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Current State of Load Capacity in Dexterous Robotic Hands

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Abstract. With rapid advances in artificial intelligence and automation, dexterous hands have evolved from experimental prototypes into practical systems, demonstrating broad application prospects in industrial automation, medical rehabilitation, and domestic services. As the principal end-effector of humanoid and service robots, the performance of dexterous hands plays a critical role in determining a robot's capability to perform complex manipulation tasks in unstructured and dynamic environments. However, inadequate load capacity remains a critical bottleneck, limiting their adaptability and operation in applications. To Address this challenge is particularly important for realizing the broader vision of intelligent robots substituting for humans in all kinds of domains where they seek to emancipate their manual labor involvement. Guided by three interrelated dimensions, structural design, actuation systems, and material properties, this research explores pathways to enhance load capacity by reviewing the underlying mechanisms, optimization strategies, and key challenges. This research integrates multidisciplinary insights to provide comprehensive references and practical guidance for the future design, improvement, and deployment of dexterous robotic hands.

Keywords: Dexterous hand, load capacity, novel structures, actuation system, materials

1. Introduction

In recent years, advancements in artificial intelligence and automation have propelled the improvement of robotics. The primary tasks of robots have shifted from repetitive operations in structured environments to complex operations characterized by environmental perception, intelligent decision-making, and autonomous action. Humanoid robots, in particular, have emerged as a focal area for both research and industry, with demand continuing to expand [1]. As the essential actuator interacting between robots and the environment, the dexterous hand is a multi-DOF mechanism that can accommodate both power grasping and fine manipulation. It has progressed from laboratory development to broader applications, showing substantial potential in industrial automation, medical rehabilitation, and domestic services [2].

Dexterous hand performance is crucial for complex robotic tasks, yet limited load capacity remains a major constraint. The requirements for compactness, lightweight design, flexibility, and environmental adaptability typically come at the expense of load capacity when compared to conventional grippers [3]. When assessing the load-carrying capacity of dexterous robotic hands,

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commonly used metrics include the finger actuation force, passive payload capacity, and the maximum grasp load. In practical applications, it is also essential to consider the "usable load" that the hand can reliably lift and maintain over time, under varying environmental conditions, sliding friction, material fatigue, and perceptual error accumulation, as well as the "lifetime working load" based on reliability factors over long timescales. Therefore, enhancing load capacity while maintaining compactness can further expand the operational capabilities of dexterous hands, enabling them to advance the broader vision of “machines replacing humans.” While progress has been made, current research focuses mainly on optimizing individual designs, lacking a systematic multi-dimensional framework. Accordingly, this work reviews advances and key challenges across three dimensions- structural design, actuation systems, and materials. At last, this work outlines some potential directions for future development to assist future research.

2. The influence of dexterous hand structure on load capacity

The dexterous hand's ability to grab and load is key to its performance, which can be attributed to the structural stiffness characteristics. These characteristics can be divided into rigid structure, flexible structure, and coupled structure.

2.1. The rigid structures on load capacity

Rigid-structure dexterous hands typically comprise rigid links and joints, with motion controlled via linkages, gears, or tendons to achieve grasping and related actions. The stiffness type offers precise control, strong load capacity, with robust durability. However, several challenges persist for dexterous-hand applications. First, the high density and weight of rigid materials increase the system mass, necessitating more complex control strategies to manage dynamics in multi-jointed systems, leading to significantly higher computational demands and reduced reliability [4]. Second, manipulation typically involves unstable point or line contact, preventing stable enveloping grasps. This inherent instability requires advanced sensory feedback to enable reliable grasping across different sizes [5].

In recent years, research on rigid dexterous hands has increasingly focused on under-actuated designs that integrate actively driven elements with passive components that conform to object geometry. Under actuation design allows passive structures to adapt to diverse object contours, enabling grasping across a wide range of sizes [6]. Nevertheless, these designs generally employ fewer actuators, which limits their load capacity compared with fully actuated counterparts of similar size [5]. To address this, Zhou et al. proposed a dexterous hand with Bidirectional Self-Locking Joints (BSJ). As shown in Figure 1(a)(b), this mechanism transfers the load-bearing constraint from motor output to structural strength, significantly enhancing load retention in static grasping tasks while simultaneously reducing energy consumption and motor wear [7].

