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Research Progress on Mechanism Design of Underactuated Biomimetic Robotic Hands

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Abstract. Aiming at the research gaps in existing reviews on underactuated biomimetic robotic hands—namely fragmented mechanism classification and the lack of horizontal quantitative comparison among multi-drive configurations—this paper adopts a systematic literature review methodology. Using transmission type as the classification criterion, underactuated biomimetic robotic hands are categorized into three mainstream systems: linkage transmission, tendon–pulley transmission, and pneumatic soft actuation. Their structural principles, differential core components, prototype performance, and inherent limitations are analyzed, and representative industrial grippers, prosthetic hands, and modular pneumatic soft grippers are compared using quantitative data on grasping force, adaptive capability, and weight. The results reveal that each configuration possesses distinct advantages and inherent deficiencies, and no single transmission structure can simultaneously achieve high payload, lightweight design, and full-shape adaptive grasping. Technical bottlenecks and future development directions are further identified, providing a reference for mechanism optimization and engineering application of biomimetic robotic hands.

Keywords: underactuated mechanism, biomimetic robotic hand, hybrid underactuated configuration, adaptive grasping, mechanism optimization

1. Introduction

With the growing demand in human-robot collaboration, minimally invasive surgery, and operations in confined spaces, robotic hands must be lightweight, compliant, and safe in interaction. Underactuated mechanisms, with fewer drive inputs than total degrees of freedom, enable adaptive grasping of irregular objects and reduce weight and control complexity. A systematic review of underactuated biomimetic hands is therefore urgently needed.

Existing reviews tend to focus on a single actuation scheme, leading to fragmented mechanism classification and a lack of horizontal quantitative comparison among different drive configurations. It remains difficult for researchers and engineers to directly weigh the performance trade-offs of linkage, tendon, and pneumatic soft underactuated mechanisms when selecting a configuration for a specific application.

This paper adopts a systematic literature review methodology. Using transmission type as the classification criterion, underactuated biomimetic robotic hands are divided into three mainstream

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systems: linkage transmission, tendon–pulley transmission, and pneumatic soft actuation. Their structural principles, prototype performance, and inherent limitations are analyzed, and representative industrial grippers, rehabilitation prosthetic hands, and modular pneumatic soft grippers are compared using quantitative data on grasping force, adaptive capability, and weight. Technical bottlenecks and future directions are identified, providing a reference for mechanism optimization and engineering application of biomimetic robotic hands.

2. Literature review

2.1. Classification of underactuated biomimetic robotic hand mechanisms

The criterion for an underactuated mechanism is that the number of independent drive inputs is less than the total degrees of freedom of the mechanism. Passive joint degrees of freedom are generated by passive components such as springs and clutches, enabling adaptive grasping of irregularly shaped objects while achieving weight and volume reduction. According to the power transmission and deformation realization methods, underactuated hand mechanisms can be divided into three core configuration systems: linkage transmission, tendon–pulley transmission, and soft actuation [1].

Among them, linkage and tendon transmissions are currently the mainstream schemes, whereas soft structures represent an emerging lightweight solution; differential and twisted-tendon transmissions serve only as derivative structures and are not included in the primary classification. Each configuration is elaborated with its structural principles, representative prototypes, and performance trade-offs in the following subsections [1].

2.2. Tendon-driven underactuated mechanisms

Tendon-driven underactuated hands employ motors, pulleys, and flexible tendons as core force-transmitting components. A single drive source is distributed to multiple finger joints: the motor pulls the tendons via pulleys to drive flexion and extension, and when some finger segments contact the object and become force-locked, the tendon tension is redistributed so that the remaining fingers continue the enveloping motion. Elastic elements embedded in the joints assist in return, and fewer actuators than total degrees of freedom reduce overall weight and control complexity [2].

A prosthetic hand prototype equipped with three types of lockable differential mechanisms was constructed in the literature, with a single motor controlling the index, middle, ring, and little fingers, while the thumb is independently actuated [2]. The gear differential prototype achieves a maximum single-finger tendon tension of 39 N with continuous rotational output. The series elastic differential features a compliant/force dual mode, with an output pulling force of 53.8 N in rigid mode. The Whiffletree differential weighs only 46 g and is suitable for precision pinching. The three prototypes grip 12 categories of daily objects and realize 16 finger flexion combinations [2].

