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Design of a soft gripper with a changeable adapter for enhanced grasping and manipulation †



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Highlights:

- A novel rigid-flexible coupled soft gripper based on a crank-slider mechanism is proposed to achieve a continuously variable volumetric workspace for diverse object scales.
- The adapter is theoretically modeled and experimentally characterized as a mechanical force amplifier, capable of significantly boosting contact force through kinematic reconfiguration.
- An intuitive Human-in-the-Loop (HITL) teleoperation strategy is established, leveraging a decoupled control architecture to validate the system's adaptability and payload stability.

Abstract: Soft grippers utilize compliant materials to achieve adaptable grasping, yet they often face challenges in accommodating objects with widely varying dimensions due to their fixed kinematic structures. This paper presents the design, fabrication, modeling, and control of a novel soft gripper featuring a rigid-flexible coupled variable range adapter. By integrating a motorized crank-slider mechanism with soft pneumatic fingers, the gripper achieves a dynamic volumetric workspace capable of manipulating objects ranging from compact to large geometries. Theoretical modeling and experimental characterization reveal that the adapter serves a dual purpose: it not only expands the effective workspace but also functions as a mechanical force amplifier, capable of exponentially boosting the contact force through kinematic reconfiguration. Furthermore, an intuitive Human-in-the-Loop (HITL) teleoperation strategy is established using wearable flex sensors. This control framework maps human gestures to robotic actuation, leveraging human visual feedback as a high-level perception loop to validate the open-loop response of the soft actuators. Experimental results demonstrate that this integrated system significantly improves adaptability and payload stability for diverse object geometries compared to fixed-base counterparts.

Keywords: soft gripper; variable grasping range; kinematic modeling; gesture control



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1. Introduction

Soft robotics has become an increasingly important area of research, offering significant advantages over traditional rigid robotic systems, particularly in applications that require delicate handling and adaptability to various object shapes. Unlike conventional mechanical grippers, which rely on rigid structures and precise mechanical control, soft grippers utilize flexible materials, such as silicone, that conform to the surfaces of objects, enabling a more natural and gentle grasp. This flexibility is particularly beneficial in tasks involving fragile or irregularly shaped items, where traditional grippers may apply excessive force or fail to secure a proper grip.

Several successful soft gripper designs have demonstrated these advantages. For instance, Ilievski *et al.* [1] developed a pneumatically actuated soft gripper that could handle objects of various shapes, showcasing the potential of soft robotics in diverse applications. Shintake *et al.* [2] introduced a soft gripper specifically designed for food handling, which could delicately grasp and manipulate different items, highlighting the utility of soft materials in environments requiring precision and gentle handling. Deimel and Brock [3] further explored soft pneumatic actuators, demonstrating their capability to perform complex manipulation tasks.

However, while these designs excel at conforming to an object's surface, they often struggle with adapting to objects of varying sizes, particularly smaller ones. Rus and Tolley [4] provided an extensive review of soft robotics, noting the limitations of current gripper designs in accommodating different object sizes. Similarly, Shepherd *et al.* [5] highlighted the adaptability of soft grippers but pointed out the challenge of maintaining effective grips on objects requiring significant changes in finger spacing. Brown *et al.* [6] also emphasized the need for more versatile designs capable of handling a wider range of object sizes.

To address these limitations, researchers have explored various strategies. Hughes *et al.* [7] and Liarokapis *et al.* [8], for example, investigated grippers that use variable stiffness materials to adjust their rigidity based on the object's requirements, though these designs still faced challenges with small objects. Several research groups have successfully utilized enhanced surface adhesion techniques, including gecko-inspired shear adhesion [9,10] and electro-adhesion [11], to achieve effective grasping of thin items. Jain *et al.* [12] changed the workspace volume of the soft gripper by adding attachments to the pneumatic brake, which allowed the gripper to adapt to more complex gripping tasks. However, end gripping can still be affected by the brake flip angle when using fingernails for gripping.

Recent reviews have summarized the rapid development of soft robotic grippers from the perspectives of actuation, materials, sensing, stiffness modulation, adhesion, and application scenarios [13,14]. These studies indicate that although soft grippers have achieved significant progress in compliant interaction and shape adaptation, maintaining stable performance across objects with largely different sizes remains a persistent challenge. In particular, fixed-base soft grippers often rely mainly on finger bending to accommodate object geometry, which limits their ability to simultaneously handle small objects requiring narrow access and large objects requiring sufficient enclosure.

To improve grasping adaptability, several studies have investigated reconfigurable or geometry-adjustable soft gripper designs. Catalano *et al.* [15] and Polygerinos *et al.* [16] discussed the potential for incorporating

more adaptable mechanisms into soft grippers, such as adjustable finger spacing. Zhou *et al.* [17] proposed a soft robotic gripper with enhanced object adaptation and grasping reliability by improving the adaptive structure of the gripper. Hao *et al.* [18] developed a soft bionic gripper with variable effective length, allowing the working length of the soft fingers to be adjusted for objects with different dimensions. Subramaniam *et al.* [19] introduced a hybrid soft gripper with active palm pose control, showing that changing the palm or base configuration can improve grasping posture and object adaptation. Wang *et al.* [20] further explored a variable-stiffness gripper with reconfigurable finger joints for versatile manipulation tasks, while Wang *et al.* [21] used targeted variable stiffness to change the bending length of a soft finger. These works demonstrate that structural reconfiguration is an effective way to improve the adaptability of soft grippers. However, many existing approaches focus on changing finger stiffness, bending length, or palm posture, while fewer designs directly regulate the initial spacing between multiple soft fingers to continuously adjust the grasping range before contact.

Small and thin objects introduce another difficulty because successful grasping depends not only on the global grasping range but also on local contact initiation at the fingertip. Teeple *et al.* [22] showed that multi-segment soft robotic fingers can improve precision grasping by controlling the contact mode along the finger. Yang *et al.* [23] demonstrated kirigami-shell-based grasping, where structural geometry enables soft grasping over a wide range of object scales. Hong *et al.* [24] proposed angle-programmed tendril-like trajectories to achieve delicate, strong, and precise grasping, highlighting the importance of trajectory and distal contact geometry for challenging objects. These studies suggest that fingertip geometry and contact path design are important for small-object manipulation. Nevertheless, combining a continuously adjustable grasping range with auxiliary fingertip contact initiation remains insufficiently explored.

In addition to mechanical adaptability, intuitive and reliable user-level control interfaces are important for validating the operability of soft grippers in practical manipulation tasks. Kim *et al.* [25] discussed the role of sensing and bioinspired design in improving the responsiveness of soft robotic systems. Similarly, Rakhtala *et al.* [26] developed a soft robotic hand with embedded strain sensors, showing that sensor information can support more direct interaction between the operator and the soft robotic device. These studies indicate that sensing interfaces can be useful for operating soft grippers, even when the main contribution is focused on hardware design and grasping performance rather than autonomous closed-loop control.

In response to these needs, this study introduces a variable-grasping-range soft gripper designed to improve adaptability across objects with different sizes and shapes. First, we present a motorized retractable finger adapter that allows the spacing between the gripper fingers to be adjusted over a wide range. This feature enables the gripper to adapt its effective grasping range to objects with different sizes, especially small objects that require narrower access. Second, the soft fingers include an auxiliary distal nail structure to improve contact initiation and edge access for small or flat objects in the current wide-fingertip configuration. Finally, a wearable-sensor-based human-in-the-loop teleoperation interface is implemented to map operator gestures to adapter spacing adjustment and pneumatic finger bending. This interface is used to demonstrate the operability and task feasibility of the proposed gripper, rather than autonomous closed-loop curvature regulation. A preliminary version of this work was presented at the 2025 30th International Conference on Automation and Computing (ICAC) [27].

2. Design

In this study, a pneumatic soft gripper with three soft fingers is designed, focusing on optimizing the gripping force and surface fit to various objects, as shown in Figure 1. The gripper operates under negative pressure, which causes the soft fingers, made of silicone skin and skeleton, to bend inward and grip the target object. Additionally, the gripper includes a retractable adapter that adjusts the relative positions of the fingers to enhance both the surface conformity of the fingers to the object and the force they exert.