Overall, the rigid-handed approach provides strong load performance but imposes greater design, control, and maintenance complexity, motivating ongoing efforts to balance these trade-offs in rigid-soft or hybrid architectures.

2.2. Soft structures on load capacity

Soft dexterous hands integrate soft materials and flexible joints to achieve manipulation through continuous deformation. These designs primarily rely on compliant structures that provide high adaptability. Compared to rigid dexterous hands, soft dexterous hands are lighter, better suited to

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conforming to irregular shapes, cushioning impacts, and providing a gentle grasp. They offer redundancy degrees of freedom rather than the limited freedom provided by normal joints. These features enable safer interaction between dexterous hands and fragile objects or humans, while also improving grasping reliability and lightweight performance. Additionally, they are more cost-effective, as their construction avoids expensive rigid metals, instead utilizing 3D-printed materials or low-cost elastic substances. These characteristics make soft dexterous hands safer for interacting with fragile objects or humans, while also enhancing grasping reliability and lightweight performance. However, soft hands typically have lower load capacities and face challenges such as response delays, reduced precision, and material degradation.

To improve load capacity, soft dexterous hands have advanced through innovations in grasping strategies and energy transduction efficiency, particularly by enlarging the contact area to strengthen grasp robustness. As depicted in Figure 1(c), Liu et al. developed a two-finger soft gripper with dual modular pneumatic actuators and a variable chamber height structure (DMVCHA) to increase output force and concentrate contact pressure [8]. As shown in Figure 1(d), Wang et al. designed SpiRobs, a gripper constructed from highly elastic, fatigue-resistant TPU and inspired by the logarithmic spiral geometry of octopus tentacles. By integrating climbing and wrapping grasping strategies, SpiRobs significantly improves load capacity, enabling it to grasp objects spanning more than two orders of magnitude in size and weighing up to 260 times its own weight [9].

In sum, soft dexterous hands, though inherently limited in load capacity, have achieved notable improvements through thoughtful structural design and biomimetic strategies. As material performance and design optimization continue, soft- and hybrid-structure approaches hold substantial promise for enhancing load capacity.

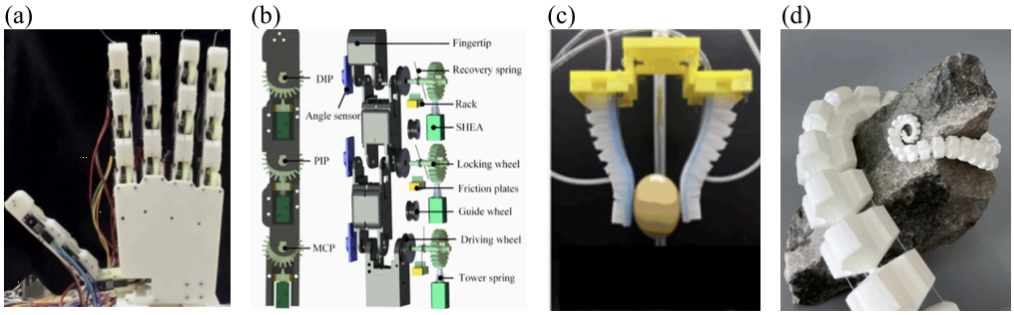

Figure 1. Rigid and flexible structures in dexterous hands

2.3. Rigid-soft coupling structures on load capacity

In nature, efficient gripping systems often feature a layered architecture, each layer serves a distinct functional purpose. The system typically consists of a macro-scale rigid skeleton, an intermediate layer of flexible connecting elements, and a micro-scale friction or adhesive surface layer. The rigid skeleton provides the macro-scale load capacity and maintains the shape stability of dexterous hands, while the flexible connection layer adjusts point-contact configurations and modulates contact pressure at each point in response to load changes. Friction-adhesion microstructures further increase contact points, aiding in load stress dispersion. Based on the layered structural and functional layering, rigid-soft coupling structures integrate rigid skeletons or links with soft surfaces, flexible joints, or soft actuators, achieving a balance between load capacity and dexterity, which have emerged as a central direction in current research.

Representative approaches include:

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1. Rigid-soft coupling with stiffness-tunable modules, such as folded-plate mechanisms (FPM) integrated with granular jamming, which enable high payload capacity and stable multidirectional grasping [10].

