High-DoF Dexterous Soft Hand With an Enhanced Thumb-Palm Composite Design Enables Robust Grasp and Dexterous Manipulation

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***Abstract*—Soft robotic hands, owing to their compliance and adaptability, have been widely studied, however, the inherent softness and limited Degrees of Freedom (DoFs) often limit their use to grasping rather than dexterous manipulation. In this work, we present a high-DoF soft hand with an enhanced thumb-palm composite featuring a bio-inspired soft-rigid hybrid structure. The composite integrates two orthogonal servomotors and a soft bending actuator arranged in series, enabling a wide-range workspace, high-DoF actuation, precise thumb trajectories, and multidirectional force output. We further adopt four two-chamber bending actuators as fingers to form efficient coordination with the thumb to achieve a more robust grasp and dexterous manipulation. We characterize the workspace of the hand and the mechanical performance of the thumb-palm composite, validating the kinematic model and the grasp enhancement via the soft-rigid hybrid structure. Standardized assessments, including the Kapandji test and the Feix GRASP taxonomy, are conducted using the proposed hand, demonstrating the thumb dexterity and grasp diversity of the proposed design. Finally, experiments across various daily and task-oriented scenarios show that the hand provides a wide-range thumb workspace, stable and versatile force output, and effective finger coordination, thereby enabling robust grasping and dexterous manipulation across diverse applications. The stability and repeatability of the hand are further validated through repetitive execution tests.**

***Index Terms*—Soft robotic hand, soft-rigid hybrid structure, grasp, dexterous manipulation.**

I. Introduction

HUMAN hands are remarkable for their high DoFs, exceptional dexterity, and ability to perform both precise and wide-range movements while ensuring stable force output in daily tasks [1], [2]. Therefore, replicating such versatile functions has long been a major research goal in robotic hands. While high-DoF rigid hands achieve complex manipulation, they often suffer from mechanical complexity, bulky structures, and limited interaction compliance [3], [4], [5], [6]. Recently, soft hands offer a promising alternative owing to their structural simplicity, inherent compliance, and scalability for high-DoF designs [3], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16].

Despite the advantages, existing soft hands are primarily optimized for stable grasping, lacking sufficient DoFs for dexterous manipulation. One critical limitation is the dexterity of the soft hand's thumb-palm composite. In the human hand, as shown in Fig. 1(a), the thumb is capable of dexterous motion with multiple DoFs enabled by its anatomical structure [1]. It plays a central role in manipulation by providing a wide workspace, omnidirectional force output, and efficient coordination with the palm and other fingers. Nevertheless, achieving comparable dexterity in soft hands remains challenging, particularly regarding force generation and finger coordination.

To enhance thumb dexterity, researchers have introduced various soft actuation strategies at the carpometacarpal (CMC) joint [3], [12], [13], [17], [18], [19], [20], [21], [22], [23]. Approaches include adding a single basal bending joint for pronation [13], [17], arranging multi-directional bellows [12], [19], or utilizing parallel-chamber actuators [18] have been proposed. However, the inherent softness of the soft actuators serving as the CMC joint may compromise the output force. Soft-rigid hybrid approaches have also been explored to improve the CMC functionality [24], [25], [26], [27], [28], [29], [30], [31], [32], [33]. For instance, coupling soft bellows with rigid links enables the generation of specific motion trajectories [34]. Alternatively, actuating rigid skeletons via shape-memory alloys [29] or complex cable arrangements [27] can achieve versatile manipulation, but these often significantly increase design and control complexity. Directly mimicking the physiological structure of the human hand is also investigated by researchers [24], [35], [36], [37]. Detailed reproductions of anatomical features, such as ligamentous joints and tendon sheaths, enable human-like grasps [24], [36]. However, faithful anatomical replication typically entails fabrication challenges and complex control requirements.

To address the trade-off between the structural and control complexity of rigid hands and the limited force output and