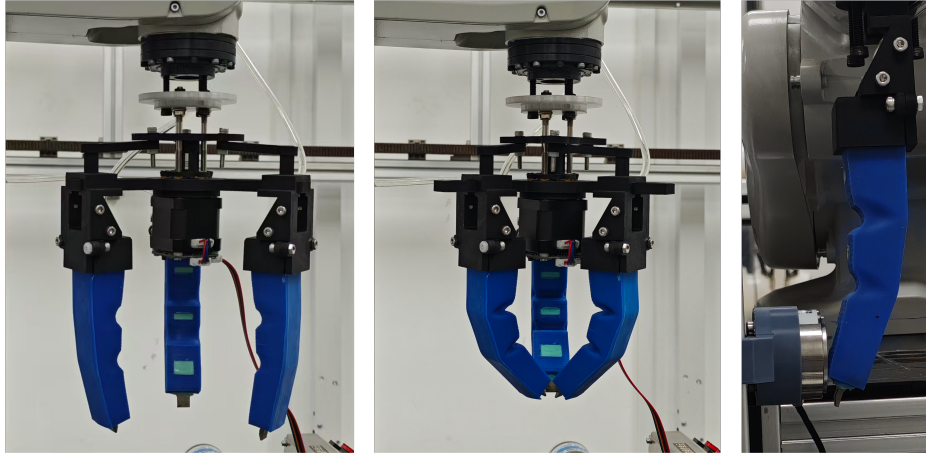


Figure 1. Changeable adapter enhances soft gripper grasping ability.

2.1. Principle of pressure exertion

The external surface shape of a soft finger denoted as S , is a critical factor that determines how the finger interacts with objects. This shape is directly influenced by the internal air pressure P within the finger. In a non-operational state, under standard atmospheric pressure, the finger maintains its initial shape, S_0 , as shown in Figure 2a. This shape represents the finger's relaxed state, where no external forces or internal pressure deforms the silicone material.

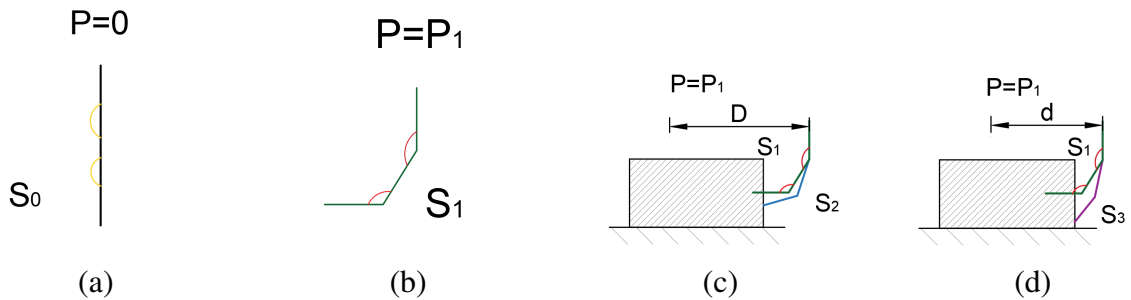


Figure 2. Operating principle of the variable-range soft gripper. **(a)** Finger state without applied working air pressure or load; **(b)** finger state with working air pressure applied but without load; **(c)** finger state with both working air pressure and load applied; **(d)** finger state after reducing the finger spacing under the conditions shown in (c).

When the internal air pressure increases to a certain level, P_1 , the finger bends and adopts a new shape, S_1 , as shown in Figure 2b. This new shape is stable and represents the finger's form when it is not

in contact with any object. The degree of bending is often represented by the angle α . The higher the internal air pressure, the greater the angle α , and hence, the more pronounced the curvature of the finger. This shape S_1 is important because it sets the baseline for how the finger will deform when it encounters an object during gripping.

When the gripper is activated to pick up an object, the soft fingers make contact with the object's surface. This contact induces a deformation in the fingers as they adapt to the shape of the object. The external surface shape of the finger now changes from S_1 (its shape under no load) to S_2 (its shape under load), as shown in Figure 2c. This deformation is represented by the variable ΔS , which is the difference between S_1 and S_2 .

As the finger deforms, the silicone material resists this change due to its inherent elasticity. This resistance generates an elastic force that acts against the deformation, contributing to the overall gripping force. The larger the deformation (ΔS), the greater the elastic force generated, which directly enhances the grip on the object. This elastic force is crucial for the stability of the grip, ensuring that the object does not slip or move once grasped.

Based on the above, the pressure exerted by the soft fingers during operation is influenced by three main factors:

Internal Air Pressure (P): The internal air pressure controls the initial shape S_1 of the fingers before they make contact with the object. A higher internal pressure results in a more pronounced curvature and a greater degree of deformation when the finger grips an object.

Deformation Variable (ΔS): The extent of deformation from S_1 to S_2 is directly related to the gripping force. Larger deformations indicate that the fingers are generating a stronger elastic force to maintain the grip. The deformation variable ΔS is a direct determinant of the force that the gripper can apply to the object.

Material Elasticity (E): The modulus of elasticity of the silicone material plays a vital role in determining how much force the finger can exert for a given deformation. A higher modulus of elasticity means that the material can resist deformation more effectively, generating a greater force to hold the object securely.

2.2. Principle of adapter-assisted grasping

The primary function of the retractable adapter is to control the spacing between the gripper's fingers, thereby influencing their initial positioning relative to the object being gripped. In a typical gripping scenario, the distance between the fingers and the object is a critical determinant of how much the fingers must deform to achieve a secure grip. By adjusting this spacing, the adapter can bring the fingers closer to the object before the actual gripping force is applied. This initial positioning is crucial because it sets the stage for the subsequent deformation of the fingers, which directly affects the gripping force.

By reducing the initial distance between the fingers and the object, the adapter effectively increases the deformation variable ΔS during the gripping process. This amplification of ΔS means that the difference between the unloaded shape S_1 and the loaded shape S_3 is greater, resulting in a stronger elastic force. As shown in Figure 2d, when the fingers are positioned closer to the object through the adapter's adjustment, the external surface shape of the fingers S_3 becomes more deformed upon contact with the object compared to their shape S_2 . This increased deformation ΔS_{13} is significantly larger than ΔS_{12} ,

which results in a larger elastic force being generated by the fingers, which enhances the gripping pressure applied to the object.

At the same time, the deformation of S_2 and S_3 to S_1 is converging towards the state of S_0 , it is converging towards a situation where the fingers are almost parallel to the surface of the object to be grasped. Therefore, reducing the gap between the fingers will result in a larger surface area for the fingers to participate in the grasping task when a load is applied, which will largely improve the surface fit between the fingers and the object.

2.3. Adapter design

The overall structure of the gripper, as shown in Figure 3a, has three soft fingers connected through a centrally positioned retractable adapter. This adapter's function is to adjust the relative positions of the fingers, which is essential for the gripper's ability to handle objects of various sizes and shapes. The adapter allows for the dynamic adjustment of the three fingers' positions, ensuring that they can conform more effectively to the surface of the object being gripped, thereby improving both the surface fit and the gripping force.