2. Anthropomorphic hand designs based on rapid pneumatic networks (FPN) and combined with flexible sheets to effectively enhance lateral load capacity [11].

3. Flexible joints coupled to rigid frames, which maintain load capacity while addressing integration and lightweight challenges inherent in conventional rigid joints, as depicted in Figure 2(a) [12].

4. Palm modules employing soft-hard hybrids, which increase contact area and distribute stresses during grasping, thereby improving grasp stability, as shown in Figure 2(b) [13].

Through various structural designs and material combinations, dexterous hand demonstrates significant advantages. It possesses the high stability advantages offered by flexible materials, while also leveraging rigid structures to enhance the load-bearing capacity of the dexterous hand. However, challenges such as material ratio set, structural coupling design, and dynamic control still constrain the performance improvement of dexterous hands. A higher proportion of flexible materials may compromise the load-bearing capacity of the structure, while the use of rigid materials will increase control complexity. Additionally, the junction between a rigid skeleton and soft materials exhibits a severe stress mismatch due to the abrupt change in material modulus, which can easily become a weak point prone to fatigue failure. This phenomenon leads to a discrepancy where the actual load-bearing capacity reported in many studies falls below the theoretical value.

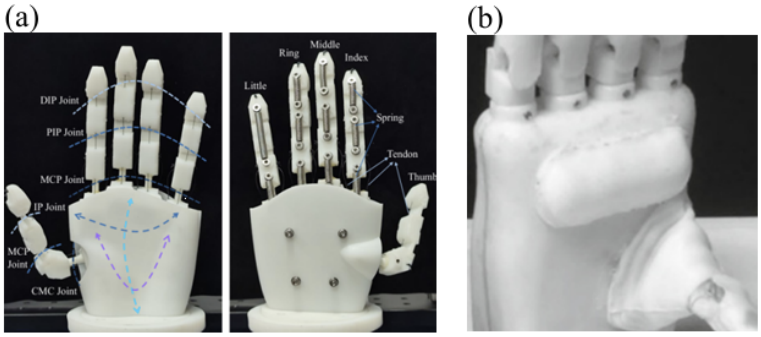

Figure 2. Rigid and flexible structures in dexterous hands

3. The influence of the actuation system on load capacity

The load capacity of a dexterous hand results from the coordinated interaction of the actuation and transmission systems. The key to performance enhancement lies in the integrated design and optimized combination of these two systems.

3.1. Actuation modalities

Actuation supplies the energy for dexterous hands and influences output force, response speed, and control precision, thereby determining load capacity. The principal actuation methods currently in use are electric motors, fluid power (hydraulic, pneumatic) systems, and smart-material actuators.

Among these, electric motors are the most widely used, offering high force output, precise control, rapid response, technological maturity, and high energy-conversion efficiency. Motors generate torque directly or via gear reductions to drive joints; load capacity depends on motor torque output and efficiency. Heavier loads need more powerful motors. But that usually means bigger

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parts or extra gears, which adds weight and takes up space. To solve this, researchers are trying new kinds of motors that can maintain load capacity while enhancing compactness and dexterity. Some recent examples are hollow-cup motors, brushless DC motors (BLDC), and quasi-direct-drive systems [14]. Hollow-cup motors and BLDC motors can provide higher rotational speeds, enabling larger torque output, while quasi-direct-drive systems eliminate the need for reduction gears, substantially reducing the volume of the drive system.

Fluid-power actuation employs incompressible liquids (hydraulic) or compressible gases (pneumatic) to drive expandable and contractible chambers, with deformation constrained by structural boundaries to achieve hand actuation. Hydraulic systems provide high output torque and load advantages, but are heavy and less suitable for compact hands, primarily serving industrial manipulators. Pneumatic actuation, by contrast, offers compliance, lightweight construction, and low cost, making it well-suited for human-robot interaction and soft grasping. However, the comprehensibility of gases can reduce control accuracy under load and limit overall load capacity. Strategies to enhance load performance include reinforcing soft materials with fibres (glass or carbon fibre) to constrain deformation and using positive-negative combinations of pneumo-actuation to stiffen fingers [15]. Due to the inherent compliance, pneumatic actuators are widely employed in soft dexterous hands and in rigid-soft hybrids, with representative actuators.

