Customize-Your-Joy Hand: A user-oriented, cost-effective 22-DOF platform for future human-robot community

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Abstract—**Humanoid dexterous hands have significant potential in prosthetics, service robotics, and high-performance manipulation. However, existing designs often struggle to balance the challenging requirements of lightweight design, high biomimicry, personalized customization, and low cost. To address these challenges, we present the CYJ Hand (Customize-Your-Joy Hand), an innovative 22-DOF humanoid dexterous hand. Featuring a highly biomimetic structure, the CYJ system weighs only 750 grams（forearm included）. Its modular design supports user-oriented customization while simplifying assembly, maintenance, and functional expansion. Inspired by Da Vinci's mechanics, the CYJ Hand integrates a novel, controllable tendon mechanism that allows for reconfigurable tendon routing and actuation system to meet diverse needs. Constructed with 3D printing and affordable commercial materials, the hardware cost for the CYJ Hand structure (excluding actuators) is under $60. Experimental results demonstrate that the CYJ Hand achieves a 100% success rate in both the Kapandji Test and GRASP taxonomy, and further exhibits dynamic grasping, in-hand manipulation, sub-millimeter motion repeatability (~0.7 mm), and reliable load-bearing performance, validating its exceptional dexterity and biomimetic design. With its comprehensive advantages and innovations， the CYJ Hand provides a versatile platform for the future applications and research in personalized prosthetics and dexterous robotic manipulation, bridging the gap between high dexterity and accessibility in humanoid robotics. Related files and methods are open-sourced at GitHub repository.**

Index Terms-- **Mechanism Design, tendon/wire mechanism, user-oriented customization, humanoid dexterous hand, reconfigurable transmission and actuation**

I. Introduction

As one of nature's most complex "tools" ,the human hand integrates a flexible structure, precise actuation, advanced sensing, and efficient control, demonstrating unparalleled perception and dexterity [1].The primary distinction between the human hand and traditional mechanical grippers lies in its flexibility and versatility. Through the evolution of the hand, humans have set themselves apart from other species on Earth. By designing tools to be used with our hands and mastering the use of fire, we have paved the way for transforming and conquering the natural world. Similarly, the design of humanoid dexterous hands (HDHs) aims to enable patients and robots to seamlessly interact with human-designed environments, tools, and workspaces, bridging the gap between human capabilities and robotic functions. Incorporating the characteristics of the human hand into the design of HDHs is not only a pursuit of biomimetic perfection but also a critical strategy for advancing intelligent and biomimetic technologies toward the future [2], [3].

Over the past two millennia, materials used in HDHs have evolved from wood to alloys and, more recently, to 3D-printed materials. Their functionality has also progressed from static ornaments to simple prosthetics and, ultimately, to systems with degrees of freedom (DOFs) approaching those of the human hand. Despite significant progress, current HDHs still face challenges in achieving universality due to a fundamental conflict among high biomimicry, low cost, and customization. Mass-produced HDHs struggle to accommodate the diverse needs of individual patients or robotic models, while custom designs require specialized manufacturing, making them costly and difficult to scale. This trade-off limits the ability of existing solutions to offer versatile, cost-effective designs suitable for widespread adoption: (i) In the field of anthropomorphic prosthetic hands (APHs), despite the commercial success of biomimetic designs such as Ottobock's Bebionic hand [4], Ossür's iLimb hand [5], and the Vincent hand [6], the growing needs of amputees often lead to increases in size, weight, and cost when integrating more advanced functions and sensory systems [7]. (ii) In the field of dexterous robotic hands (DRHs), actuators, gears, and linkages provide reliable and stable solutions [8]–[10]. However, it inevitably increases weight and inertia, complicates motor optimization, escalates costs, and imposes greater load demands on both robotic and patient arms. (iii) In the research field, HDHs incorporating flexible joints [11], [12], ball-and-socket joints [13], and high pairs joints typically offer enhanced compliance and a wider range of motion. Other notable HDHs, such as the FLLEX hand [14], Zhu Yiming's finger [2], X-Hand III [15], and Xu Zhe's hand [16], have integrated additional human-like structural elements, making their appearance and functionality almost indistinguishable from that of a natural human hand. However, despite these advancements, they still encounter significant limitations in terms of interchangeability, manufacturing complexity, impact resistance, and durability.

Beyond sensors and algorithms that can enhance system performance, the development of more humanized, lightweight, and cost-effective HDHs requires innovative structural designs and transmission mechanisms. After several iterations, we introduce the Customize-Your-Joy Hand, a 22-DOF humanoid dexterous hand as a balanced solution to address the challenges aforementioned. With 3D printers, fasteners, and high-tensile fishing lines, the CYJ Hand struc-