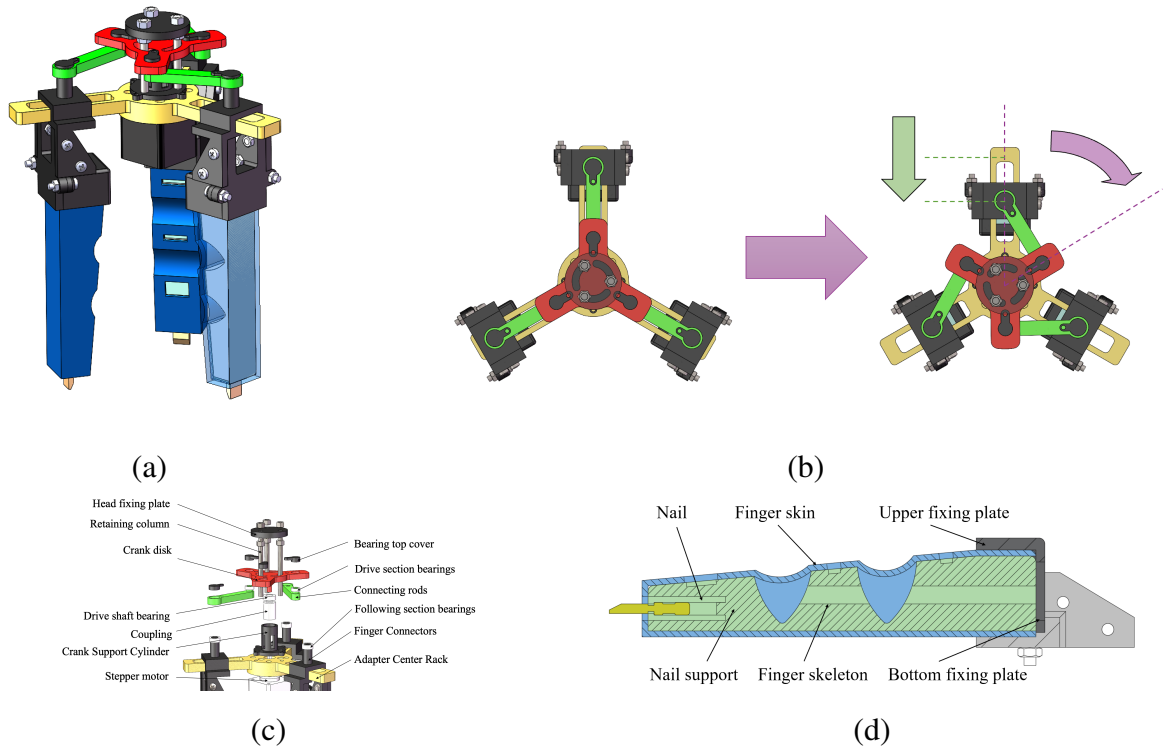


Figure 3. Mechanical design of the variable-range soft gripper. **(a)** Overall design of the soft gripper with a variable-grasping-range adapter; **(b)** schematic of the adapter motion principle; **(c)** exploded view of the adapter mechanical structure; **(d)** cross-sectional view of the soft finger structure.

The working principle of the retractable adapter, as shown in Figure 3b, is based on a crank-slider mechanism. In this mechanism, the rotational motion of the crank disk is converted into linear motion, which adjusts the position of the fingers along their respective guide rails. The crank's rotation drives the connecting rods, causing the fingers to slide inward or outward, depending on the direction of rotation.

The extent of finger displacement is determined by the crank's rotational angle, which allows for precise control over the fingers' positions relative to the object.

To minimize the overall weight of the gripper, thus reducing the load on the robotic arm to which it is attached, the crank disk, which plays a central role in this mechanism, is designed. Only one stepper motor is required to drive the crank disk, and three crank-slider mechanisms used to drive finger displacement along the guideway can be controlled simultaneously.

As shown in Figure 3c, the entire adapter design is based axially on the centerline of the adapter center rack's center disk, with the axial geometric centerlines of all active parts coinciding with it. Among them, the centerline of the output axis of the stepper motor is ensured to coincide by the fastening of the four positioning holes on the upper side of the motor. The fix of the centerline of the crank disk is assisted by a crank support cylinder. The power input shaft at the bottom of the crank disk is connected to the crank support cylinder through the drive shaft bearing, while the crank support cylinder is fastened to the center disk of the guide rail through the four positioning holes at the bottom to fix the position of its centerline. After positioning, the output shaft of the stepper motor is connected to the input shaft of the crank disk through a coupling.

Meanwhile, the crank disk serves as the uppermost member of the adapter, but it is a kinematic member that keeps rotating during the gripping execution, so it cannot be connected to the robotic arm. To solve this problem and still maintain the strict symmetry of the entire adapter structure, three uniformly spaced retaining columns are mounted on the center disk of the guideway, with threaded ends and a head fixing plate mounted on the upper end, which is clamped in a fixed position by three pairs of nuts and is used for the connection to the robot arm. At the same time, the three retaining columns pass through a rounded hole in the crank disk, which ensures that it rotates properly while limiting the travel of the fingers on the guide.

2.4. *Soft finger design*

The soft finger is indispensable as the main actuator of the grasping action, as shown in Figure 3d. In this study, the main body of the soft finger consists of two parts, the finger skin and the finger skeleton, which are made of silicone materials with different properties, and then positioned through the locating holes to complete the fit and sealed by the silicone adhesive. First, the finger skeleton is made of a relatively hard silicone material, which is mainly used to support the skin cavity, and the joints at the end of the finger are the key parts involved in the grasping process. Secondly, the skin of the finger, as the main bearer of deformation in the grasping process, should have a certain degree of elasticity. Especially when the finger is in contact with the grasped object, the elasticity of the skin determines the grasping force of the finger.

Meanwhile, the end of the finger is also designed with a nail, which serve to change the shape of the end of the finger so that it can perform better when grasping smaller objects. The nail is mounted in the nail support, which is made of the same material as the finger skeleton, but is designed as a separate part to ensure that the nail can be mounted from its rear end.

To clarify the function of the nail structure, Figure 4 illustrates the contact-establishment process for a small target object. When the finger spacing is large, the swept region of the soft fingers may not overlap with the target object, resulting in no effective contact. Reducing the finger spacing moves the fingers closer to the target and improves the geometric accessibility of the gripper. However, for very

small or flat objects, the relatively wide soft fingertip may still limit distal contact initiation. The nail extends the local distal contact path and helps the fingertip reach the object during the final contact stage.

Finally, the first end of the soft finger consists of the upper and bottom fixing plates, which are connected to the nut through screws and can be used to control the gap between the two plates through the position of the nut, thus fixing the finger more securely. The bottom fixing plate has two through holes for connection to the adapter's rails. Two through-holes are provided in the bottom fixing plate for connection to the slider on the adapter's guide rail.

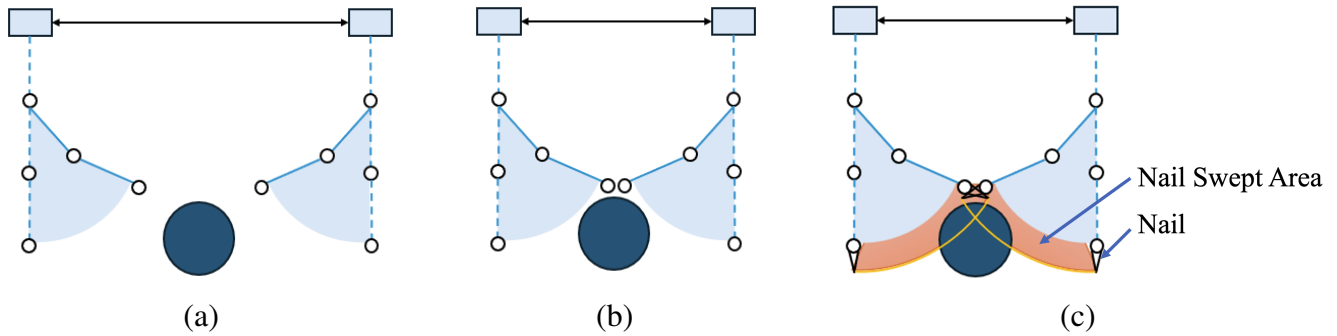


Figure 4. Geometric role of the auxiliary nail during contact establishment. (a) With a large finger spacing, the target object remains outside the reachable region of the soft fingers; (b) Reducing the finger spacing moves the fingers closer to the target, but distal contact may still be insufficient for small objects; (c) The nail extends the local distal contact path and helps establish effective contact with the target object.

3. Fabrication

3.1. Adapter

The retractable adapter, serving as the central load-bearing component, requires high structural rigidity and wear resistance to ensure precise linear motion. Consequently, Carbon Fiber Reinforced Polylactic Acid (PLA-CF) was selected as the fabrication material due to its superior flexural modulus compared to standard PLA. However, printing large aspect-ratio components like the guide rail disk at high extrusion temperatures (210 °C) often induces significant residual thermal stresses. These stresses typically lead to warping deformation due to uneven cooling rates between the printed layers and the heated bed, compromising the flatness required for smooth sliding.