Smart-material actuation employs materials that actively change shape, stiffness, or other properties under external stimuli (thermal, electrical, magnetic) without the requirement for auxiliary transmission systems, offering low mass and high energy density. This approach is particularly suitable for biomimetic hands. For example, curved shape-memory alloy (SMA) actuators have been used to emulate muscle–tendon function, significantly enhancing flexibility and adaptability [16]. However, limitations include slow response and limited load capacity hinder their application in high-frequency and heavy load tasks.

The various actuation methods possess distinct advantages and limitations. Strategically integrating these approaches enables a synergistic combination that complements their capabilities, thereby effectively enhancing the performance of dexterous hands. For instance, a pneumatic-motor hybrid system can leverage pneumatic drives to provide large-range joints motion and high-force output, while employing electric motors to achieve high-precision and torque control. This integration enables the dexterous hand to adapt to a wider spectrum of tasks, including delicate manipulation and safe human-robot collaboration. Besides, some researches have proposed SMA structures that can influence the stiffness or transformation state of the material at specific temperatures, thereby adjusting the output force or working range of the dexterous hand and enhancing its adaptability to varying loads.

3.2. Transmission system

Transmission mechanisms convey actuation power from the actuator to the hand's distal joints. Their design directly influences force transmission efficiency and stability, thereby shaping overall load capacity. Common mechanical transmission modalities include gears, tendons, lead screws, and linkages; their relative advantages and drawbacks are summarized below.

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Table 1. Classification of transmission methods for dexterous hands

Transmission mode	Principle	Advantages	Disadvantages
Gear [15]	Gear meshing	High efficiency; compact	Noisy, short transmission distances
Tendon [16]	Tendon cord pull	Lightweight, flexible remote drive application, remote drive.	Prone to wear, elasticity affects accuracy
Lead screw [17]	Converts rotary to linear	High precision, strong load capacity	Low efficiency, wears easily, requires lubrication and high precision
Connecting rod [18]	Joints connect rigid links	Stable, rigid, reliable	Complex design, bulky, may have dead points

The common transmission methods used for dexterous hands are illustrated in Table 1. Gear drives offer high transmission efficiency but are prone to vibration and noise. The tendon transmissions are light and flexible. The lead screw provides precise conversion from the rotating motion to linear motion, but the efficiency is relatively low. The connecting rod actuation has a strong load capacity but a large volume. Among these, tendon transmission systems are particularly prevalent because they decouple heavy actuators from distal joints, reducing end-effector weight and inertia and thereby enhancing agility. However, tendon-driven dexterous hands still face several challenges. Firstly, friction between the tendons and the structural components of the hand (pulleys or guide holes), coupled with the elastic deformation of the tendons, leads to energy loss. This results in reduced transmission efficiency and compromised control accuracy. Secondly, prolonged friction and large-range bending of the tendons can induce significant wear and rupture, which adversely affects both the practical load-bearing capacity and maintainability of the dexterous hand. Indeed, as the tensile and torsional strength of tendons directly influences their load-bearing ability, a series of research efforts is dedicated to optimizing both material composition and load-bearing structural design. For example, a common strategy is to select materials with high tensile strength and low friction coefficient for tendon construction. Similarly, some researches have also increased the diameter of the winding pulleys or the number of winding loops. This approach optimizes stress distribution, thereby enhancing the tolerable tension of the tendons and ultimately the overall load-bearing capacity.

In summary, it is uncommon for dexterous hands to employ single actuation method from Table 1, most contemporary designs integrate two or more transmission mechanisms to achieve better performance. In these designs, different mechanisms are selectively employed at various locations according to specific task requirements, thereby enhancing the overall performance of the dexterous hand. For instance, gear or connecting rod are typically adopted in regions requiring high torque output (wrist, palm, or proximal finger joints), whereas tendon-driven actuation is preferred in areas demanding adaptability rather than large force exertion, such as the distal finger segments.

4. The influence of material properties on load capacity

The mechanical properties of the materials used in a dexterous hand, such as strength, stiffness, elasticity, and durability, directly influence load capacity, adaptability, and reliability. Materials are typically classified as rigid, elastic, and smart materials.