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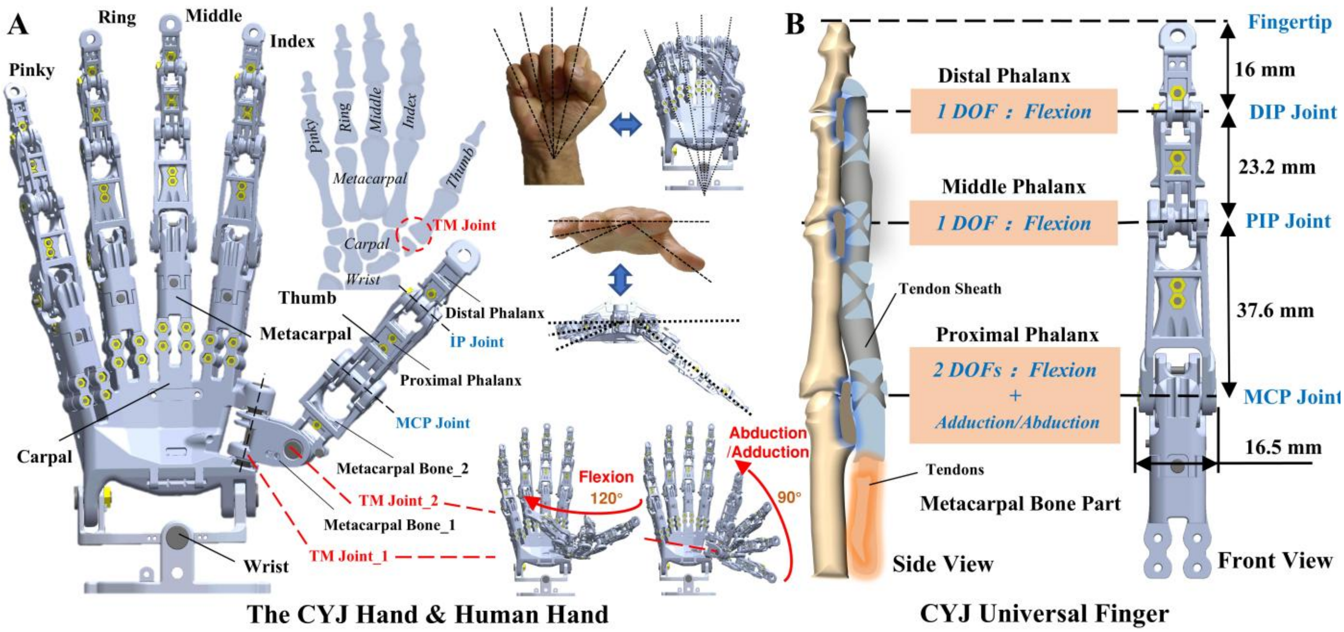

Figure 1. Biomimetic Design of the CYJ Hand. (A) 3D model schematic of the CYJ Hand. (B) Detailed view of the universal finger structure.

ture can be conveniently fabricated for under $60 in hardware cost. This versatile platform can serve as both a customizable prosthetic designed for specific needs and a robotic hand for algorithm deployment.

Unlike prior works focusing on either high performance [17] or extreme affordability [18], the CYJ Hand introduces a new design paradigm that bridges this divide through: (i) A 22-DOF, highly biomimetic, and lightweight (153 g) 3D-printed HDH structure that supports user-oriented customization for both patients and robots. (ii) A tendon-driven transmission system inspired by human muscle-tendon mechanics, featuring a controllable tendon mechanism that enables reconfigurable tendon routing and actuation systems. (iii) A modular design that allows for easily replaceable and upgradeable parts, facilitating maintenance and functional expansion. (iv) A rapid manufacturing process with significant cost advantages, enabling easy assembly and scalability, while maintaining a structural load-bearing capacity of 4 kg per finger and 10 kg for the entire hand. (v) Excellent performance in motion, dynamic and static grasping, as well as in-hand and tool-use manipulation tasks, as demonstrated in experimental evaluations. This system-level co-design strategy enables accessible dexterous manipulation through a user-oriented, cost-effective 22-DOF platform, paving the way for practical applications in human-robot communities (open-sourced at GitHub repository).

II. Biomimetic Design of The CYJ Hand

A. Skeletal structure

The human hand, with its intricate anatomical structure, serves as the gold standard for dexterity and adaptability. Its skeletal framework comprises 27 bones, and its weight typically accounts for approximately 0.6% of an individual's body mass [19] (e.g., ~420 g for a 70 kg adult). In comparison, the CYJ Hand weighs only 153 g, significantly lighter than both the human hand and most existing HDHs. When integrated with the forearm (including actuators), the total weight of the CYJ system is 750 g—less than one-third the weight of a human arm [20], [21] (2.31 kg for hand + forearm in a 70 kg adult). This lightweight design is achieved through a combination of 3D-printed materials and optimized mechanical structures, while maintaining a 1:1 scale with the human hand in terms of shape, size, and functionality. The overall structure, illustrated in Fig. 1.A, includes eight primary components arranged to match the anatomical layout of the human hand, and achieves 22 DOFs for enhanced dexterity and motion capabilities.

The interphalangeal joint design is a cornerstone of HDH structures. In the human hand, joints are capable of withstanding high forces while maintaining precise alignment, supported by a complex interplay of muscles, tendons, and ligaments. As shown in Fig. 1.B, the structure of the CYJ universal finger mirrors that of the human hand, with three phalanges (proximal, middle, and distal) and three joints (MCP, PIP, and DIP). The fingers excluding the thumb share nearly identical structures, expect for the shorter proximal phalanx of the pinky finger. Inspired by the design principle of 'more human than human' [22], the CYJ Hand employs traditional mechanical hinge joints enhanced with sliding bearings and biomimetic contours. This modular design not only mimics the functionality and joint constraints [23] of the human hand but also reduces costs and optimizes resource utilization.