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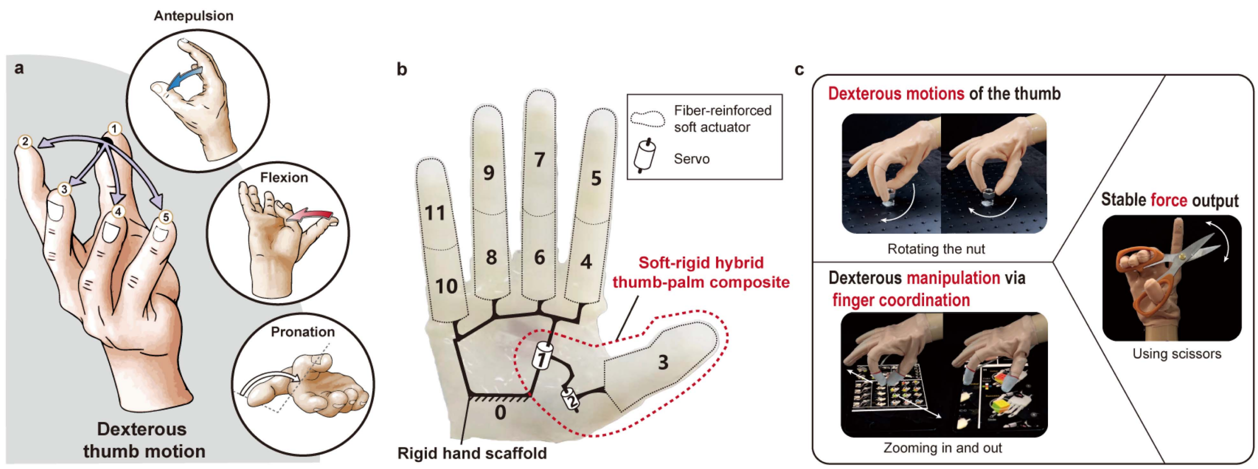

Fig. 1. Overall illustration of our proposed high-DoF hand with enhanced thumb-palm composite and its application. a) The dexterous thumb motion of the human thumb and its motion primitives. b) The DoF and actuation layout of the proposed hand. c) Typical manipulation demonstrations showcasing different functional aspects of the proposed hand. Here, the dyed soft hand is adopted for the experiments.

TABLE I
COMPARISON WITH THE STATE-OF-THE-ART SOFT AND SOFT-RIGID HYBRID HANDS

Dexterous hand	Actuation method	Active DoFs	Finger Force (N)	Hand payload (N)	Grasping	Manipulation Capabilities
8-DoF gripper [9]	Pneumatic	8 (F: 8S)	2.3	4.7	Power, pinch	Object rotating
RBO hand 3 [12]	Pneumatic	16 (T: 4S, F: 12S)	8.3	39	K: 10/10, G: 33/33	Object reorientation
Neuroprosthetic hand [13]	Pneumatic	6 (T: 2S, F: 4S)	1.9	>20	Power, pinch, lateral, K: 4/10	NP
BCL-26 [22]	Pneumatic	26 (T: 3S, F: 12S)	NP	21.9	K: 10/10, G: 33/33	Object pose adjustment
Biomechanical hand [24]	Motor+tendon	12 (T: 5R, F: 7R)	3.1	NP	Power, pinch, G: 14/33	NP
Modular bio-hand [26]	Pneumatic+skeleton	20 (T: 4S, F: 16S)	3.5	NP	G: 32/33	Unscrewing bottle cap
Soft-rigid hand [27]	Motor+tendon	8 (T: 2R, F: 4R + 2S)	3	NP	Power, pinch	Object reorientation, knob screwing
Underactuated gripper [15]	Pneumatic+skeleton	12 (F: 12S)	NP	20	Power, pinch	Object rotating
19-DoF hand [29]	SMA+tendon	19 (T: 5R, F: 12R)	8	26	K: 8/10, G: 33/33	Syringe and scissor use
Metamorphic hand [30]	Pneumatic+motor	6 (T: 1S, F: 4S)	NP	NP	Power, pinch, G: 30/33	Screen rolling
SoftHand Pro-2 [33]	Motor+tendon	2 (Decoupled motion)	NP	NP	Power, pinch	Object rotating
This work	**Pneumatic+motor**	**11 (T: 2R+1S, F: 8S)**	**4.17**	**41.94**	**K: 10/10, G: 33/33**	**Dexterous manipulation via: 1) wide workspace (rotating nut, rubbing cards, screen scrolling); 2) omni-directional force (using spoon/scissors); 3) finger coordination (screwing bulb, screen zooming, turning pages).**

T: Thumb. F: Fingers. S: Soft actuation. R: Rigid motor. K: Kapandji test. G: Feix Taxonomy. NP: Not provided. SMA: Shape-memory alloy.

dexterity of soft hands, we present a high-DoF soft hand with a bio-inspired soft-rigid hybrid thumb-palm composite (Fig. 1(b)). By emulating the human CMC joint using two orthogonal servomotors in series with a soft bending actuator, this design achieves a large controllable workspace, multidirectional force output, and compliant interaction without significantly increasing control complexity. We validate the system through comprehensive kinematic and mechanical characterization, standardized dexterity assessment test, and a range of versatile manipulation experiments across different scenarios (Fig. 1(c)). As compared in Table I, the proposed hand offers a favorable balance between actuation complexity and practical performance. Specifically, it achieves full scores in standardized dexterity tests, a competitive payload capacity (41.94 N), and a highly versatile manipulation performance across various scenarios.