The tendon-driven scheme reduces the number of actuators and enables lightweight, adaptive grasping without complex force-control sensors, but suffers from tendon–pulley friction loss, limited stroke of Whiffletree and pulley differentials, extra energy consumption of the series elastic differential, and a relatively large gear-differential size that hampers miniature prosthetic integration [2].

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2.3. Linkage-type underactuated mechanisms

Linkage underactuated hands employ a rigid linkage assembly as the core transmission unit, consisting overall of a base, drive motor, gear transmission pair, multiple sets of linkages, torsion/compression spring elastic elements, and finger segment components [3]. For example, the Hoeken-type finger adopts a composite configuration of a parallel four-bar mechanism and a Hoeken linkage. Pin shafts connect the linkages in series to form a closed kinematic chain, and springs are embedded as passive elements at the finger segment joints. With the number of actuators less than the joint degrees of freedom, adaptive grasping motion is achieved through the combined action of linkage constraints and elastic deformation, as shown in Figure 1 [3].

Figure 1. Hoecken gripper [3]

The literature presents a Hoeken linkage industrial gripper as a typical prototype, equipped with 2 drive motors and 4 active degrees of freedom, with a parallel gripping range of 14 cm and an adaptive grasping range of 6 cm [3]. The prototype completed grasping tests on various workpieces including tape, balls, plates, and cups, with a linear motion error of only 0.3% and stable grasping performance. It is suitable for industrial scenarios such as assembly line operations and material sorting, and represents a linkage-type industrial gripper that balances parallel gripping and irregular object enveloping [3].

Linkage mechanisms feature rigid transmission, low transmission loss, stable gripping force, and controllable trajectories, suiting industrial heavy-load conditions. However, stacked linkages occupy large internal space, the compliant adaptive range is limited, and complex multi-DOF linkage layouts are difficult to design, making it hard to achieve both large stroke and lightweight construction [3].

2.4. Soft underactuated mechanisms

Soft underactuated hands dispense with rigid linkages and pulley transmission pairs, employing an integrally molded matrix of silicone, hydrogel, or elastic composite materials with embedded fluid channels or intelligent deformable materials, and no discrete rotational joints [4]. Passive degrees of freedom are generated by the inherent elasticity of the material itself, and adaptive enveloping grasping is achieved through deformation. The overall structure comprises three layers: a soft body, embedded actuation chambers, and a variable stiffness module. Integral molding is realized through

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molding or 3D printing, yielding a lightweight structure with no sharp contact boundaries and higher human–robot interaction safety.

The mainstream soft actuation methods fall into two categories. Pneumatic artificial muscles generate continuous bending deformation through the pressure difference within the chamber, featuring a large strain range and stable output; they are divided into PneuNet and fiber-reinforced configurations [4]. Shape memory alloys (SMA) achieve contraction actuation through crystalline phase transformation triggered by heating via electrification, with an extremely simple structure and no need for pneumatic pipelines, but suffer from response lag and relatively small output force. The two actuation methods are often combined with variable stiffness granular interlayers to improve grasping stability.

Soft mechanisms provide inherent compliance for irregular workpieces, an integral lightweight structure, and safe human–robot collaboration, but soft materials are prone to fatigue and wear, deformation is strongly nonlinear, pneumatic schemes require an external air pump, and SMA actuation demands complex temperature control with much lower load capacity than rigid transmission [4].