To mitigate this issue and ensure geometric accuracy, a two-stage thermal treatment process was implemented. Specifically, the raw PLA-CF filament was first dried at 55 °C for 4 hours prior to printing to eliminate moisture-induced defects. Subsequently, the printed components underwent a specialized post-process annealing cycle, where they were heated to 60 °C—slightly above the glass transition temperature (T_g)—and held for 30 minutes, followed by slow cooling to room temperature. This thermal conditioning promotes polymer chain rearrangement and increases crystallinity, effectively releasing internal residual stresses and stabilizing the dimensional accuracy of the guide rails.

Following this treatment, particular attention was paid to the geometric tolerances for the shafts, which were made significantly larger than those for the holes to ensure that the components could move smoothly once assembled. Due to the challenges of 3-D printing threaded holes, knurled nuts were used

to create the necessary threads on the guide rail center plate, as shown in Figure 5a. This solution allows for secure and functional connections where direct 3-D printing of threads is not feasible. Additionally, the components were designed with stepped dimensions for the transmission shafts to ensure accurate positioning of the bearings. This stepwise design is critical for maintaining the alignment and stability of the bearings, which are essential for the smooth operation of the adapter.

The adapter center rack, being the design datum of the entire mechanism, served as the core reference during assembly. The fabrication process began with the precise installation of the stepper motor and the crank support cylinder, ensuring that these components were correctly aligned and securely attached. This careful assembly ensured that the adapter could function as intended, with all parts moving in harmony to adjust the positions of the gripper fingers during operation.

3.2. Soft finger

As shown in Figure 5a, the fabrication of the soft fingers involved creating molds for the finger skin, skeleton, and nail support. These molds were produced using 3-D printing technology. The fabrication process for the fingers involves pouring silicone into these molds, with specific considerations required depending on the model and the type of silicone material used.

For the finger bone, Smooth-On Smooth-Sil 960 silicone was selected due to its higher viscosity and tendency to form large air bubbles. To address this issue, the silicone must be degassed in a vacuum chamber before being poured into the mold. Additionally, since Smooth-Sil 960 tends to expand slightly as it cures and has a higher hardness, the mold's side surfaces were designed with slight draft angles to facilitate easy demolding after curing.

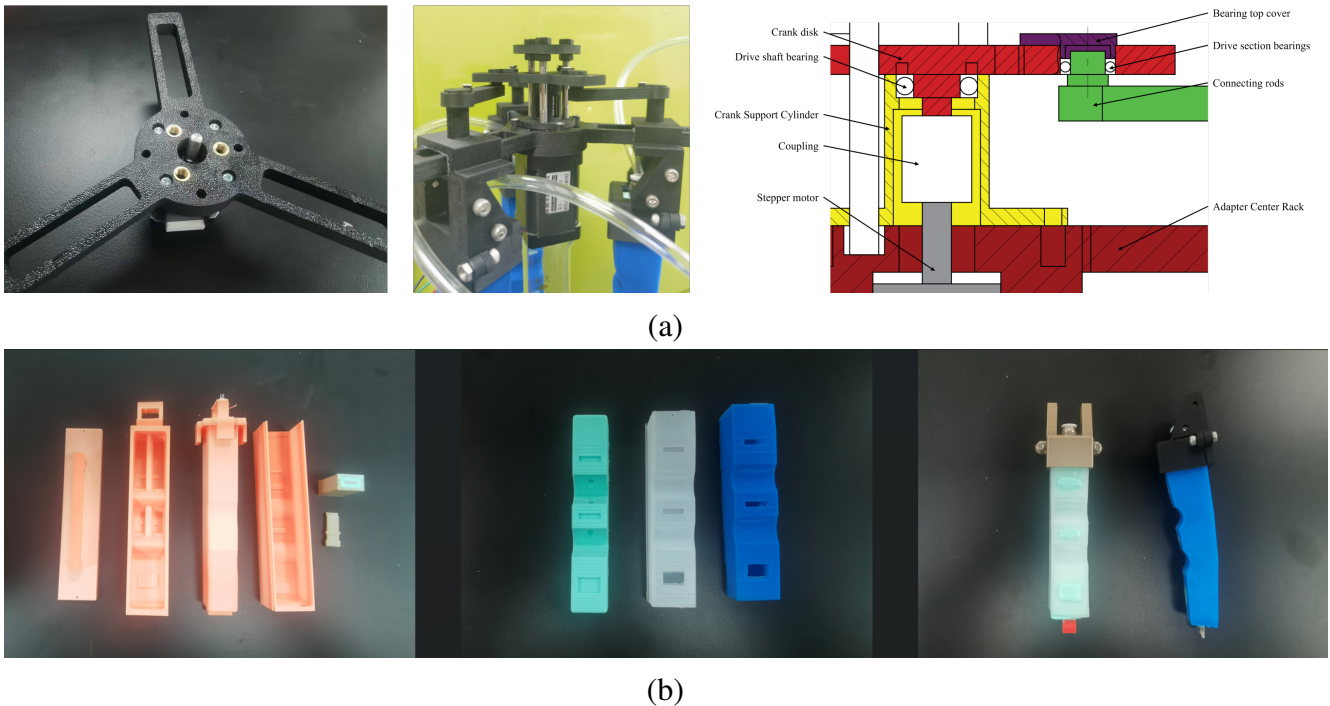


Figure 5. Fabrication and assembly of the adapter and soft fingers. **(a)** Adapter center-rack fasteners and locating holes, assembled adapter, stepped transmission shafts, and bearing positioning; **(b)** molds for the soft finger components, fabricated finger skeleton and skin, and the assembled soft finger.

For the finger skin, two materials were considered: Ecoflex 00-30 and Mold Star 30. Ecoflex 00-30 is highly flexible and offers excellent elasticity, while Mold Star 30 is less stretchy but provides greater tensile strength and resistance to deformation. Although these materials do not have the same bubble formation issues as Smooth-Sil 960, the pouring process needs to be carefully controlled to avoid trapping air within the mold, particularly due to the complex structure of the molds. This is essential to ensure a smooth, bubble-free finish on the finger skin.

The nail support is made from the same Smooth-Sil 960 silicone as the skeleton, chosen for its hardness and structural stability. The nails themselves are fabricated from PLA material using 3-D printing, offering a sturdy, lightweight solution that integrates well with the silicone components.

The key design, material, and experimental parameters used in the following modeling and characterization sections are summarized in Table 1.

Table 1. Summary of key design, material, and experimental parameters.

Parameter	Symbol	Value/Material
Crank radius	R	30 mm
Connecting rod length	L	40 mm
Adapter-adjusted finger position range	x	20–80 mm
Finger skin material	–	Mold Star 30
Finger skeleton material	–	Smooth-Sil 960
Nail support material	–	Smooth-Sil 960
Nail material	–	PLA
Adapter structural material	–	PLA-CF
Pneumatic deformation pressure range	P	0 to –70 kPa

4. Modeling and analysis

To precisely control the finger spacing and analyze the grasping force capability, a kinematic and static model of the adapter's crank-slider mechanism was established. The geometric schematic of the mechanism is illustrated in Figure 6.

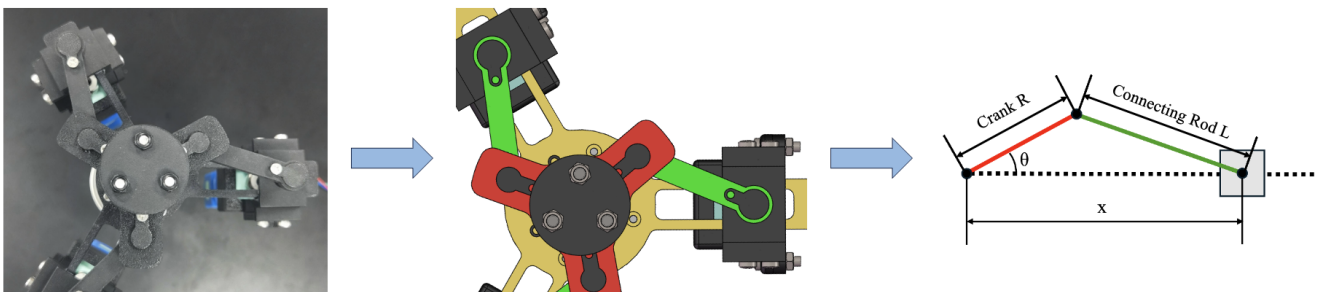


Figure 6. Geometric schematic of the crank-slider mechanism.