The thumb is crucial for hand function, contributing more than 50% to the hand's grasping ability [24]. The TMC (carpometacarpal joint) grants it a greater range of motion than the other fingers, enabling it to create an overlapping workspace with the opposing fingers and enhancing its control capabilities [25]. As shown in Fig. 1.A, the TMC joint in the CYJ Hand is divided into two segments: the first segment handles flexion-extension, while the second segment manages abduction-adduction. The flexion-extension segment is positioned along the extension of the carpal bone and hinged using a bolt acting as an axle with two thrust bearings, which were chosen over ball joints for their higher load capacity, reduced mechanical complexity, and ease of manufacturing. This dual-segment design was adopted to address the signif-

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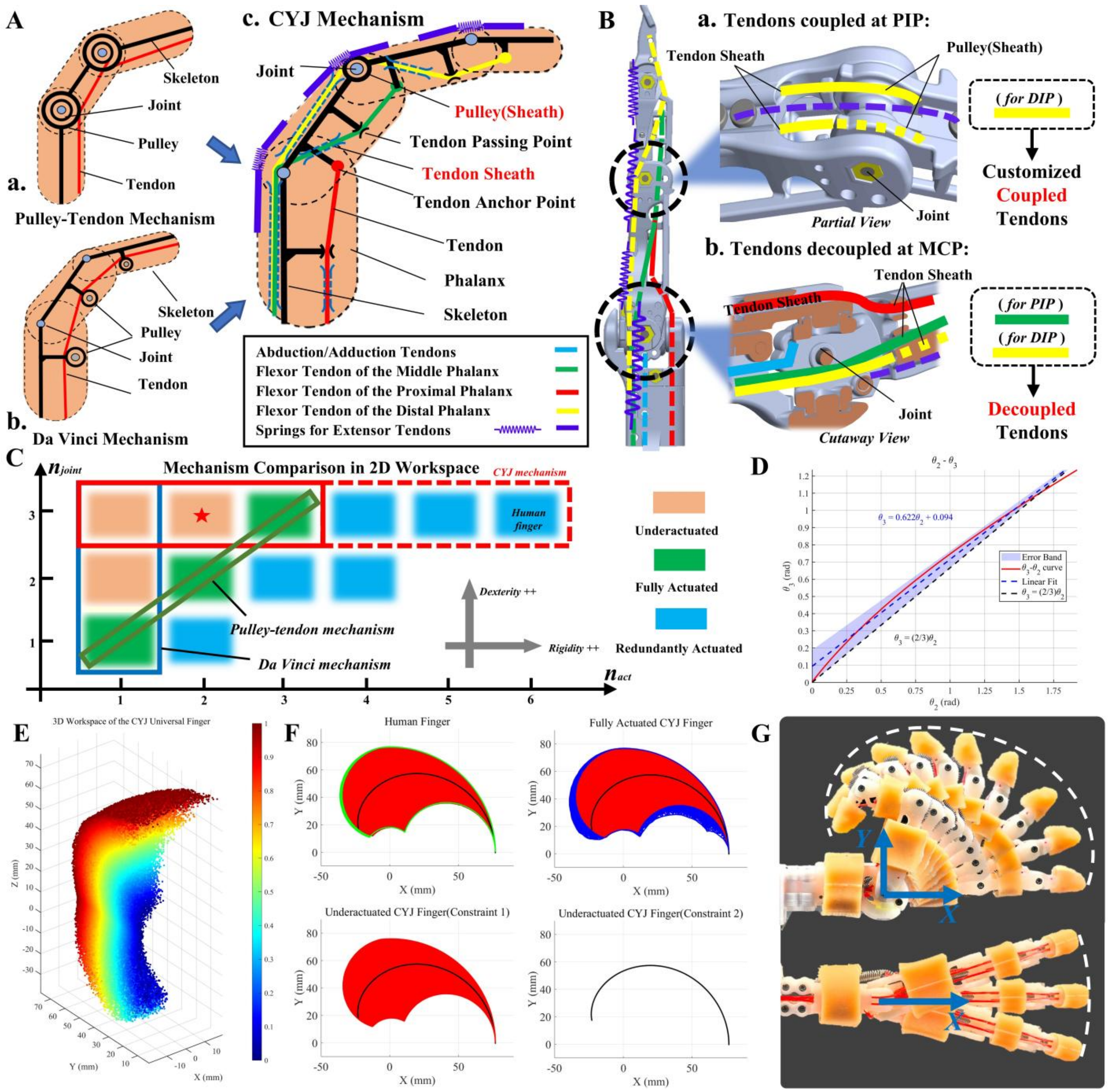

Figure 2. Tendon-driven system and CYJ mechanism. (A) Detailed illustration of the CYJ mechanism. (B) The tendon responsible for DIP flexion is customized-coupled at the PIP joint, while the tendons driving DIP and PIP flexion are highly decoupled at the MCP joint. (C) Mechanism comparison in planar flexion workspace. (D) Linear relationship between the DIP (θ_3) and PIP (θ_2) joint angles, demonstrating a coupling pattern consistent with that of the human finger. (E) 3D reachable workspace of the CYJ universal finger. (F) Planar flexion workspaces of the CYJ universal finger under different actuation modes. (E) Flexion and abduction-adduction motion of the CYJ universal finger with joint and fingertip.

icant challenges of replicating the TMC's saddle-shaped surface with a biomimetic ball-and-socket joint, which would require at least four independently controlled tendons and still fail to fully replicate natural motion. In contrast, the CYJ Hand's design not only simplifies control and hardware implementation but also provides greater flexibility and precision in thumb positioning, resulting in a larger functional workspace and enhanced dexterity during complex grasping tasks. The metacarpal, proximal phalanx, and distal phalanx of the thumb are similar to the corresponding bones of the CYJ universal finger but are approximately 1.5 times larger to enhance strength and dexterity. Compared to Xu Zhe's model [16], which employs a single-segment TMC joint, this approach offers a more practical and effective solution for achieving human-like thumb functionality.