3. Comparative case analysis of typical mechanisms

3.1. Analysis of typical mechanisms in tendon-driven biomimetic prosthetic hands

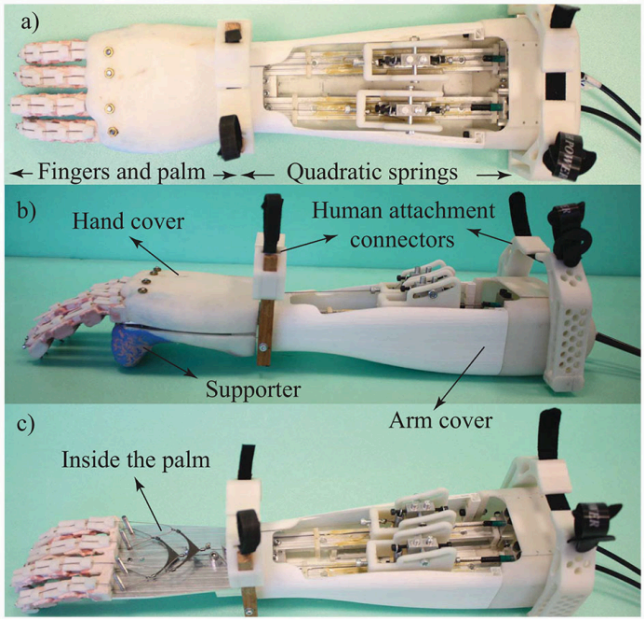

Figure 2. (a) Top view, (b) side view, and (c) interior of the transradial hand prosthesis prototype [5]

Tendon transmission relies on Bowden cables and antagonistic tendons to transmit driving force, allowing motors and energy-storage elements to be mounted externally at non-actuating ends such as the forearm; it is the mainstream transmission scheme for lightweight prosthetic hands, offering overall weight reduction, passive adaptive grasping, and hardware-based variable stiffness adjustment [5]. The under-wrist four-finger variable stiffness prosthetic hand designed by Hocaoglu et al. employs antagonistic tendons combined with nonlinear cam springs to form a variable stiffness actuator (VSA) drive unit. Through a single transmission structure, it simultaneously achieves finger pose regulation and continuous stiffness adjustment, and its multi-joint flexible fingers accomplish

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segmented flexion via underactuated tendon routing, enabling enveloping grasping of spherical, cylindrical, and other irregular objects without multiple actuators [5]. The prototype has an overall self-weight of only 1.1 kg, with a minimum-to-maximum joint stiffness range of 135–545 N·mm/rad (Figure 2) [5].

3.2. Comparative analysis of typical mechanisms in rigid linkage transmission

Purely rigid linkage mechanisms rely on hinges and parallelogram rigid links to transmit driving force, with no flexible medium in the transmission path. They exhibit high transmission efficiency, large structural stiffness, and prominent peak grasping force, but lack sufficient joint passive compliance, resulting in poor conformability when grasping irregular objects (Figure 3) [6]. Guan et al. quantified the performance of purely rigid linkage transmission through controlled experiments: under unified drive power, the maximum five-finger grasping force of the multi-finger hand reached 44.5 N, with a maximum single-fingertip pressure of 8.20 N (Figure 4) [6]. However, pressure-distribution experiments showed that the contact area is concentrated during grasping, with a small effective contact area that tends to cause local overload and crushing damage on thin-walled and fragile workpieces. Meanwhile, the fully rigid stacked structure results in a relatively large finger outer diameter and low biomimetic fidelity, limiting its use in confined spaces. Such mechanisms achieve finger-segment coordination through geometric constraints, feature simple control logic, and are free from cable wear and slack failures during long-term operation, making them suitable for power gripping of regular industrial parts [6].