4.1. Kinematic analysis

The adapter utilizes a crank-slider mechanism to convert the rotational motion of the stepper motor into the linear displacement of the soft fingers. The following derivation considers one crank-slider branch,

since the three branches are driven synchronously by the same crank disk. Let R denote the radius of the crank disk (30 mm), L denote the length of the connecting rod (40 mm), and θ denote the motor rotation angle. Here, θ is defined as the angle between the crank and the guide-rail direction, with $\theta = 0^\circ$ corresponding to the fully extended state. The distance from the finger base to the center of the adapter is denoted as x .

As shown in Figure 6, the slider position x can be expressed as the sum of two projections along the guide rail: the projection of the crank radius and the projection of the connecting rod. The crank endpoint has a horizontal projection $R\cos\theta$ and a vertical offset $R\sin\theta$ relative to the guide direction. Since the connecting rod has a fixed length L , its projection along the guide rail is obtained from the geometric constraint

$$l_x^2 + (R\sin\theta)^2 = L^2, \quad (1)$$

where l_x is the guide-direction projection of the connecting rod. Therefore,

$$l_x = \sqrt{L^2 - (R\sin\theta)^2}. \quad (2)$$

The finger position is then obtained as

$$x(\theta) = R\cos(\theta) + \sqrt{L^2 - (R\sin(\theta))^2}. \quad (3)$$

For control purposes, the inverse kinematics is formulated to map the desired finger position x to the required motor angle θ . Rearranging Equation (3) gives

$$x - R\cos\theta = \sqrt{L^2 - R^2\sin^2\theta}. \quad (4)$$

Squaring both sides and using $\sin^2\theta + \cos^2\theta = 1$, we obtain

$$x^2 - 2Rx\cos\theta + R^2 = L^2. \quad (5)$$

Thus,

$$\cos\theta = \frac{x^2 + R^2 - L^2}{2Rx}, \quad (6)$$

and the inverse kinematic relationship is

$$\theta(x) = \arccos\left(\frac{x^2 + R^2 - L^2}{2Rx}\right). \quad (7)$$

Substituting $R = 30$ mm and $L = 40$ mm gives the expression used in this study:

$$\theta(x) = \arccos\left(\frac{x^2 - 700}{60x}\right). \quad (8)$$

4.2. Static force analysis

To evaluate the force transmission efficiency, we analyzed the relationship between the motor output torque τ and the linear pushing force F_{finger} . Using the principle of virtual work, the force transmission is given by:

$$F_{finger} = \frac{\tau}{\left| \frac{dx}{d\theta} \right|} \quad (9)$$

The derivative $dx/d\theta$ is calculated as:

$$\frac{dx}{d\theta} = -R \sin(\theta) - \frac{R^2 \sin(\theta) \cos(\theta)}{\sqrt{L^2 - (R \sin(\theta))^2}} \quad (10)$$

The mechanical advantage profile, shown in Figure 7b, reveals a critical characteristic of the design. As the crank angle approaches the dead center ($\theta \rightarrow 0^\circ$), the mechanical advantage increases exponentially, exceeding 0.9. This “High Force Region” ($0^\circ - 10^\circ$) serves as the physical basis for the proposed force enhancement strategy. By driving the mechanism towards this kinematic singularity, the system can mechanically amplify the input torque, generating large locking forces to secure heavy payloads without requiring high-pressure pneumatic actuation.

Furthermore, the torque requirement analysis in Figure 7c indicates that the motor torque required to maintain a constant grasping force follows a parabolic trend, peaking at approximately $\theta = 65^\circ$. This peak value defines the necessary torque rating for motor selection. Crucially, the required torque decreases significantly as θ approaches 0° . This suggests that the gripper is inherently energy-efficient when holding large objects at the fully extended state, as the mechanical structure bears the majority of the load rather than the motor coil.

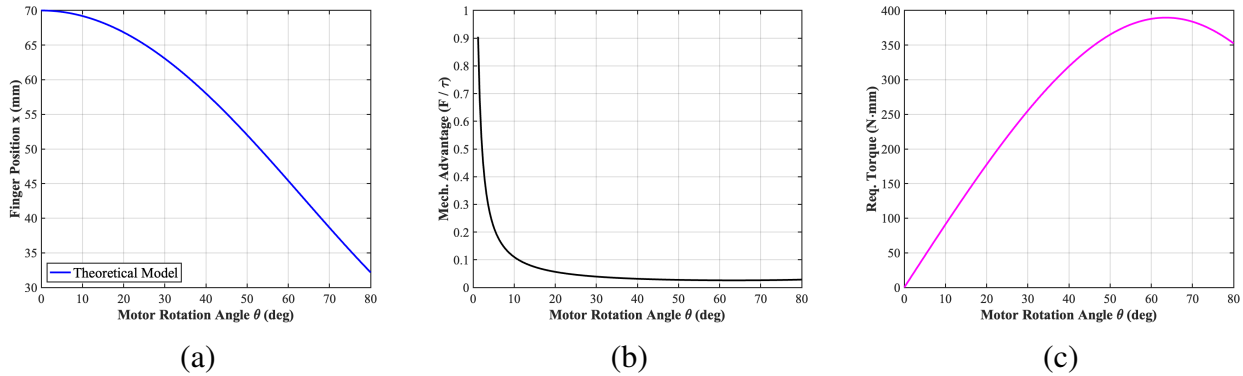


Figure 7. Theoretical analysis of the adapter mechanism. (a) Kinematic relationship between motor angle and finger position, showing non-linear resolution; (b) Mechanical advantage profile highlighting the high force amplification near the dead center ($< 10^\circ$); (c) Motor torque required to maintain a constant 10 N grasping force, showing energy efficiency at low angles.

5. Characterization

To evaluate the mechanical performance and validate the variable grasping range capability, we conducted a series of empirical characterization experiments, ranging from single-finger deformation to system-level workspace and force analysis.

5.1. Pneumatic deformation analysis

Since the soft fingers rely on the complex deformation of hyperelastic materials, their kinematic behavior is empirically characterized rather than analytically modeled. To quantify the bending response for

subsequent workspace analysis, we tracked the deformation trajectory of a single finger under varying pneumatic loads. As shown in Figure 8a, seven key markers (Points 1–7) were defined along the finger’s lateral profile.

Figure 8b presents the measured displacement trajectories of these key points as the internal pressure decreases from 0 kPa to -70 kPa. The experimental results reveal a highly consistent inward bending profile. Specifically, the fingertip (Point 7) demonstrates a stable displacement path in both X and Y axes. This empirically determined trajectory provides the necessary kinematic data to define the finger’s sweeping range, serving as the physical basis for constructing the volumetric workspace model in the following section.

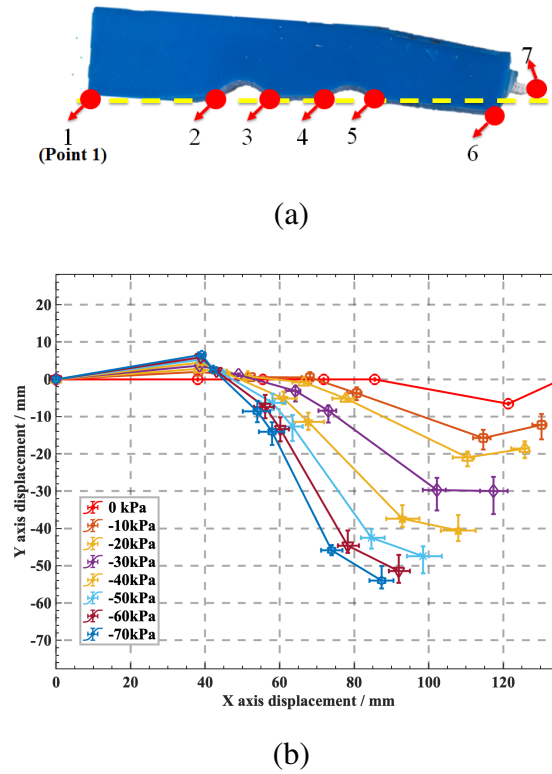


Figure 8. Pneumatic deformation characterization. **(a)** Definition of the seven tracking markers on the soft finger; **(b)** Displacement trajectories of key points under pressures ranging from 0 to -70 kPa.