B. Tendon-driven system

Tendon-driven transmission, inspired by human muscles and tendons, is widely adopted in HDHs with external actuation systems. Notable examples such as the Shadow Dexterous Hand [17] and Awiwi Hand [26], which demonstrate considerable potential of this approach. Tendon-driven systems typically utilize high-tensile polymer materials (e.g., nylon, fluorocarbon fiber, or UHMWPE), offering low density, high strength, and excellent flexibility [27], [28]. Unlike rigid linkages and gears, which are prone to damage under high-impact forces, flexible tendons can absorb energy, elongate, and recover after force release. This energy-absorbing capability enhances durability and protects both the structure and actuators. Moreover, this compliant transmission mechanism is particularly suited for human-robot interaction, as it reduces the risk of injury during overload conditions.

The underactuated mechanism, with origins traced back to Leonardo da Vinci [22], is widely used in high-DOF HDHs to reduce weight and complexity. However, the conventional pulley-tendon mechanism [29] (Fig. 2.A.a) and Da Vinci mechanism (Fig. 2.A.b) adds mechanical complexity and increases end-effector mass due to the use of multiple shafts and pulleys. As shown in Fig. 2.A.c, the CYJ mechanism we developed requires only tendon displacement to infer and control joint flexion angles, eliminating the need for additional angle sensors. It integrates the advantages of former designs into a more compact and flexible architecture:

- **Compactness**: The CYJ mechanism eliminates the need for pulleys that are coaxial with joints or mounted on the frontal surfaces of the phalanges. Instead, it employs rigid and lubricated tendon sheaths embedded within biomimetically shaped finger bones. As shown in Fig. 2.B.a, the yellow tendons pass through sheaths located along the anterior and posterior sides of the joints, and in Fig. 2.B.b, the red tendons pass through the palmar side of the metacarpal bone.
- **Customizable decoupling/coupling strategies**: As shown in Fig. 2.B, the tendon responsible for DIP flexion is customized-coupled with the PIP joint to ensure coordinated motion. Meanwhile, the tendons actuating the DIP (the yellow tendon) and PIP (the green tendon) joints are structurally decoupled at the MCP joint to preserve actuation independence. Notably, the coupling strategy adopted in the CYJ mechanism closely mirrors the dynamic inter-joint coordination observed in human fingers [23], as shown in Fig. 2.D. The distance from the joint center to the tendon is a customizable parameter that enables dynamic adjustment of joint constraints. By adjusting this radius, the same joint flexion angle can be achieved with different tendon displacements, offering greater flexibility in design and control.
- **Reconfigurable transmission solutions**: Another key advantage of the CYJ mechanism is its ability to reconfigure the degrees of actuation (DOAs) As shown in Fig. 2.C, the CYJ mechanism achieves greater dexterity and rigidity, while also supporting extension toward antagonistic actuation. A more detailed explanation of the practical implementations is provided in Section III.A.

We modeled the CYJ finger's kinematics to estimate its theoretical 3D reachable workspace (4-DOF, 4-DOA), as shown in Fig. 2.E. A comparative analysis of the 2D planar flexion workspace (excluding adduction/abduction) was also conducted. As shown in Fig. 2.F, the fully actuated configuration (blue region) achieves a workspace of 5129.73 mm², while the human finger model with inter-joint coupling constraints (green region) reaches 4363.19 mm². In comparison, the 3-DOA underactuated configuration (red region), which adopts a coupling strategy, yields a workspace of 4171.91 mm², representing 81.3% of the fully actuated case and 95.6% of the human finger model.

Moreover, the red and green regions exhibit a high degree of overlap, further indicating that the biomimetic