This letter is structured as follows. Section II details the design and fabrication of the proposed hand. Section III characterizes its kinematic and mechanical properties. Sections IV and V evaluate its performance through standardized dexterity tests and versatile manipulation tasks among various scenarios. Section VI provides a discussion of the proposed approach and concludes the letter.

II. Design and Fabrication

A. Overall Design of the Hand

As shown in Figs. 1(b) and 2(a), the proposed hand has a total of 11 DoFs, with 9 soft bending DoFs and 2 rigid rotating DoFs. The structure of the entire hand mimics the joint distribution of the human hand, and it consists of a thumb-palm composite, four 2-chamber bending actuators [38], soft cover skin, and other accessories. Here, the thumb-palm composite is designed to mimic the CMC joint and thumb functionality of the human hand (Fig. 2(b)). It consists of two orthogonal servomotors arranged

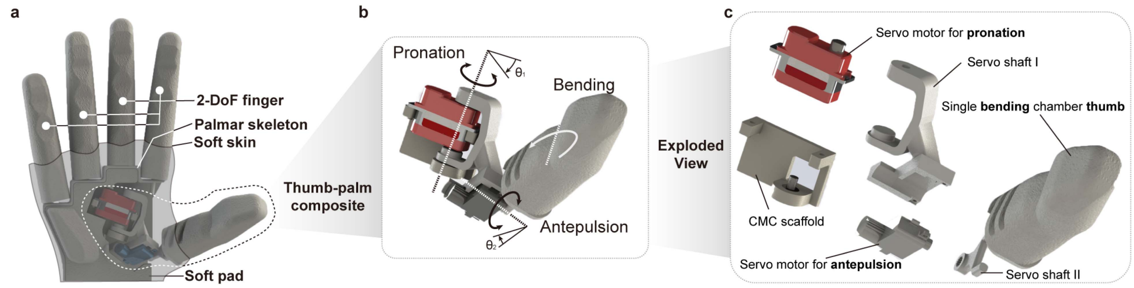

Fig. 2. Constitution and assembly of the proposed hand. a) The overall illustration of the hand. b) The overall view of the thumb-palm composite. c) The exploded view of the thumb-palm composite with three DoFs.

in series to mimic the pronation and antepulsion [1] of the human thumb (Fig. 1(a)). A single-chamber bending actuator serves as the thumb for the soft hand with a length of 80 mm, corresponding to its human counterpart. The other four fingers use two-chamber bending actuators, which can independently bend at both joints to achieve a wide planar workspace. This design ensures diverse finger motions [38] and enables effective cooperation with the soft thumb. The silicone soft pad here is adopted to mimic the human palm, providing passive compliance and stable support when grasping and manipulating.

B. Design of the Thumb-Palm Composite

The schematic view and exploded view of the thumb-palm composite are shown in Fig. 2(b), (c), respectively. To mimic the functionality of the human CMC joint, we adopt two serial orthogonal servomotors to reproduce the antepulsion and pronation motion (see Fig. 1(a)). In this serial configuration, the independent orthogonal motion of both servos can be coordinated to further increase the reachable workspace. Moreover, the servomotors enable accurate execution of predefined thumb motions through precise angle control and trajectory tracking, supporting a wide range of manipulation tasks. Their high force-generating capacity also supports omnidirectional force output across the workspace. For the soft thumb, the effective actuator length is deliberately designed as a trade-off between compliance and force transmission. We adopt the distance from the thumb tip to the metacarpophalangeal (MCP) joint as its length. This approach offers three main advantages: firstly, the thumb's compliance ensures adaptability to objects, reducing control complexity and preventing damage; second, the compliant thumb actuator, in serial with the powerful CMC joint, facilitates stronger grasping of objects. During the grasp, the CMC joint primarily provides strong force output while the compliant thumb provides adaptive contact with the object [21]; third, shortening the thumb increases its passive bending stiffness, mitigating excessive bending under external forces and increasing the force output capacity.