5.2. Volumetric workspace analysis

The proposed mechanism creates a dynamic “Volumetric Workspace” by coupling the adapter-controlled finger position ($x \in [20, 80]$ mm) with the continuous bending deformation of the soft fingers. This coupling allows the gripper to access a continuous 3D spatial volume rather than being limited to a single grasping trajectory.

The resulting workspace is visualized in Figure 9, which exhibits the geometry of an inverted conical shell. The red and blue surfaces denote the kinematic boundaries corresponding to the maximum (80 mm) and minimum (20 mm) adapter extensions, respectively. The green region represents the effective volumetric grasping zone where stable contact can be established. This spatial analysis confirms the gripper’s geometric capacity to accommodate objects of varying dimensions and to operate effectively across different depths within the reachable envelope.

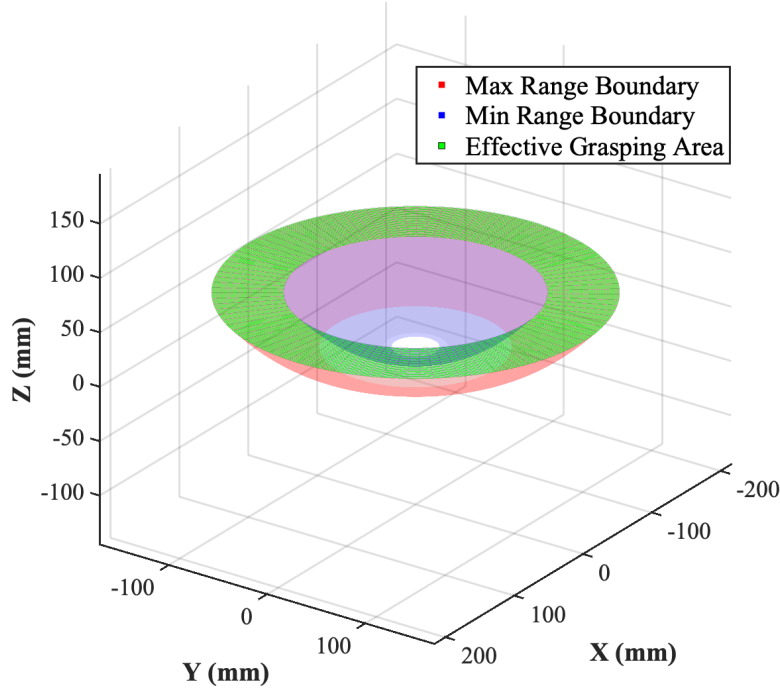


Figure 9. Visualization of the volumetric workspace. The green region represents the effective grasping volume generated by sweeping the finger trajectory across the adapter’s variable range (20–80 mm).

5.3. Spacing-ablation grasping test

To quantitatively evaluate the necessity of the retractable adapter, a spacing-ablation grasping test was conducted. In this test, the gripper was operated under several locked finger-spacing configurations, and each locked configuration was treated as a fixed-base counterpart. The pneumatic pressure was kept constant at -40 kPa for all trials, so that the effect of finger spacing could be isolated from the effect of pneumatic actuation. Eight objects with different characteristic sizes, ranging from 5 mm to 58 mm, were tested. For each object-spacing combination, 10 repeated grasping trials were performed. A trial was counted as successful when the gripper established stable contact with the object, lifted it from the support surface, and maintained the grasp without obvious slipping or dropping.

Figure 10 shows the resulting success-rate map. The results demonstrate a clear spacing-dependent grasping behavior. Small objects, such as objects with characteristic sizes of 5 mm and 9 mm, can be grasped more reliably at smaller finger spacings, whereas larger objects require larger spacings to provide sufficient geometric accommodation. When the object characteristic size exceeds the fixed finger spacing, the gripper cannot enclose the object, and the grasping success rate becomes zero. This result directly reflects the kinematic limitation of a fixed-base configuration.

In addition, the success-rate distribution shows that no single fixed finger spacing achieves uniformly high success across all tested objects. For example, smaller spacings are suitable for small objects but fail for larger objects, while larger spacings are more suitable for large objects but cannot reliably establish contact with very small objects. Therefore, the proposed retractable adapter is necessary because it allows the gripper to reconfigure its finger spacing according to the target object size, thereby expanding the effective grasping range compared with any single fixed-spacing configuration.

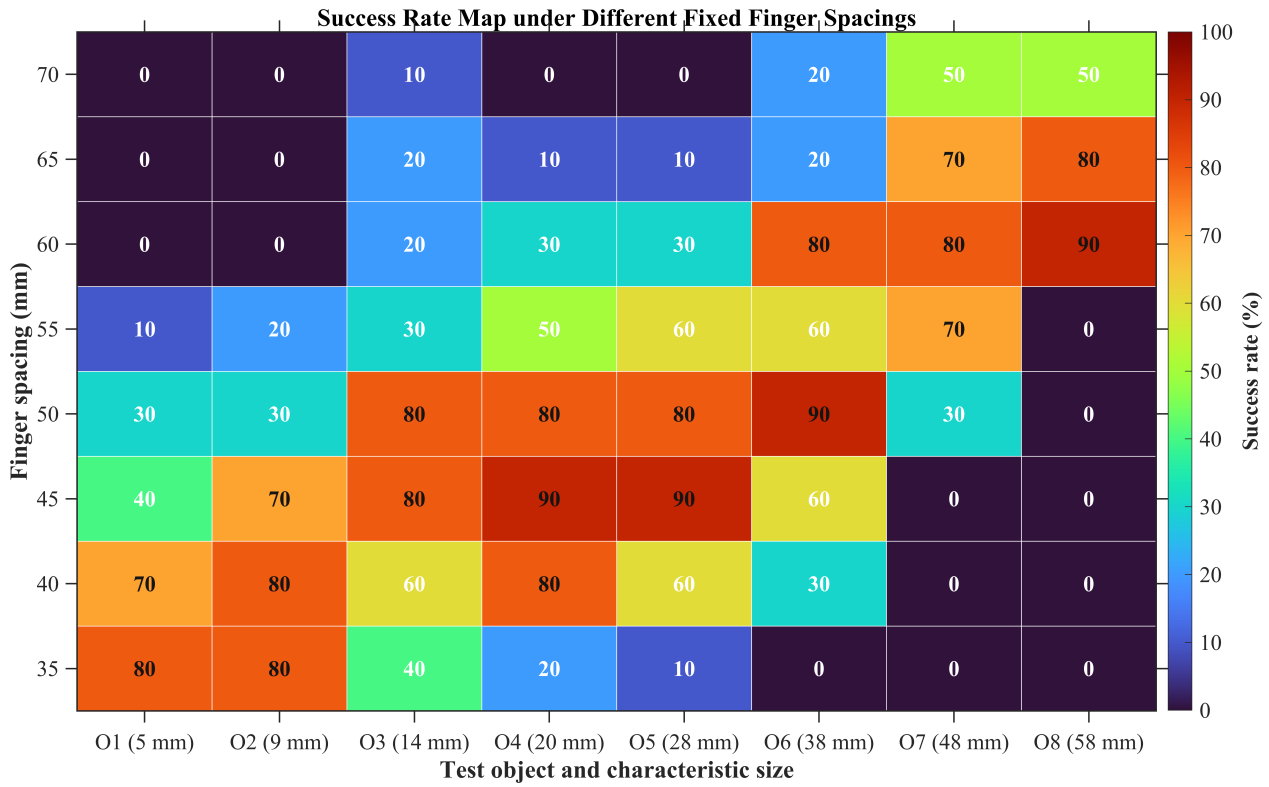


Figure 10. Success-rate map under different fixed finger spacings.