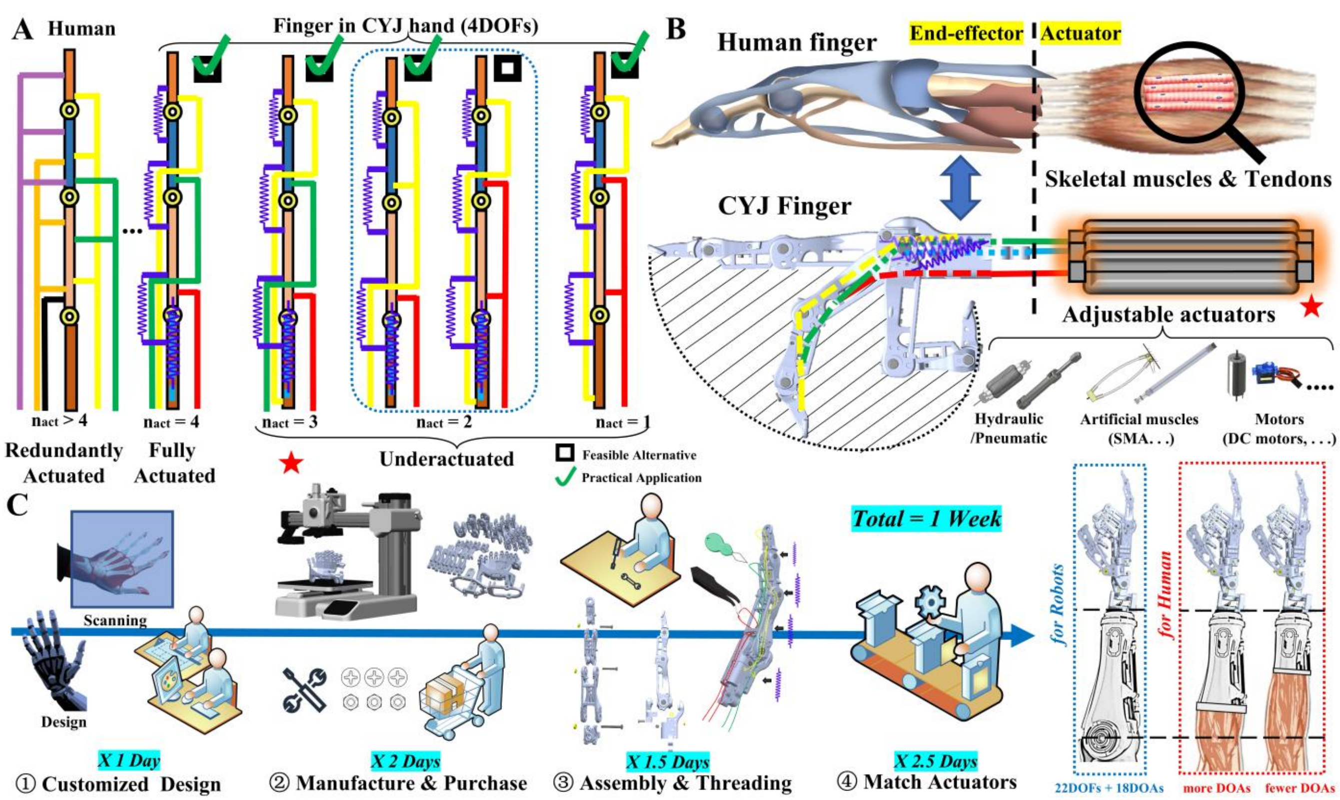

Figure 3. Reconfigurable and customizable solutions. (A) Comparison between the abstract models of CYJ universal fingers with customizable DOAs. (B) Adjustable actuation system of the CYJ universal finger. (C) Fabrication flowchart of the CYJ Hand.

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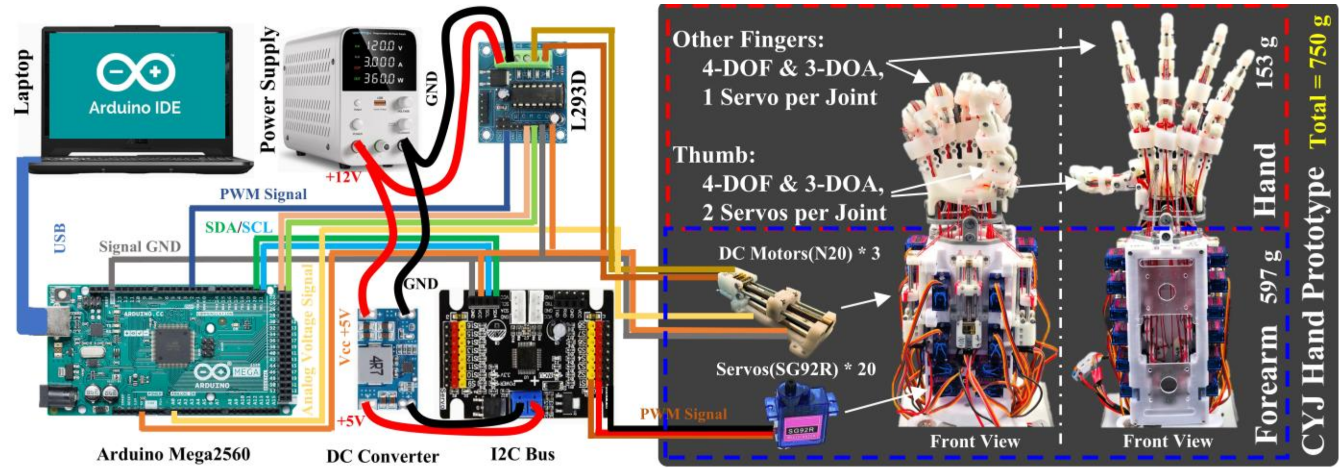

Figure 4. The control system and the actuation system configuration of the CYJ Hand prototype.

coupling design employed in the CYJ finger closely resembles the kinematic behavior of the human hand. These results suggest that the 3-DOA underactuated design not only satisfies biomimetic performance criteria but also provides a more efficient workspace, making it better suited for anthropomorphic manipulation than the fully actuated 4-DOA counterpart. Additionally, the fourth subfigure of Fig. 2.F illustrates the case where all flexion joints are actuated by a single tendon set (i.e., fully coupled linkage). In this configuration, the workspace degenerates into a single curved trajectory. The realization of these features relies heavily on the CYJ Hand's unique structural design. As shown in Fig. 2.G, the CYJ finger (4-DOF, 3-DOA) supports both flexion and abduction–adduction motions.

III. Reconfigurable and Customizable Solutions

A. *Reconfigurable tendon routing*

With advancements in manufacturing, actuators, and control algorithms, achieving dexterity beyond 3-DOF in a single finger has become feasible. While Section II.B introduced the features of the CYJ mechanism, this section elaborates on how it functions as configurable, bio-inspired transmission solution rather than a compromise to simplify actuation system. As shown in Fig. 3.A, it enables customizable DOAs for each finger without structural modifications, enabling flexible tendon routing and diverse actuation modes. Each finger, as well as the entire hand, can be reconfigured with under-actuated, fully-actuated, or over-actuated mechanisms. For instance, more tendons and actuators can be allocated to key fingers (e.g., thumb and index), while less critical fingers (e.g., ring and pinky) are assigned fewer DOAs, leveraging their inherent enslaving effects [30]. This approach reduces the number of tendons and actuators, minimizing weight and complexity without compromising functionality.