C. Fabrication

The fabrication of the proposed hand involves a scalable process combining soft casting, 3D printing, and mechanical assembly. The soft thumb and fingers are fiber-reinforced soft actuators; to ensure reproducibility, their step-by-step molding

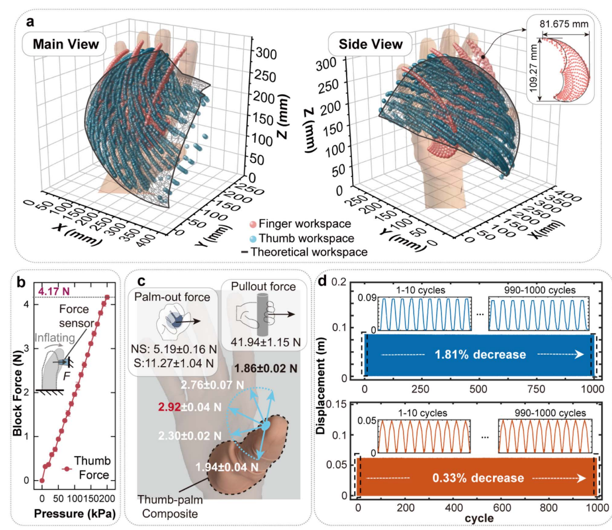

Fig. 3. Kinematic and mechanical characterization of the proposed hand. a) The workspace of the entire hand. Here, the workspace of the thumb is indicated by the blue points, while the counterpart for the other fingers is shown in red. The theoretical workspace derived from the kinematic model is represented by the black mesh. The high consistency between the experimental points and the theoretical boundary explicitly validates the effectiveness of our kinematic modeling. Both the main view and side view are given to more clearly demonstrate the shape and relationship of the workspaces. b) The block force of the soft thumb. c) The force generation capacity of the thumb-palm composite. and the entire hand. In addition to the omnidirectional force output of the thumb (bottom), the palm-out force (top left) and the pullout force (top right) are also shown. Notably, the palm-out force under servo engagement (S) is 217% of that without servo engagement (NS), demonstrating the effectiveness of the rigid-soft hybrid architecture in enhancing grasp robustness. d) Repeatability characterization over 1000 continuous actuation cycles. The displacement trajectories demonstrate the high consistency and robustness of the system, showing merely a 1.81% performance decrease for the soft-rigid hybrid thumb-palm composite (top) and a 0.33% decrease for the 2-DoF soft finger (bottom).

and fabrication procedures follow the established protocols detailed in [13], [18], [38].

The soft skin and palmar pad are fabricated via a soft casting method by pouring silicone rubber (Ecoflex-0020, Smooth-On) into customized molds. Notably, the liquid silicone can be uniformly tinted with specialized pigments (Silc Pig, Smooth-On) prior to curing to simulate diverse human skin tones. This dyeing process exclusively alters the visual appearance without changing the material's inherent physical properties or passive compliance. In this work, both white and dyed versions were fabricated for characterization and experimental validation (Figs. 4–5).

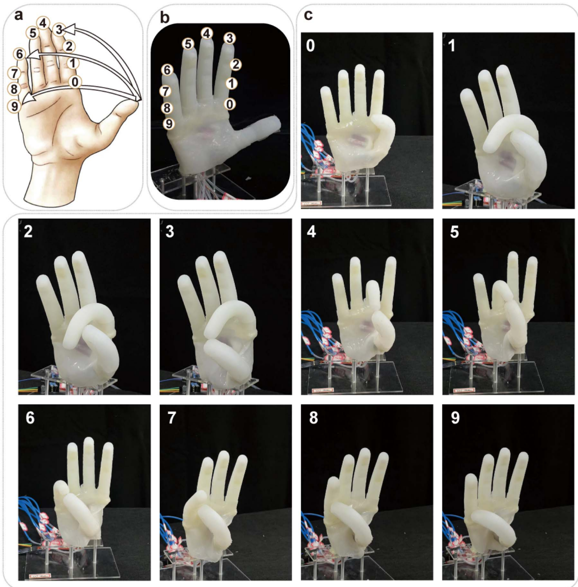

Fig. 4. The Kapandji test. a) The demonstration of the standard Kapandji test. b) The corresponding points on the proposed hand. c) The proposed hand can achieve all the test points and obtain a full score in the Kapandji test.

For the rigid components, the hand skeleton, CMC scaffold, and servo shafts are fabricated using stereolithography (SLA) 3D printing (Lite 450HD, UnionTech). During the assembly phase, the micro servomotors (HV70 and HV75 K, MKS Servo) are sequentially integrated into the corresponding scaffold and shafts via bearings and screws to form the proximal rigid joints, followed by the serial attachment of the soft thumb actuator and the encapsulation of the soft skin.