Rigid materials provide high modulus and tensile strength, resulting in minimal deformation under load and thus higher load capacity and grasp stability. Metals such as steel, aluminum alloys, and titanium exhibit exceptional stiffness and hardness. Among them, aluminum alloys are

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particularly prevalent in dexterous hands due to favorable strength-to-weight ratios and cost. Polymers such as acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) are common for cost-effective fabrication, while engineering polymers like PEEK and PEI provide superior mechanical properties [19]. Composite materials, such as carbon fiber reinforced polymers (CFRP) and glass fibre reinforced polymers (GFRP), combine high fiber strength with the lightness of polymers, offering excellent strength-to-weight performance [20].

Elastic materials are primarily applied for soft joints or fingertip coverings to enhance compliance, adaptability, and safety. Although their inherent load capacity is limited, increasing the contact area helps distribute forces and improve grasp stability. Silicone elastomers are the most common soft materials, while their baseline mechanical properties are modest, performance can be significantly enhanced through additives, crosslinking-network optimization, and composite formation. Notable approaches include incorporating iron oxide and carbon nanotubes (CNTs) into the elastic matrix to boost strength, toughness, and durability, or employing polyamidoamine (PAMAM) dendrimers as crosslinking agents to fabricate high-temperature vulcanized silicone elastomers (MCSR) with tensile strengths up to 9.34 MPa and tear strengths up to 47.71 kN/m [21]. Additionally, thermoplastic polyurethane (TPU) elastomers combine wear resistance with high elasticity and are widely used in soft robotics [9]. The material properties of TPU arise from its distinctive microstructure. The segmented block copolymer architecture comprised of hard segments formed from diisocyanatos and short-chain extenders and soft segments formed from long-chain polyols. The hard segments provide strength and wear resistance, while the soft segments confer elasticity and flexibility.

Smart materials offer active, externally stimulated morphing, stiffness modulation, or other property changes, enabling novel design opportunities and performance enhancements in dexterous hands. Common smart materials include shape memory alloys (SMA) [16], shape memory polymers (SMP) [22]. Owing to unique advantages such as shape-memory effects, and high energy density, these materials hold considerable potential for enabling lightweight, compliant, and multifunctional dexterous hands.

5. Conclusion

This work addresses the load-capacity challenges of robotic dexterous hands, analyzing the underlying mechanisms across three key dimensions: structural design, actuation systems, and material properties. The literature indicates that integrating high-performance composite materials within rigid-soft hybrid structures, combined with hybrid actuation and mixed transmission systems, can substantially enhance overall performance. Rigid-soft hybrids fuse the load-capacity advantages of rigid architectures with the adaptability and lightness of soft components. High-strength, high-weight materials and highly elastic functional soft materials provide substantial potential. Hybrid actuation and composite transmission systems effectively integrate benefits across multiple dimensions, achieving high load capacity while maintaining overall lightness.

Future work should emphasize deeper interdisciplinary integration to advance dexterous hands toward higher load capacity and greater dexterity. In structural design, biologically inspired mechanisms that achieve high load capacity and efficient grasping should be explored. In actuation, the development of novel, efficient actuators and hybrid actuation–transmission system should be pursued in concert with intelligent control strategies. In materials, the expansion of smart materials, biomimetic materials, and sensing-integrated flexible functional materials is essential. Taking deep bio-inspired design as an example. This promising research avenue involves systematically delving into the hand structure, force application strategies, and tissue characteristics of humans and other

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animals possessing strong grasping abilities. Building upon the bio-inspired principle, deep imitation learning can then be employed to translate complex grasping strategies into the design of dexterous hands through approaches such as inverse reinforcement learning (IRL). By following this path, from biological systems to algorithms and ultimately back to engineering solutions, it is highly anticipated that the practical load capacity can be significantly enhanced without compromising dexterity. Through these advancements, dexterous hands have the opportunity to overcome current load limitations and surpass human capabilities in the integrated performance of dexterity, load capacity, and adaptability. Higher integrated performance enables dexterous hands to have broader application prospects in intelligent manufacturing, medical rehabilitation, and domestic services. In smart manufacturing, they can perform increasingly diverse tasks, demonstrating significant potential from aerospace manufacturing to deep-sea maintenance. In domestic range, they can substantially enhance the capabilities of care and household robots, making them more human-like and expanding societal acceptance, ultimately realizing the vision of machines replacing humans.

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