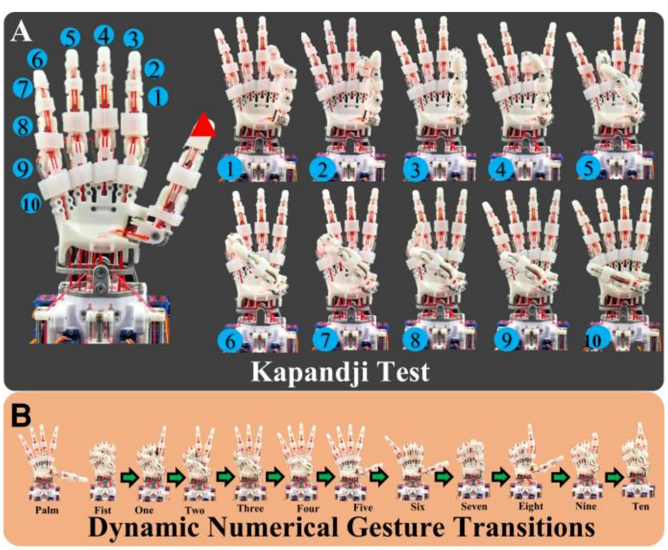

Figure 5. Demonstrations of motion capabilities of the CYJ Hand.

B. *Reconfigurable actuation system*

As shown in Fig. 3.B, the actuation system of the CYJ Hand also provides significant flexibility, supporting various actuator types—such as electric motors, hydraulic or pneumatic actuators, and artificial muscles [31]—as well as customizable actuator quantities. This versatility allows selective optimization of actuator types and configuration for specific joints based on their functional requirements. For example, joints requiring high force output but lower response frequency (e.g., wrist and thumb TMC joints) can utilize hydraulic systems or SMA (shape memory alloy), which excel in delivering high torque and compact size. Conversely, joints demanding high precision, fast response, and moderate force (e.g., finger PIP and DIP joints) are better suited for electric motors, which offer superior controllability and dynamic performance. This hybrid actuation strategy is inspired by the human musculoskeletal system, where different muscle types (e.g., slow-twitch and fast-twitch fibers) are distributed across the hand and arm to optimize force output, response speed, and energy efficiency.

C. *Customizable solutions*

The CYJ Hand operates on two levels of hybridization:

- **Transmission Mode Hybridization**: Reducing structural complexity and overall weight.
- **Actuator Type Hybridization**: Optimizing performance across diverse tasks.

This dual-level hybridization represents not only a technical innovation but also a practical customization strategy. Users can tailor both actuation and transmission configurations according to specific functional requirements. For instance, a prosthetic user may prioritize high force output for heavy lifting, whereas a service robot may demand