III. Characterization

To validate the effectiveness of the thumb-palm composite and our proposed hand, we conducted both kinematic and mechanical characterization of the soft hand, including the workspace analysis, repeatability test of finger and CMC composite, force generation test of the CMC composite, pullout force test, and comparative grasp evaluations with and without the hybrid CMC composite.

A. Workspace

As analyzed in the design part, the proposed thumb-palm composite can be modeled as a soft-rigid serial kinematic chain. The actuation input of the thumb is defined as

$$\mathbf{q}_t = [\theta_1,\ \theta_2,\ p]^\top, \tag{1}$$

where θ_1 and θ_2 denote the joint angles of the two orthogonal servomotors at the thumb base (Fig. 2(b)), and p represents the actuation pressure of the soft thumb.

The two base orthogonal servomotors are modeled as revolute joints, whose forward kinematics can be described using standard Denavit–Hartenberg (DH) formulation. The soft thumb actuator is approximated using a constant-curvature model. The overall forward kinematics of the thumb tip can therefore be expressed as

$$\mathbf{T}_t(\theta_1, \theta_2, p) = \begin{bmatrix} \mathbf{R}_t & \mathbf{p}_t \\ \mathbf{0}_{1\times 3} & 1 \end{bmatrix} = \mathbf{T}_1(\theta_1)\mathbf{T}_2(\theta_2)\mathbf{T}_s(p), \tag{2}$$

where $\mathbf{R}_t \in SO(3)$ and $\mathbf{p}_t \in \mathbb{R}^3$ denote the orientation and position of the thumb tip, respectively, and $\mathbf{T}_s(p)$ represents the pressure-dependent transformation of the soft thumb under the constant-curvature assumption.

The reachable workspace of the thumb tip is then defined as

$$\mathcal{W}_t = \{\mathbf{p}_t \in \mathbb{R}^3 \mid \theta_1 \in [\theta_1^{\min}, \theta_1^{\max}], \theta_2 \in [\theta_2^{\min}, \theta_2^{\max}], p \in [p^{\min}, p^{\max}]\}, \tag{3}$$

which demonstrates the coupled contribution of rigid joint rotations and soft actuator deformation to the overall thumb workspace.

In order to evaluate the workspace of our proposed hand, we apply sweeps of actuation pressures (0 kPa to 200 kPa) to the air chambers and sweeps of angles (0° to 80°, 0° to 90°, respectively) to the servo motors. Then we use the optical tracking system (Motive, OptiTrack) to measure the coordinates of the endpoints of the thumb and fingers. The workspace of our proposed hand is shown in Fig. 3(a), with the workspace of the thumb and fingers shown in blue and red colors, respectively. The identical actuation inputs are fed into the forward kinematic model to obtain the theoretical workspace (black mesh in Fig. 3(a)). The experimentally measured workspace agrees well with the theoretical boundary. This alignment validates the effectiveness of the model and indicates its potential utility for guiding trajectory planning and grasp execution. The characterization results highlight three key advantages of the proposed design. First, the thumb's wide spatial workspace validates the dual-servomotor configuration, providing the foundation for diverse grasping gestures. Second, the continuity of this workspace allows for flexible trajectory planning, which is essential for complex manipulations requiring precise thumb engagement. Finally, the substantial workspace overlap between the thumb and the remaining fingers ensures highly efficient coordination during dexterous tasks. By co-designing their trajectories, specific grasp and manipulation gestures can be obtained. The details are discussed in Section V. Furthermore, to verify the prolonged kinematic consistency of the actuation chains, we conducted a 1000-cycle repeatability test. The displacement trajectories demonstrate little degradation (Fig. 3(d)), decreasing by only 1.81% for the thumb-palm composite and 0.33% for the soft finger.

B. Force Output Performance

We characterize the force output performance of the proposed hand, ranging from the single soft thumb, thumb-palm composite, to the whole-hand grasp.

First, with the thumb base fixed, we aligned a force sensor along the fingertip's bending direction and applied stepwise pressures (0 to 200 kPa, 10 kPa increments) over three trials. The soft thumb generates a maximum blocked force of 4.17 N (Fig. 3(b)), which is comparable to the existing dexterous soft-rigid hands (Table I) and is sufficient for typical daily

Fig. 5. The Feix GRASP taxonomy carried out by the proposed hand. Our hand can achieve all the 33 grasps in the GRASP taxonomy. Here, the dyed soft hand is adopted for the experiment.

manipulation tasks [39]. This demonstrates that the proximal rigid CMC joint provides a stable foundation for the compliant thumb, inherently enhancing the output force and overall grasp stability and stiffness by reshaping the contact geometry [21].

