Project exemplifies this approach with its simple, modular design.

Perceptual Bionics: Embeds tactile, force, and temperature sensors in fingerpads to replicate human skin's sensory feedback, enabling slip detection and force control. Notable technologies include BioTac and GelSight.

Flexible Structures & Biomimetic Materials: Utilizes soft joints and elastomers to imitate tendon and skin mechanics, enhancing compliance and safety. The Harvard Soft Hand is a representative example.

In summary, the human hand serves as a comprehensive model for bionic replication, guiding the development of dexterous hands through structural, sensory, and material emulation.

3. Structural Bionics and Engineering Implementation: Analysis of Typical Mechanical Designs in Dexterous Hands

3.1. Development History of Dexterous Hands

The development of dexterous hands began in the 1970s, with the earliest designs primarily functioning as simple grasping devices. A milestone was achieved in 1977 with the creation of the Stanford/JPL Hand, which was among the first to implement three-finger coordination and multi-degree-of-freedom control [7]. This was soon followed by the Utah/MIT Hand, developed through collaboration between MIT and the University of Utah. It featured 16 degrees of freedom and integrated tactile sensors, marking the advent of the "structure + perception" era in dexterous hand research [8].

During the 1990s, the University of Tokyo introduced the Gifu Hand series, which successively improved joint configurations and actuation methods, laying a solid foundation for skeletal design in biomimetic hands [9]. Entering the 21st century, Germany's DLR developed the DLR-HIT Hand II, incorporating a modular joint architecture and high-density actuator layout [10]. Meanwhile, the UK-based company Shadow Robot launched the Shadow Dexterous Hand, which integrates 20 degrees of freedom and a pneumatic muscle actuation system. It has been widely used in academic research and high-end service robot platforms [11].

In China, research teams from institutions such as Beijing Institute of Technology and Harbin Institute of Technology have developed dexterous hands like the BIT-Hand and HIT/DLR Hand, focusing on tendon-driven mechanisms, autonomous sensing, and control algorithms. Supported by the national "863 Program," these efforts have made significant progress [12].

Overall, the evolution of dexterous hands has followed a trajectory from structural imitation to sensor integration, and now toward intelligent control. The field continues to advance in the direction of higher compliance, greater redundancy, and deeper integration with artificial intelligence.

3.2. Analysis of Representative Dexterous Hands

3.2.1. Shadow Dexterous Hand

The Shadow Dexterous Hand, developed by the UK-based Shadow Robot Company, is a highly biomimetic robotic hand. Its initial development began around 1997, with continuous improvements leading to a mature commercial version after 2005, which has been iteratively updated ever since. Its appearance and motion closely resemble the human hand, making it widely used in academic research, robotic system integration, and human-robot interaction.

The hand features 20 joints and 40 muscle-like pneumatic actuators, enabling complex movements such as grasping, pinching, and rotation. It employs tendon-driven actuation, where each tendon is controlled by precision motors, combining flexibility with accuracy. The actuators are externally mounted, avoiding integration inside the hand itself, which reduces the hand's size and weight. The tendon transmission mimics human tendons, offering flexibility and passive compliance. It supports force feedback during complex actions, facilitating safe grasping of fragile or irregular objects.

The Shadow Hand demonstrates impressive speed, taking about 0.5 seconds to transition from fully open to fully closed. Each joint can move through its full range at a frequency of 1.0 Hz—meaning a complete back-and-forth cycle takes 1 second, with a single-direction move lasting about 0.5 seconds. In terms of precision, joint position accuracy reaches 0.2 degrees, and force sensors have a resolution of 30 millinewtons, enabling detection of very slight forces. Equipped with a total of 129 sensors—including position, force, and tactile sensors—it supports high-frequency data updates, with position data refreshed at 1000 Hz and force data at 5000 Hz, ensuring real-time feedback and precise control.

The hand weighs approximately 3.9 kg and is about 1.2 times the size of a human hand. Its total payload capacity is around 5 kg, allowing it to grasp objects of various shapes, sizes, and materials, from small delicate items to heavier tools [13, 14].

3.2.2. NASA Robonaut Hand

The Robonaut Hand, developed as part of NASA's Robonaut project (initiated in 1997), is a key component designed to replicate human hand functionality for robotic operations in space. The overarching goal of the Robonaut system is to enable robots to assist or replace astronauts in performing delicate and complex tasks in space—making the hand structure a central element in achieving this functionality.

Each finger of the Robonaut Hand features three joints, providing a total of 14 degrees of freedom, including additional DOFs in the thumb and wrist. It is driven by compact DC motors located within the wrist, utilizing a hybrid transmission system combining gears and tendons. Gear transmission is used for the primary joints to deliver high-strength, precise motion control, while tendon transmission is applied to secondary joints to reduce weight and enhance compliance.