5.4. Force profile and grasping enhancement analysis

To quantitatively characterize the grasping performance, we established a precision experimental platform utilizing a Universal Robots (UR) manipulator and a high-precision force sensor, as illustrated in Figure 11a. In this setup, the UR robot controlled the lateral distance d between the finger base and the sensor probe, while the pneumatic system applied regulated negative pressures P . This setup allowed us to map the contact force across varying spatial and pneumatic conditions.

The characterization results, visualized in Figure 11b, reveal the critical role of the adapter in establishing and maintaining a stable grasp. A distinct “effective grasping boundary” can be observed in the data. In the low-pressure region (e.g., -20 kPa), effective contact force is only generated when the object distance d is small (20–30 mm). As the distance increases beyond 35 mm, the finger’s bending curvature is insufficient to reach the object, resulting in a loss of contact (0 N force). This indicates that the adapter’s primary function is to physically translate the fingers into a valid interaction zone, enabling the gripper to grasp objects that would otherwise be out of reach for a fixed-base soft gripper operating at the same pressure.

Within the effective contact region, the adapter significantly amplifies the grasping force. For instance, at a constant pressure of -60 kPa, when the object distance is large ($d = 60$ mm), the measured contact force is relatively low at 0.19 N. However, by retracting the adapter to reduce d to 20 mm, the contact force rises to 2.1 N. It is worth noting that, unlike rigid grippers where the contact angle is the dominant factor in force transmission, soft grippers benefit from the inherent compliance of the material, which makes the grasping performance less sensitive to minor angular variations. Therefore, the observed force increase is primarily attributed to the mechanical squeezing effect generated by the adapter. This

mechanism allows the system to prioritize payload capacity by mechanically compressing the fingers against the target, validating the effectiveness of the proposed hybrid actuation strategy.

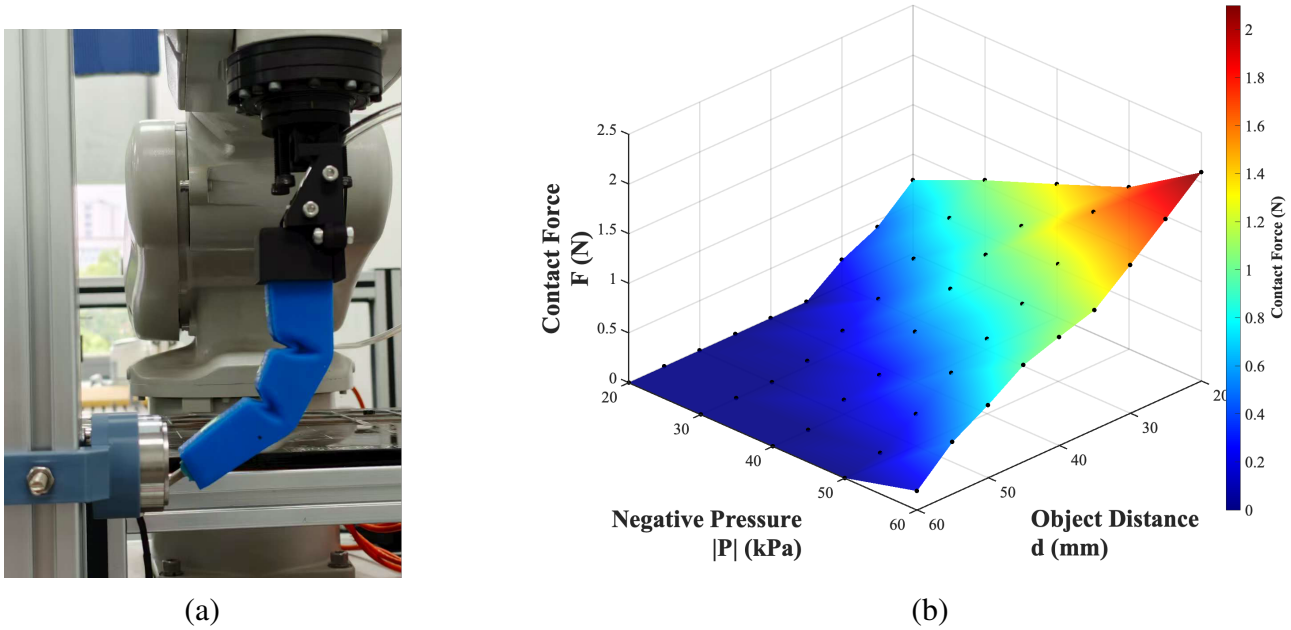


Figure 11. Force characterization. (a) Experimental setup utilizing a UR robot arm for precise distance control; (b) 3D response surface showing Contact Force (F) as a function of Pressure (P) and Object Distance (d). Note the significant force amplification as distance decreases.

6. Control strategy and experimental validation

To validate the efficacy of the proposed variable-range mechanism, we established a HITL teleoperation strategy. This section details the physical implementation of the control interface, the signal processing architecture, and the resulting grasping capabilities. The primary objective is to demonstrate that the decoupled mechanical design can be effectively and intuitively driven by human operators to achieve versatile manipulation.

6.1. Physical interface and system architecture

The control system is constructed starting from the physical sensing interface shown in Figure 12a which consists of two wearable flex sensors serving as the input terminals of the system. These sensors are attached to the index and middle fingers of the operator to capture human actuation intent. The signal processing logic is illustrated in the system architecture diagram in Figure 12b. Unlike sequential algorithmic processes this diagram explicitly depicts two parallel and decoupled signal pathways originating from the human operator. The pneumatic channel processes signals from the index finger to control the air pump via pulse width modulation (PWM) which regulates the deformation of the soft fingers. Simultaneously the kinematic channel processes signals from the middle finger to drive the stepper motor via inverse kinematics which regulates the spacing of the adapter. In this architecture the human operator acts as the central decision-making core coordinating these two independent channels through real-time visual and haptic feedback.

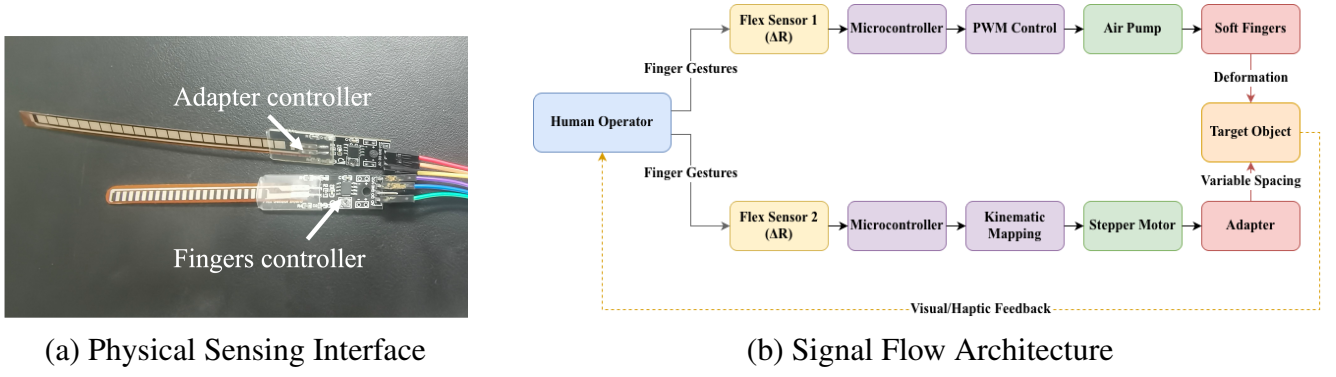


Figure 12. The control system implementation. **(a)** Wearable flex sensors serve as the physical input; **(b)** The system architecture diagram illustrating the parallel signal pathways for pneumatic and kinematic control, where the human operator functions as the decision-making core within the perception loop.