Next, we evaluated the omnidirectional force output capacity of the thumb-palm composite across five directions: thumb bending, two directions orthogonal to the bending axis, and two directions at $\pm$ 45° relative to the bending axis. The results (Fig. 3(c), bottom) demonstrate that the dual-orthogonal servomotor design not only preserves a wide range of motion but also provides versatile force output in multiple directions, consistent with the human thumb's ability to support diverse manipulation options under a given posture.

Finally, to quantitatively validate the effectiveness of the soft-rigid hybrid architecture for grasp stability, we evaluated two grasp metrics: the pullout force using a 20 mm diameter cylinder and the palm-out force normal to the palm using a 60 mm sphere. As shown in Fig. 3(c) (top), the hand achieves a pullout force of 41.94 N. More importantly, comparative measurements of the palm-out force highlight the structural advantage of our design: engaging the rigid servomotors yields 11.27 N, 217% of the 5.19 N recorded without servo engagement. This demonstrates that the proximal rigid joints effectively overcome the force limitations of traditional pure soft hands, ensuring highly robust grasping.

IV. Standardized Test

We also verify the motion dexterity and grasp diversity of our proposed hand through a sequence of standardized assessments, including the Kapandji test and Feix GRASP taxonomy.

A. Kapandji Test

The Kapandji test is widely used in robotics to evaluate thumb dexterity [1]. In this test, the thumb tip is required to reach ten predefined locations on the hand, which are widely distributed along the outer contour of the hand (Fig. 4(a)). The final score corresponds to the number of successfully reached locations, with higher scores reflecting greater thumb dexterity. In this test, we tune the servo angles and input pressures to form the corresponding gestures in which the thumb touches the given points. The results are shown in Fig. 4. We can see that our proposed hand can touch all 10 points by engaging both the thumb-palm composite and the fingers. This demonstrates the motion dexterity of the thumb composite, showcasing the functionality of our design.

B. Feix GRASP Taxonomy

The Feix GRASP taxonomy is a widely utilized and comprehensive classification system for evaluating human-like grasp capabilities in robotics [39]. It systematically categorizes 33 distinct grasp types, providing a standardized framework to quantitatively assess a robot hand's grasp versatility and dexterity. Fig. 5 shows the results of the proposed hand executing the grasps defined in the GRASP taxonomy. We can see from the results that our hand can achieve all the 33 grasps in the taxonomy, demonstrating that our hand achieves a level of grasp versatility approaching that of the human hand. In these grasps, the extended workspace of the thumb is crucial for achieving the full taxonomy because complex and delicate thumb pose adjustments and thumb opposition are needed, showcasing the functionality of our design.

V. Manipulation Experiments

To validate the effectiveness of our hand design, we conducted a series of experiments showcasing different functional capabilities of the thumb-palm composite and the entire hand. In these experiments, the functionality of the wide-range workspace and dexterous motion of the thumb, the enhanced force output capacity, and the efficient cooperation between the thumb and fingers are illustrated, respectively.

Before detailing the specific tasks, we outline our motion generation and control strategy. The system operates under an open-loop framework with both servo angles and chamber pressures as combined inputs, which avoids complex feedback strategies while ensuring high robustness by leveraging the inherent