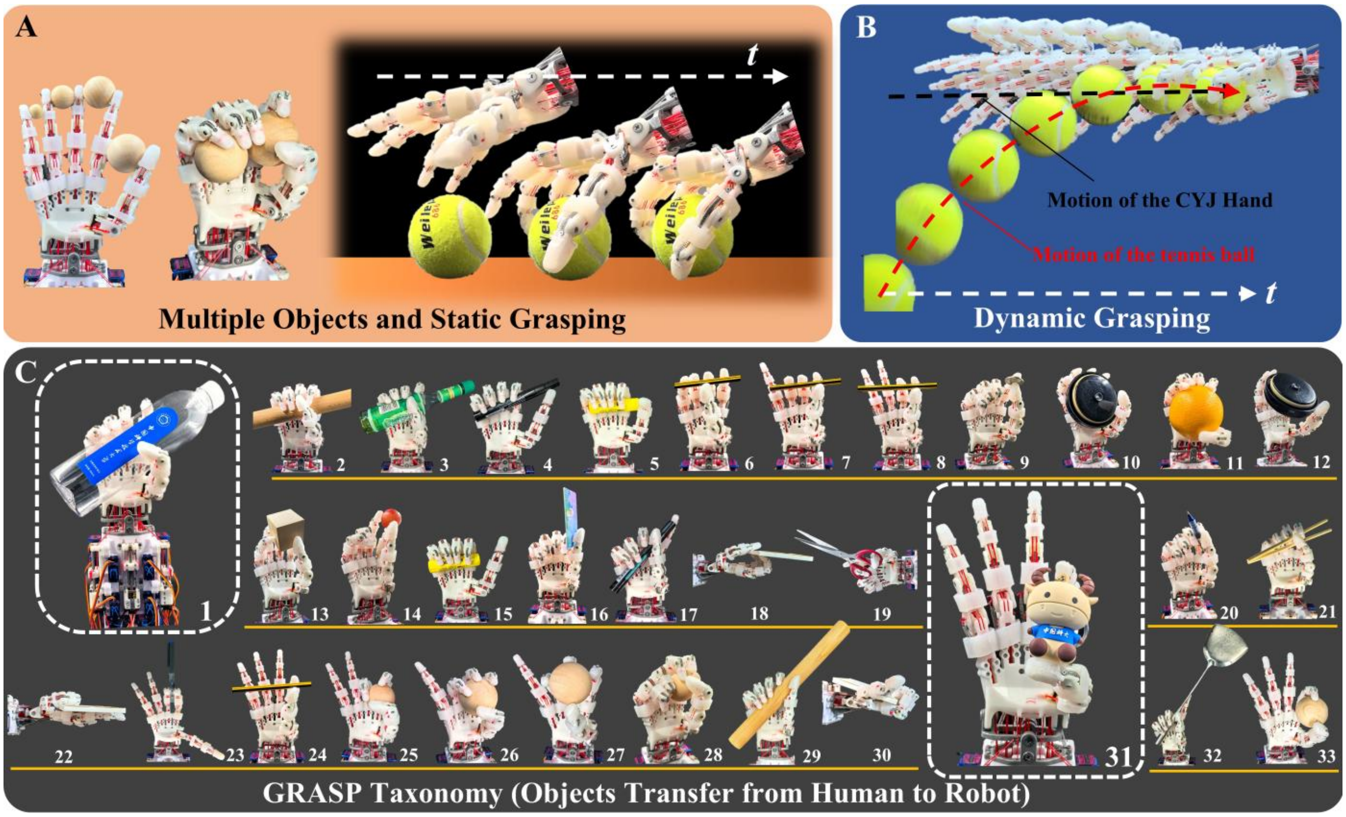

Figure 6. The grasping performance of the CYJ Hand.

high-speed precision for delicate tasks. In contrast, existing HDHs such as the Optimus robot [32], Torso robot [33], and Shadow Dexterous Hand [17] often rely on a single actuator type and fixed transmission modes, which limit their adaptability across broader user needs. Apart from this, the design also minimizes rotational inertia and enhances end-effector load capacity. As a result, this approach broadens the functional capabilities of the CYJ Hand and demonstrates a high level of user-oriented versatility in HDH design.

Moreover, the CYJ Hand model is developed using parametric 3D modeling, which enables personalized customization in physical dimensions and appearance. The digital 3D models allow for precise adjustments to meet the specific requirements of patients [34], such as age group (child or adult), gender, and ethnicity, providing a highly personalized prosthetic solution. For example, the hand's size, finger length, and joint proportions can be tailored to match the user's anatomy, ensuring both comfort and functionality. This level of customization, combined with the CYJ Hand's lightweight design and cost-effective manufacturing, minimizes the financial burden on patients while providing a versatile prosthetic solution.

Beyond prosthetics, the CYJ Hand's development lowers the barrier to entry for global researchers. By offering an open-source, customizable platform, it enables further advancements in robotics, artificial intelligence, and related fields. Additionally, the scalable manufacturing process and modular design have the potential to significantly lower the base cost of large-scale humanoid robot applications, making advanced robotic hands more accessible to researchers worldwide.

As shown in Fig. 3.C, the CYJ Hand and its integrated forearm can be fabricated through four streamlined steps: customized design, manufacture & purchase, assembly & threading, and actuator integration. The total process takes approximately one week. With most components 3D printed, the total hardware cost of the CYJ hand remains under \$60, and the full prototype under \$200.

In the prototype, the forearm integrates 20 servos and 2 DC motors to actuate the fingers and wrist, as illustrated in Fig. 4. The thumb employs a fully-actuated mechanism (4-DOF, 4-DOA) for enhanced precision, while the remaining fingers utilize under-actuated configurations (4-DOF, 3-DOA) to reduce complexity and weight. Overall, the CYJ Hand operates in an under-actuated configuration (22-DOF, 18-DOA), with a total mass of 750 g, including the forearm.

IV. Performance Evaluation of the CYJ Hand

A. Motion Capabilities

To evaluate the motion capabilities of the CYJ Hand, we conducted the Kapandji Test [35] , which assesses the thumb's ability to touch specific areas on the hand (Fig. 5.A). The test scores range from 0 (no opposition) to 10 (maximum opposition), with full scores rarely achieved by most HDHs due to limited thumb dexterity [11]. While less biomimetic designs typically score 1-2 points, and advanced designs may reach 6-8 points [15], [36], the CYJ Hand achieved a perfect score of 10, matching the performance of a healthy human hand. Moreover, the CYJ Hand can perform various complex human-like and beyond-human gestures. As illustrated in Fig. 5.B, it demonstrated the ability to continuously execute dynamic numerical gesture transitions. Motion capture tests showed ~0.7 mm repeatability across 20 cycles, validating the CYJ fingers' consistency and precision.

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B. Grasping Performance

As shown in Fig. 6, the grasping performance of the CYJ Hand was evaluated in both static and dynamic scenarios, demonstrating not only stable grasping of multiple objects but also successful capture of a flying tennis ball. To further assess its versatility, we conducted a comprehensive experiments based on the GRASP taxonomy [37], which classifies 33 common human grasp types across 17 object shapes. Achieving all grasp types remains a significant challenge for many rigid-structured HDHs [16], [38] , yet the CYJ Hand successfully completed all 33 types, as shown in Fig. 6.C. These results underscore the CYJ Hand's high dexterity and practical utility, enabling both robotic systems and prosthetic users to interact seamlessly with diverse tools and environments.

C. Manipulation and Human-Robot Interaction

We further demonstrated the CYJ Hand's capabilities in fine manipulation and human–robot interaction. As shown in Fig. 7.A, the CYJ Hand acquired basic skills in in-hand manipulation through training, including the rotation and repositioning of a cube and a sphere. It also demonstrated the ability to use tools, notably exhibiting preliminary typing functionality on a laptop keyboard in a human-like manner (Fig. 7.B). Furthermore, it engaged in interactive tasks such as fingertip contact, handshake, and rock-paper-scissors, as illustrated in Fig. 7.C. These demonstrations highlight the CYJ Hand's biomimetic morphology and structural design, as well as its sufficient motion precision and speed—features essential for service robots and prosthetic applications. More details, including load-bearing capacity tests, are available in the supplementary materials and movies.

