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Shape Adaptable Gripper with Toggle-Linkage-Based Variable Stiffness

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***Abstract*— This paper introduces a novel gripper that achieves both shape-adaptive grasping and variable stiffness. It is realized through an integration of the "soft gripper," capable of grasping objects while conforming to their shapes, and a toggle-linkage-based variable stiffness mechanism that does not hinder its grasping ability. Such features enable the gripper to securely manipulate and transport objects where soft/flexible grippers struggled, without being dependent on the shape of the object. Consequently, the proposed mechanism is expected to be capable of firmly grasping objects of various shapes. This paper details the idea, theory, prototype, and experimental validation of the proposed gripper. The paper particularly focuses on, it focuses on the compatibility of shape-adaptive grasping and variable stiffness for the prototype based on the idea, demonstrating its feasibility.**

I. Introduction

Over the years, the development of highly adaptable grippers has garnered considerable attention from researchers. Such grippers, capable of grasping objects of various shapes without the need for attachments, can contribute to improving productivity in industries and societies.

Various approaches have been proposed for such grippers in the past. One notable attempt is the multi-joint hand driven by impedance control of finger actuators [1], which can control the forces exerted on objects, enabling flexible grasping. However, the number of joints is limited, restricting their adaptability. On the other hand, researchers have proposed flexible grippers using flexible materials from the perspective of soft/flexible robots [2]. While these hands provide continuous shape adaptation to objects, they struggle with the reliable manipulation and transportation of heavy grasped objects.

Hirose et al. proposed a "soft gripper" that conforms to the shape of objects for holding [3]. It is composed of strategically antagonistic tendon drive and multi-joint structure, enabling highly adaptable grasping despite being made of high-rigidity materials. However, it faces challenges strongly influenced by gravity and inertia due to its antagonistic principle, making it difficult to tilt or handle objects swiftly while grasping.

Our research team has previously proposed several soft/flexible robots with variable stiffness [4]–[6]. Fig. 2 depicts the first prototype based on the idea of integrating wire-driven circumferential layer jamming mechanism and

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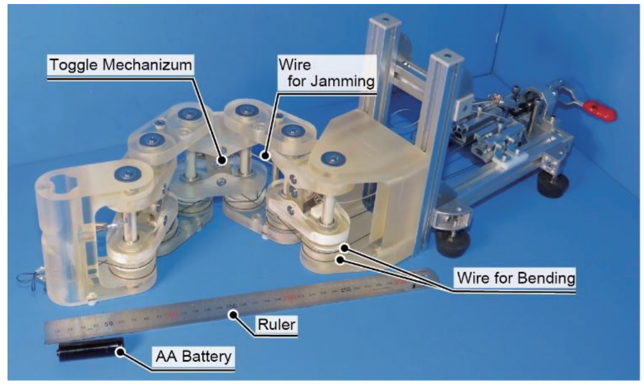

Fig. 1. Shape-adaptive gripper with toggle-linkage-based variable stiffness mechanism.

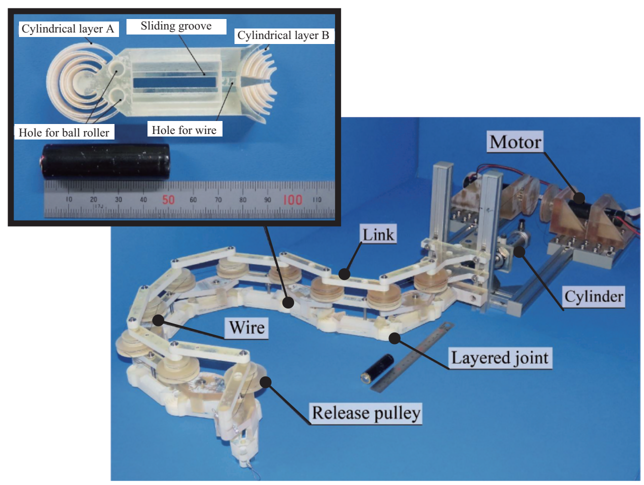

Fig. 2. The first prototype. Each joint is equipped with circumferential layer jamming, which transitions to a high stiffness mode when the wire is pulled.

the "soft gripper." Such variable stiffness mechanisms based on wire-driven and friction offer better responsiveness compared to phase-change materials [7], [8] and easier stiffening compared to granular vacuum type [9], [10], allowing for power-efficient driving compared to electric clutches/brakes. Furthermore, unlike the air pressurized/vacuum type [11], it does not require a pump. However, this idea failed to prevent variations in inter-axis distance, hindering the functionality of the "soft gripper."