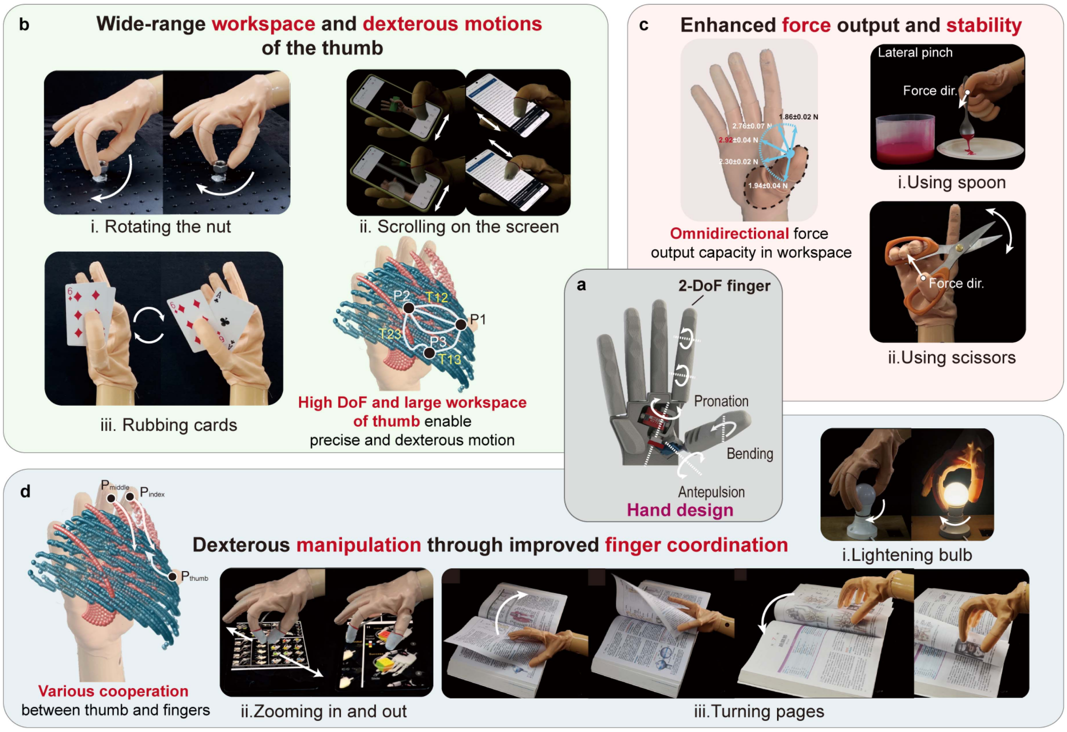

Fig. 6. The manipulation tasks executed by the proposed hand showcase the advantages of our thumb-palm design. a) The hand design scheme showing the DoFs involved in the manipulation. b) Manipulation tasks showcasing the wide-range workspace and dexterous motions of the thumb. c) Manipulation tasks showcasing the omnidirectional force output capacity. d) Manipulation tasks achieved by effective coordination between the thumb and other fingers. Here, the dyed soft hand is adopted for the experiments.

passive compliance of our soft-rigid design. We adopt a human-inspired approach to generate actuation inputs: for static grasping, we predefine typical grasp postures (power grasp, pinch, etc.) with adjustable actuation intensities to adapt to diverse object geometries [18]; for dynamic manipulation, we employ a keyframe-based strategy [12], generating continuous complex trajectories by interpolating critical poses. Consequently, even relying solely on open-loop commands, the proposed hand achieves highly effective and robust manipulation.

A. The Dexterous and Wide-Range Motion of the Thumb

The introduction of the dual-orthogonal servomotor design provides the soft thumb with a wide-range workspace and dexterous motions (see Fig. 6(a)). Corresponding principles and experiments are shown in Fig. 6(b). From the principle scheme at the bottom right of Fig. 6(b), we can see that the wide workspace of the thumb reflects its ability to move over a large range; meanwhile, the high-DoF design enables versatile motion trajectories for the thumb. These principles ensure that the thumb can both be actuated to a wider range to form efficient grasps (see Fig. 5) and can be programmed to execute designed trajectories to enable precise functional manipulation. In the bottom right subfigure of Fig. 6(b), three representative points of the thumb workspace are illustrated. They are connected by a series of curves lying within the workspace, which means that these curves are all achievable thumb trajectories. This demonstrates that our design provides considerable potential for enhancing thumb functionality for performing complex manipulation. We apply three experiments as an illustration. In task I, we design the motion trajectory of the thumb, which can make it form a pinch gesture against the index and middle finger and exert a torque on the grasped objects (see the supplementary video), therefore the nut can be fastened. In task II, we programmed the thumb to move vertically and horizontally, as well as normal to and away from the screen surface to enable scrolling up/down and left/right on the mobile phone. The screen can be manipulated continuously without mistakes. In the task relative to screen manipulation, conductive fingerstalls (Conductive finger cots, KOVOL) are worn on the corresponding thumb or finger tips to mimic the electrical conductivity of human fingertips, which is essential for touchscreen operation. To demonstrate the precise motion potential of the thumb, in task III, we design a delicate rubbing action of the thumb and finger, the motion trajectory of the thumb is set to be a small-radius circle centered on the fixed index-fingertip. In this experiment, the cards can be rubbed apart and consolidated consecutively.