6.2. Actuation mapping and response

The reliability of this architecture relies on the precise mapping between human input and robotic output across two distinct channels. The specific actuation responses are visualized in Figure 13. First, as shown in Figure 13a, the kinematic channel exhibits a linear mapping where the flexion of the middle finger drives the stepper motor. This action retracts the adapter to reduce the grasping diameter, directly translating the operator’s spatial intent into mechanical reconfiguration. Simultaneously, Figure 13b demonstrates the pneumatic channel, where the bending of the index finger regulates the PWM signal of the air pump, causing the soft fingers to curl and conform to the object’s surface. The distinct separation of these two mapping profiles confirms that the hardware allows for fully independent control of the grasping range and the wrapping curvature. This “One-to-One” mapping strategy ensures that the operator’s intuitive hand gestures are accurately translated into the decoupled mechanical behaviors of the gripper.

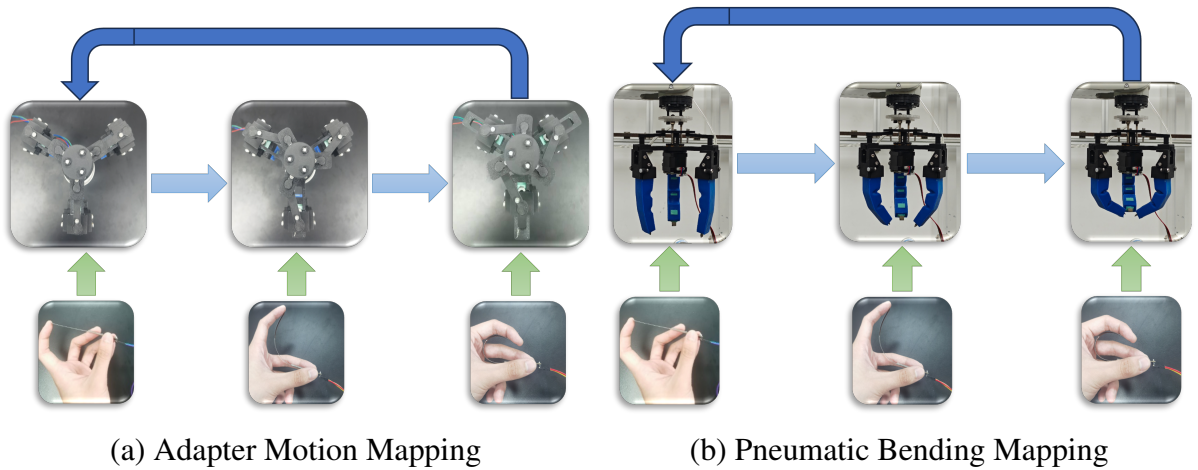


Figure 13. Verification of the decoupled actuation mapping: **(a)** The mechanical channel regulates the workspace size by adjusting adapter spacing; **(b)** The pneumatic channel controls the soft finger curvature for shape conformity.

6.3. Grasping demonstration

The ultimate validation of the proposed architecture is demonstrated through the system's ability to manipulate objects with diverse characteristics. Figure 14 presents the experimental results of grasping trials conducted on various daily objects. The results indicate that the decoupled control architecture enables the gripper to adapt to extreme geometric variations. For instance, the system successfully transitioned from grasping a large-diameter jar to a small beaker by utilizing the kinematic channel to reconfigure the workspace size. Furthermore, the capability to handle heavy payloads, such as the 500 g storage tank, validates the force enhancement potential of the mechanism. In this scenario, the operator utilized the kinematic channel to mechanically compress the gripper base after establishing contact, thereby generating sufficient locking force to prevent slippage. These successful manipulations confirm that the proposed hardware, driven by the intuitive signal flow architecture, can effectively address the trade-off between adaptability and payload capacity in unstructured environments.

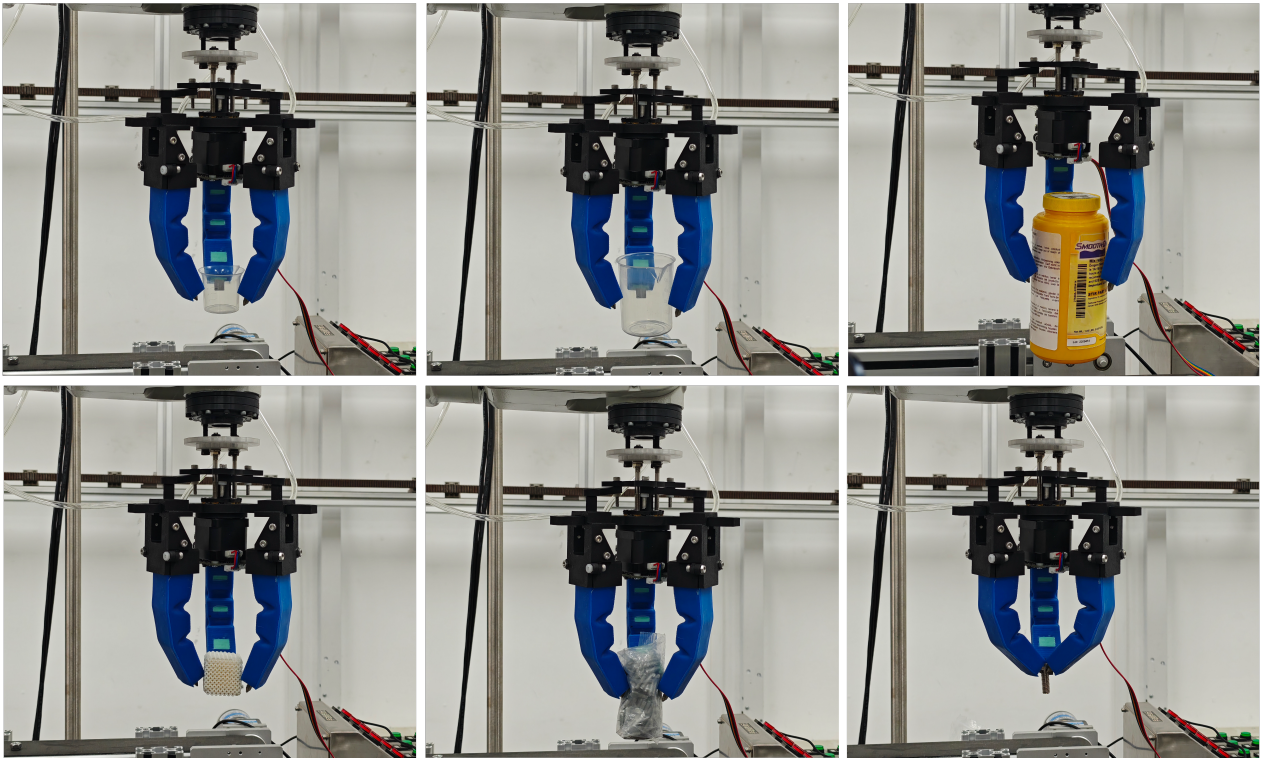


Figure 14. Experimental grasping results. The successful manipulation of objects ranging from large jars to small beakers and heavy spray cans validates the effectiveness of the decoupled control architecture.

7. Conclusion

In this article, a novel soft gripper featuring a rigid-flexible coupled variable range adapter was designed, fabricated, and characterized. By integrating a crank-slider mechanism with pneumatic soft fingers, the system addresses the limitations of traditional fixed-base grippers in accommodating diverse object sizes.

Theoretical modeling and experimental characterization revealed that the adapter serves a dual purpose: it not only expands the effective volumetric workspace but also functions as a mechanical force amplifier. The force profile analysis demonstrated that by kinematically reconfiguring the finger spacing,

the contact force can be increased by over ten-fold without additional pneumatic energy. Furthermore, an intuition-driven Human-in-the-Loop teleoperation strategy was established to validate the system's controllability. The experimental results confirmed that the decoupled control architecture allows the operator to independently modulate the grasping range and compliance based on visual feedback, ensuring versatile manipulation of objects with varying geometries and weights.

Data availability statement

The data or datasets that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of generative AI and AI-assisted technologies

During the preparation of this manuscript, the authors used ChatGPT and Grammarly solely to improve language and readability. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the integrity, originality, and accuracy of the publication.

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Authors' contribution

Conceptualization, methodology, validation, formal analysis, data curation, writing—original draft preparation, Chengqi Song and Jingxiang Wang; writing—review and supervision, Qinglei Bu, Jie Sun, and Qinyao Liu; funding acquisition, Qinglei Bu, Jie Sun, and Qinyao Liu. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no conflicts of interest.

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