V. Discussion

To contextualize our contributions, we compare the CYJ Hand with several notable HDHs, including the Shadow Dexterous Hand [17], Awiwi Hand [26], LEAP Hand [18], and RBO Hand 3 [11], across key metrics such as DOF, DOA, transmission mechanisms, weight, hardware cost, customization, and manufacturing complexity (Table I).

Despite its demonstrated features, the current CYJ Hand prototype has several limitations that inform future improvements. Tendon friction may be further minimized by integrating lubricated tubes and optimizing materials (e.g., PEEK) to enhance structural performance. The compact wrist design introduces slight posture coupling during radial/ulnar deviation; this can be addressed via mechanical or control-level decoupling. Additionally, the use of low-cost actuators limits high-force or high-precision tasks. Future work will explore advanced actuation modules, hybrid strategies,

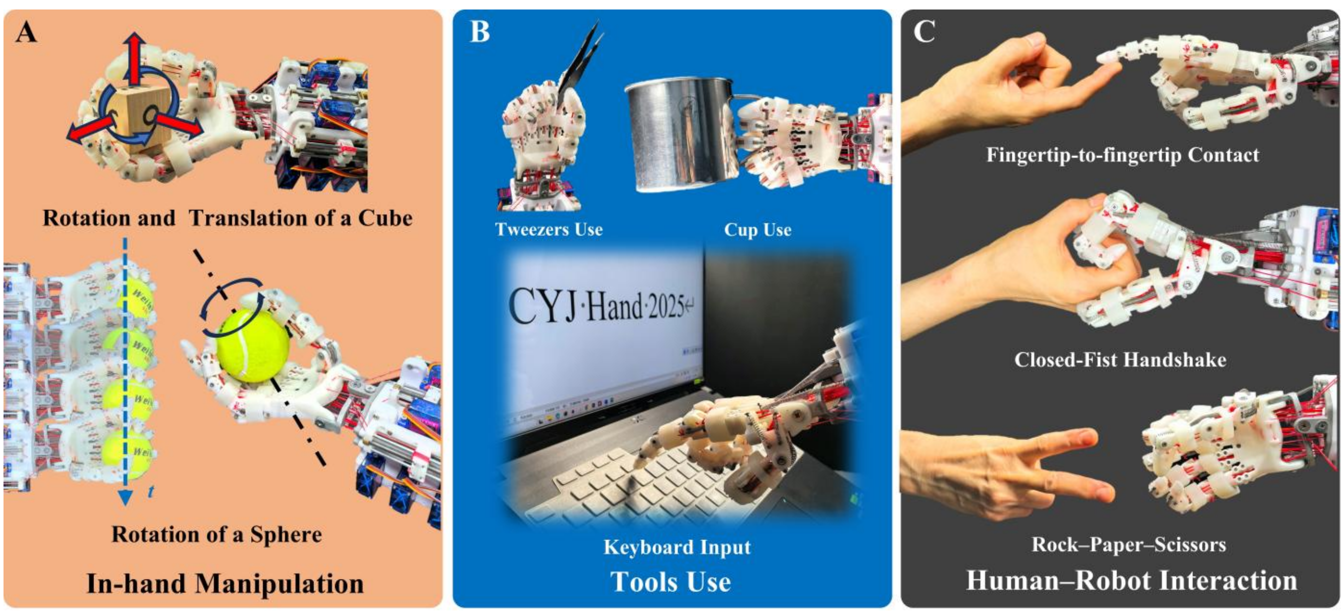

Figure 7. Demonstrations of manipulation and human-robot Interaction capabilities of the CYJ Hand.

TABLE I. COMPARISON OF CYJ HAND WITH OTHER HDHS

Property	CYJ Hand	Shadow Hand[16]	Awiwi Hand[25]	LEAP Hand[17]	RBO Hand 3[11]
DOF	22	24	19	~20	16
DOA	18	20	38	~16	16
Transmission	Tendon-driven	Tendon-driven	Tendon-driven	Direct-driven	Pneumatic
Driving	External +Motor	External + Motor	External + Motor	In-Situ + Motor	In-Situ + Pump
Weight (g)	153 (without forearm)	4300 (with forearm)	500 (without forearm)	595 (no forearm)	-
Hardware Cost (USD)	<$60	High	High	~$2k	Relatively low
Customization	High (user-oriented)	Limited	Limited	Partial	Partial
Manufacture Process	Simple (3D printing)	Complex	Complex	Relatively Simple	Relatively Simple

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and sensing integration to improve control compactness, reduce friction and creep in tendon transmission, and expand the system's functional scope.

VI. Conclusion

The CYJ Hand effectively addresses the longstanding challenges of balancing high dexterity, lightweight design, and cost-effectiveness in HDHs. By integrating a highly biomimetic structure, a novel tendon-driven mechanism and a modular design, the CYJ Hand achieves exceptional performance in several practical tests. Its user-oriented customization allows for rapid manufacturing and tailored solutions to meet diverse needs for real-world applications in prosthetics, service robotics, and human-robot collaboration. Meanwhile, its open-source design and low hardware cost significantly lower barriers to entry. In conclusion, the CYJ Hand bridges the gap between high-performance robotic systems and accessible, cost-effective technology, bringing us closer to realizing the vision of seamless human-robot interaction in everyday life.

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