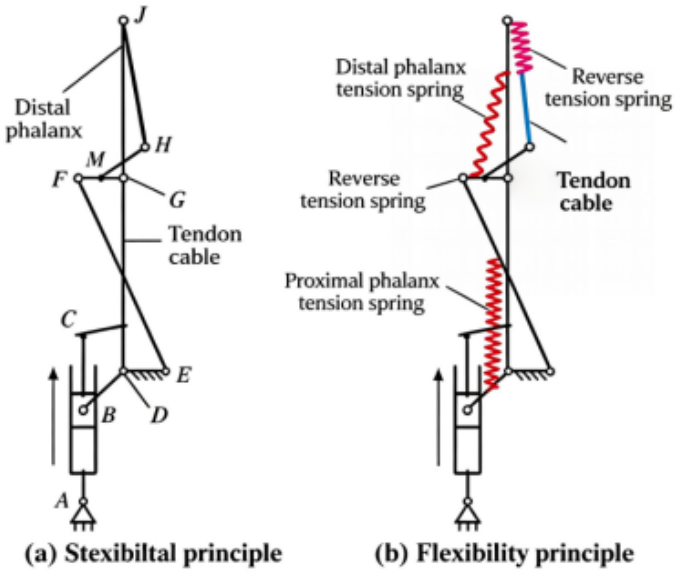

Figure 3. Structural and compliance principles of the finger

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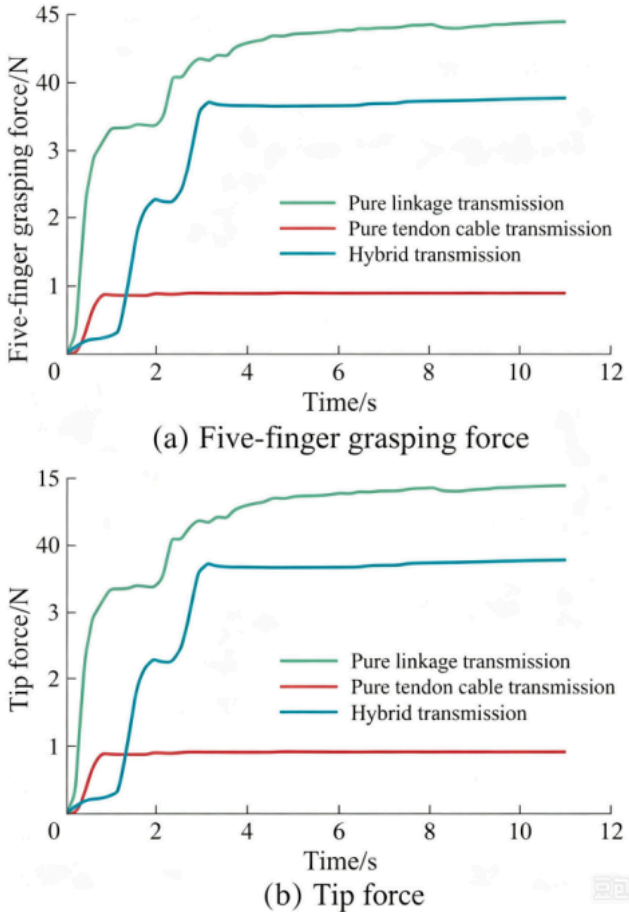

Figure 4. Comparative experimental curves of grip strength

3.3. Comparative case analysis of typical mechanisms in soft pneumatic robots

The modular scalable pneumatic soft gripper (Figure 5) is a typical representative of soft pneumatic grasping mechanisms. It employs multi-material composite silicone PneuNet pneumatic actuation units as the core actuation structure, driving finger bending through chamber inflation and deflation, and belongs to a standard purely soft pneumatic configuration without auxiliary components such as cables or shape memory alloys [7]. A magnetic self-sealing modular interface enables tool-free replacement of fingers of different sizes within 5 s. Three standardized pneumatic fingers (60 mm, 100 mm, and 150 mm) are provided, whose load capacity varies near-linearly with size and reaches a maximum gripping weight of 4.23 kg; the small fingers can manipulate tiny precision parts, allowing a single device to serve both high-precision manipulation and heavy-load grasping (Figure 6). In grasping tests on various irregular, fragile, and heavy workpieces, the overall grasping success rate reached 96.4%. The multi-layer silicone composite structure substantially improves the cyclic fatigue life, providing a standardized engineering case for industrial automation and non-destructive sorting of agricultural products [7].

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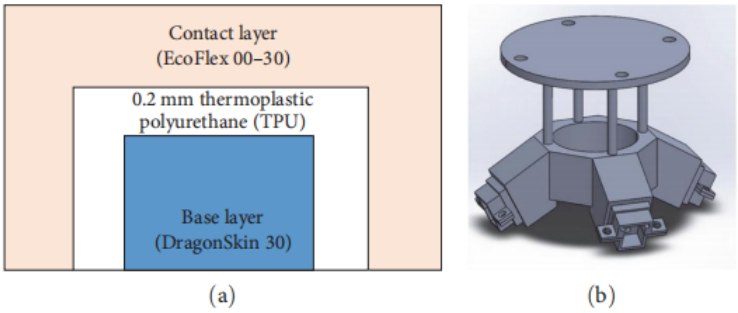