B. The Enhanced Force Output Capacity

As discussed in Section III, our thumb is feasible for omnidirectional force exertion because of the dual-orthogonal servomotor design, as also shown in the top left of Fig. 6(c). The thumb can generate force in various directions in the workspace surface, greatly ensuring the grasp robustness and force exertion on manipulation tasks. We take two experiments as the demonstration. In task I, the hand forms a stable lateral pinch to firmly hold the spoon to scoop out the thick rubber liquid, in which the spoon faces a great viscous force as well as the weight of the rubber. Herein, because of its multidirectional force-generation capability, our thumb can generate force orthogonal to the side of the index finger to firmly hold the spoon. In task II, by arranging the thumb motion, the hand can use the scissors to cut paper, during which the force requirement is dynamic and position-dependent. The successful execution of the task is also guaranteed by the omnidirectional force output capacity in the workspace.

C. The Efficient Cooperation Between the Thumb and Fingers

The various cooperations between thumb and fingers also contribute to achieving dexterous manipulation tasks, as discussed in Section III and shown in Fig. 6(d). As shown on the left of Fig. 6(d), the thumb and fingers share a large range of common workspace, which means that they can achieve effective interaction to form versatile grasps or execute manipulation tasks. In the left subfigure, three representative trajectories corresponding to thumb, index, and middle fingers are illustrated: It can be observed that, through coordinated programming of the thumb and the other fingers' trajectories, the relative positions can be deliberately designed, enabling the execution of manipulation tasks with specific motion requirements. We adopt three experiments to illustrate the principle. In task I, the trajectories of the thumb, index, and middle fingers are coordinately programmed to screw the bulb into the socket. During this process, the thumb is responsible for the rotation actuation of the bulb, while the trajectories of the other fingers are tuned as well to adapt to the thumb motion and form a stable grasp with the thumb. In task II, similarly, the trajectories of the thumb and index finger are designed to make their tips gather and move apart to fulfill the zooming in and out action of the screen. In task III, the thumb is designed to form a parallel pinch of the other four fingers to rub the page apart the book and achieve a firm pinch to turn the pages left and right.

D. Manipulation Robustness and Repeatability

To quantitatively evaluate the robustness and repeatability of the hand, we conducted repetitive execution tests on four representative tasks across the aforementioned three paradigms: rotating a nut, scrolling a screen, using a spoon, and turning pages. Each task is executed continuously for 20 trials under consistent initial setups. The proposed hand reliably completed all consecutive operations without failure (see supplementary video). This high consistency explicitly demonstrates the system's reliability and indicates that the inherent passive compliance of the soft-rigid hybrid structure effectively tolerates minor positional perturbations during repetitive manipulations.

VI. Discussion and Conclusion

In this work, we present a high-DoF soft hand centered on a soft-rigid hybrid thumb-palm composite. By integrating two orthogonal servomotors (replicating human CMC pronation and antepulsion) in series with a compliant soft actuator (replicating thumb flexion), the design accurately replicates the key kinematic and mechanical characteristics of the human thumb. Comprehensive comparison in Table I demonstrates that the proposed hybrid architecture effectively mitigates the traditional complexity-dexterity trade-off. The soft-rigid hybrid CMC composite provides a wide workspace, accurate trajectory control, and strong omnidirectional force generation, while the distal soft thumb ensures adaptive and compliant interaction.

We verified the effectiveness of this design through comprehensive characterization (including workspace and force output test and analysis). Notably, the theoretical workspace predicted by our kinematic model aligns well with experimental measurements, validating its effectiveness and potential for guiding precise trajectory planning. The kinematic model can also contribute to the performance evaluation metric definition and analysis of the work in future. Standardized tests (Kapandji test and Feix GRASP taxonomy) are also adopted to evaluate the motion dexterity and grasp diversity of the hand, in which it achieved full scores. Lastly, through a series of versatile manipulation experiments across multiple scenarios, we confirm the proposed design supports a wide-range workspace and motion dexterity of the thumb, the omnidirectional force output capacity, and enables versatile coordination between the thumb and fingers. Furthermore, continuous cyclic actuations and repetitive manipulation tasks demonstrate the system's repeatability and control robustness, ensuring its practical usability for extended operations.

Proposing a high-DoF hand is an important step, but finding ways to fully leverage its potential is equally crucial. Considering the extensive involvement of fingertips in most dexterous manipulations, future iterations will introduce varying fingertip materials to optimize contact friction and mechanics. In future work, based on the proposed high-DoF soft hand and the established kinematic model, we plan to integrate proprioception sensors and tactile sensors to achieve its precise closed-loop control via teleoperation. This will enable the dynamic generation of high-precision manipulation sequences and provide high-quality demonstration data for imitation learning frameworks, ultimately leading to more generalized, human-like grasp gestures and manipulation sequences.

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