The fingertips can achieve velocities exceeding 2 m/s, making the hand well-suited for rapid grasping and manipulation tasks. In terms of precision, the hand integrates an advanced tactile sensing system, including six-degree-of-freedom force-torque sensors capable of measuring contact forces, shear, and slip at the fingertips. In total, approximately 80 sensors are embedded throughout the hand, ensuring high accuracy during operations. Additionally, the system features a built-in calibration mechanism to maintain consistent precision over time. The hand weighs approximately 2.5 kg and is about 1.1 times the size of a human hand. Each finger can support a payload of about 1 kg, while the entire hand can handle up to 10 kg. Specifically engineered for the space environment, the Robonaut Hand is capable of stable operation in microgravity, vacuum conditions, and extreme temperatures—making it suitable for a wide range of space mission scenarios [15, 16].

3.2.3. DLR Hand II

The DLR Hand II, developed around 2000 and officially released in 2001, represents a significant advancement over DLR's first-generation hand from the late 1990s. As one of the most advanced dexterous hands of its time, the DLR Hand II marked a milestone in humanoid robotic hand development, showcasing state-of-the-art achievements in anatomical mimicry, system integration, and control algorithms. It is widely regarded as a symbol of the maturity of high-performance dexterous hand technology in the early 21st century.

The hand features 20 joints—four per finger, including a specially designed thumb—and 12 degrees of freedom, with several joints driven in a coupled manner to reduce the number of actuators and optimize spatial efficiency. It is powered by high power-density brushless DC motors and uses a hybrid transmission system combining tendon-driven and gear-driven mechanisms. The gear drive offers precise and efficient motion transmission, while the tendon system provides flexibility and compliance. The maximum joint rotation speed reaches 360°/s, enabling rapid and responsive movement. The hand is equipped with approximately 60 sensors, which support precise motion control and feedback. With a weight of about 2 kg and a size nearly identical to that of a human hand, each finger can carry a load of around 0.5 kg, with the whole hand capable of handling up to 5 kg.

The overall design achieves a balance between dexterity and complexity, resulting in a compact, reliable structure that is well-suited for executing intricate manipulation tasks [17].

3.2.4. Schunk SVH

The SCHUNK Dexterous Hand, also known as the SCHUNK 5-Finger Hand, is a highly biomimetic robotic hand developed by SCHUNK GmbH & Co. KG, a leading German company specializing in automation and gripping technologies. Officially released in 2012, this dexterous hand combines industrial-grade reliability with a human-like design, making it suitable for a wide range of applications, including human-robot interaction, robotics research, grasping experiments, and prosthetic simulation.

The hand features 19 joints and 9 actuated degrees of freedom. The thumb includes four joints and can move independently, while the other four fingers closely mimic the anatomy and motion of a human hand. Actuation is achieved through electric motors coupled with tendon-driven transmission systems. The drive motors offer a maximum speed of 500 rpm and a resolution of 2000 steps per revolution, supporting high-precision operations. The hand is equipped with approximately 30 sensors, providing sufficient accuracy for industrial grasping tasks.

With a weight of around 1.1 kg and dimensions approximately 1.1 times the size of a human hand, the SCHUNK Hand maintains a form factor close to the natural human hand. It has a total payload capacity of 2.5 kg, with each finger capable of bearing approximately 0.5 kg. Designed with a high degree of anthropomorphism and precise motion control, the hand is well-suited for various industrial grasping applications. It is also easy to integrate into industrial robotic platforms and is compatible with collaborative robot systems [19].

3.2.5. HIT Dexterous Hand (Harbin Institute of Technology)

Harbin Institute of Technology (HIT) is one of the pioneers in dexterous hand research in China. Its Robotics Institute has long been dedicated to the design, control, and application of high-degree-of-freedom biomimetic hands, earning significant recognition in both domestic and international academic communities. Beginning in 1999, HIT collaborated with Germany’s DLR to develop early dexterous hand prototypes (HIT/DLR Hand). By the early 2000s, the institute began releasing its own independently developed versions, gradually transitioning to fully autonomous designs. The HIT Hand II was introduced around 2010.

The HIT dexterous hand features 20 joints and 15 actuated degrees of freedom, driven by electric motors and tendon-based transmission systems. It is equipped with approximately 60 sensors, providing effective tactile feedback for fine manipulation tasks. The hand weighs around 1.6 kg and is slightly larger than a human hand. Each finger can support a load of up to 0.8 kg, and the entire hand has a total payload capacity of about 6 kg.

The hand adopts a modular design, making it easier to maintain and integrate into robotic platforms. Its control system and perception algorithms are entirely self-developed, enabling high-precision manipulation and robust performance in complex scenarios [20, 21].

4. Functional Implementation and Application Cases of Dexterous Hands

Multi-DOF Coordination and Precision Grasping Capability: A high-degree-of-freedom structure forms the foundation for human-like manipulation. The Shadow Dexterous Hand, equipped with 20 points and 40 muscle-like pneumatic actuators, is capable of performing 24 large-range movements and fine manipulation tasks similar to those of a human hand. It integrates position, force, and pressure sensors, enabling closed-loop control that allows for stable grasping of complex and delicate objects—such as bubble wrap and glass cups [12, 14].