Figure 5. Design of the soft gripper. (a) Structural layers of finger design. (b) CAD model of finger mount [7]

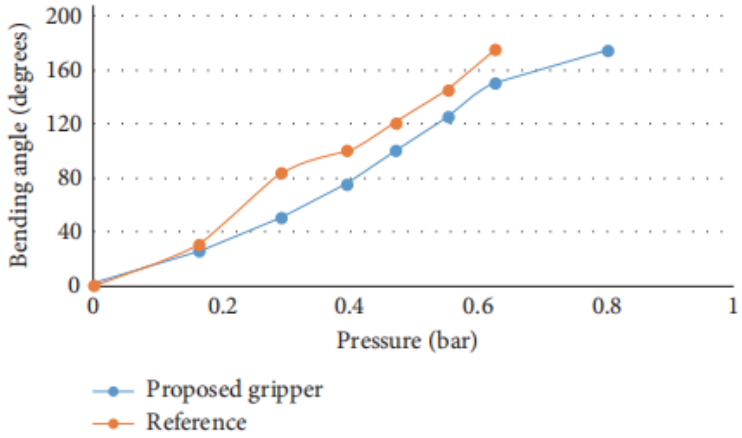

Figure 6. Comparative analysis of the bending angle for pressure difference [7]

4. Discussion

4.1. Existing challenges

Each of the three types of underactuated biomimetic robotic hands faces distinct technical bottlenecks. Linkage mechanisms offer high transmission rigidity and stable grasping force, but linkage stacking occupies a large space, the passive compliance range is narrow, and local stress overload is prone to occur when grasping thin-walled fragile parts [6]. Tendon transmission exhibits a prominent lightweight advantage, but cable friction, creep, and slack introduce strong nonlinearity, making high-precision tension distribution difficult to achieve [2]. Pneumatic soft grippers demonstrate excellent conformability to irregular objects, but silicone is prone to fatigue and wear under long-term cycling, the accompanying air pump limits overall portability, and the pressure–deformation coupling nonlinearity increases control difficulty [7]. Meanwhile, existing configurations generally suffer from low integration of tactile sensing and insufficient precision in force-position cooperative control. It remains difficult to simultaneously achieve payload, adaptability, and lightweight design. Most prototypes remain at the laboratory verification stage, lacking standardized modular mass production schemes, which limits their large-scale deployment in medical and industrial scenarios [4].

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4.2. Future development directions

Future research should focus on three major directions: hybrid actuation, smart materials, and data-driven control. Linkage–tendon–pneumatic hybrid transmission configurations should be developed to combine high payload with compliant grasping, paired with magnetic modular interfaces to expand applicable scenarios [6, 7]. Self-healing soft composite materials and distributed micro tactile sensing should be developed to improve the durability of pneumatic actuators, while physics-informed neural networks and reinforcement learning should be introduced to compensate for nonlinear errors and simplify dynamic modeling, thereby promoting the engineering application of biomimetic robotic hands in minimally invasive surgery, agricultural product sorting, and rehabilitation prosthetics [4, 5].

5. Conclusion

This paper reviews the three mainstream configurations of underactuated biomimetic robotic hands—linkage, tendon, and pneumatic soft actuation—and compares their structural characteristics, performance trade-offs, and applicable scenarios. The results confirm that each configuration possesses distinct advantages and inherent deficiencies, and that no single transmission structure can simultaneously achieve high payload, lightweight design, and full-shape adaptive grasping, corroborating the research gap consisting in fragmented classification and lack of cross-configuration comparison identified at the outset of this paper.

Through quantitative comparison of multiple prototypes, this study improves the existing theoretical framework, which previously analyzed only a single actuation mechanism individually, and provides a practical reference for configuration selection and structural optimization of underactuated robotic hands in minimally invasive surgery, industrial sorting, and rehabilitation prosthetics. Future work should construct a linkage–tendon–pneumatic hybrid actuation prototype and combine tactile sensing with intelligent control algorithms to experimentally validate the comprehensive performance of hybrid transmission schemes.

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