Adaptive and Compliant Grasping: The three-finger compliant design of Schunk SDH-2 conforms to irregular objects, enabling an "enveloping" grasp. With flexible mechanics and closed-loop control, it outperforms traditional grippers in stability when handling bottles and electronic components [6, 11]. Harbin Institute of Technology's HIT-Hand employs tendon-driven actuation and compliant control, offering highly adaptive grasping with low energy consumption. It is well-suited for lightweight collaborative robots and can stably grasp daily objects like medicine bottles and spoons in medical prosthetic systems [20, 21].

Perception Integration and Tactile Feedback: The Shadow Hand integrates pressure, position, and force sensors, and can be equipped with BioTac or GelSight tactile systems to detect object hardness and pressure distribution, allowing real-time adjustment of grasping strategies to protect fragile items [10, 14]. NASA's Robonaut 2 goes further with a tactile sensor array and series elastic actuators (SEAs), enabling exceptional force control and impedance regulation. Its control system processes over 350 sensor readings to execute complex tasks in zero-gravity environments, such as opening drawers, turning knobs, and plugging connectors [7, 8, 16].

Complex Task Execution in Special Environments: As the first humanoid robot operating in orbit, Robonaut 2 on the ISS features a highly redundant actuation system for stable and fault-tolerant space operations. Its derived Robotic Grasp Assist Glove reduces astronaut fatigue, simulating human-like manipulation with ergonomic support [2, 8, 13, 16].

Intelligent Collaboration and Human-Robot Interaction: The TeachNet system for the Shadow Hand uses end-to-end neural networks for vision-driven teleoperation, allowing novices to intuitively mimic hand gestures via depth images [17]. "Zero-shot" grasping systems dynamically adjust strategies based on tactile feedback, achieving up to 73% success rates for previously unseen objects [18].

5. Conclusion

5.1. Analysis of Technological Development Trends

1) Structural Perspective: From Rigid Biomimicry to Soft Robotics Integration

Although representative dexterous hands such as the Shadow Hand and DLR Hand II have achieved a high degree of anthropomorphism in structural design, they primarily rely on rigid components, which tend to result in high cost, considerable weight, and increased susceptibility to damage. To address these limitations, recent developments have shifted toward soft robotic hands and flexible material structures. Projects like MIT’s C-Skin and the Harvard Soft Robotic Glove utilize materials such as silicone and TPU membranes to create compliant finger joints, offering advantages in terms of reduced cost and enhanced adaptability [29,30]. However, current soft hands still struggle to achieve high-precision force control and often require integration with rigid components for full functionality.

2) Actuation and Control: Evolution from Servo Motors to Intelligent Tendon Systems

Traditional dexterous hands often use servo motors and gears, resulting in bulky, slow systems. The trend is shifting toward tendon-driven mechanisms and compact actuators like piezoelectric and magnetorheological types. Institutions such as HIT, Tokyo Tech, and DLR are exploring human–robot hybrid muscles to better mimic biological motion. Meanwhile, control is advancing beyond PID and hybrid force-position schemes to reinforcement learning and biomimetic synergy control. For instance, DLR’s motor synergy model enhances adaptability and predictive performance in dynamic environments [31].

3) Perception and Interaction: Advancing Toward Multimodal Integration and Active Sensing

Modern dexterous hands are no longer merely actuators—they function as integrated sensing-action end-effectors. By incorporating multimodal sensing technologies such as vision (RGB-D), tactile sensing (e.g., BioTac, GelSight), force feedback, and temperature detection, these hands are capable of active perception and task anticipation. For example, MetaAI's Touch Grass project is exploring how AI systems can use tactile input to determine task allocation and adapt execution strategies accordingly [32].

Future developments are expected to further merge active perception with dynamic control, shifting the paradigm from "executing predefined tasks" to "recognizing task demands and autonomously adapting strategies."

5.2. Trends in Application Expansion

The applications of dexterous hands are gradually expanding beyond industrial and laboratory settings into diverse fields such as medical rehabilitation, service, extreme environment operations, education, and scientific research. Examples include:

Medical Rehabilitation: For instance, the intelligent prosthetic system developed by the University of Tokyo integrates dexterous hands with electromyographic (EMG) recognition, enabling partial restoration of grasping ability for patients with cerebral palsy.

Human–Robot Collaborative Interaction: Service robots equipped with dexterous hands can perform complex tasks in home care, nursing, and companionship scenarios, such as feeding, dressing, and opening bottles.

Space and Disaster Emergency Response: Products like NASA's Robonaut demonstrate that dexterous hands can replace humans in remote operations within space stations, power plants, and hazardous zones prone to explosions.

These developments are driving dexterous hands from being viewed as "complex research apparatus" toward becoming practical and versatile technology platforms.

5.3. Personal Reflections

Future progress requires interdisciplinary collaboration across mechanical design, materials science, AI, and neuroscience to enable "intelligent manipulation"—the capacity to understand tasks, plan actions, adapt in real-time, and execute with precision. Researchers must also avoid over-complexity; simple solutions like 3D-printed two-finger grippers prove highly practical in industrial settings, underscoring that functionality, not complexity, is the design imperative.

Dexterous hands are evolving from biomimetic structures to intelligent, real-world applications, with future efforts focused on generalization, cost control, and sensor fusion to balance innovation with practical deployment.

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