In this study, we introduce a new gripper capable of shape adaptation with a toggle linkage-based variable stiffness mechanism (Fig. 1). This mechanism, preventing variations in inter-axis distance, is suitable for integration with the "soft gripper," and the non-linear drive by toggle linkage favors

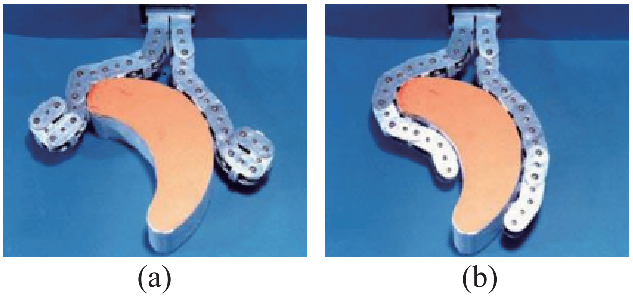

Fig. 3. Prototype of ”Soft Gripper [3].” It is capable of equi-pressure grasping, enveloping objects from the base of the gripper. (a) gripping while enveloping, (b) completed grip.

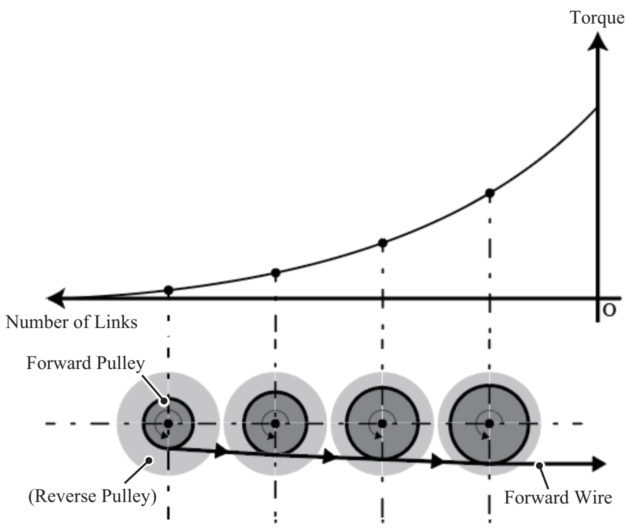

Fig. 4. Schematic diagram of the forward rotating pulley provided on each joint of ”soft gripper.”

maintaining the gripper's stiffness.

This paper presents a prototype based on this idea, focusing on the feasibility of achieving both shape-adaptive grasping and variable stiffness. Section 2 presents the idea and model, Section 3 introduces the prototype, and Section 4 discusses effectiveness through experiments and validation.

II. Theory and Design

In this section, we first explain the antagonistic principle of shape adaptation based on the ”soft gripper.” Next, we derive the necessary conditions for achieving both aspects, considering the aforementioned first prototype. Finally, we introduce the toggle linkage-based variable stiffness mechanism and its configuration theory.

A. Principle of ”Soft Gripper”

Figure 3 shows Hirose et al.'s prototype of the ”soft gripper.” Despite being made of rigid materials such as metal, its densely packed multi-joint structure endows it with high shape adaptability. Notably, it achieves equi-pressure grasping from the base of the gripper, as if enveloping, through antagonistic tendon drive and an asymmetric dual-pulley configuration.

Now, imagine a cantilever beam subjected to a uniformly distributed load. In materials mechanics, a Shear Force Diagram (SFD) with a linear slope and curvilinear Bending Moment Diagram (BMD) would be depicted. In other words, by aligning the torque at each joint with this BMD, equi-pressure grasping of the grasped object can be achieved. Fig. 4 illustrates a schematic diagram of the forward rotation pulleys installed on each joint axis of the ”soft gripper” [1]. In this paper, the rotation of joints in the direction enveloping the object is termed ”forward rotation,” and the opposite is termed ”reverse rotation.” Equi-pressure grasping is achieved through a series of tension-driven wires and pulleys adjusted in diameter to match the BMD according to the distance from the root of the link.

Another system consists of tendons and pulleys for obtaining reverse rotation torque. Although they are positioned overlapping with the pulleys for forward rotation, the wires are wound opposite to generate reverse rotation torque. Importantly , since the diameters of these pulleys are all the same, unlike the forward rotation system, the reverse rotation torque is equal at all joints. Consequently, by balancing the torque from these asymmetric dual systems of tendons, it becomes possible to drive the object from the base as if enveloping it.

Our gripper proposed in this paper follows a similar principle.

B. First Prototype and Inter-Axial Distance Issues

The first prototype shown in Fig. 2 employed a variable stiffness mechanism with circumferential layer jamming driven by a single wire. Specifically, it featured male and female circumferential layer structures on the links before and after the joints, functioning by pulling the links towards each other through the wire to generate friction.

Such a structure implies variations in the inter-axis distance of the joints. This behavior is incompatible with the requirement stated earlier that the pulley diameters in the ”soft gripper” theory need to be adjusted to match the BMD. Thus, it can be said that a prerequisite for a variable stiffness mechanism acceptable within the theory is that the inter-axis distance remains constant.

C. Toggle Linkage-Based Variable Stiffness

Figures 5 and Fig. 6 depict schematic diagrams illustrating the principle of the toggle linkage-based variable stiffness mechanism proposed in this paper and the integrated overall view. Each rotation pair of links and pulleys is smoothly connected with bearings. Additionally, only the upper plate of the toggle linkage has a pair that slides over the axis in addition to rotating.

The toggle linkage formed at point ABC, driven by the force F_{in} [N] via wires, outputs an orthogonal force F_{out} [N]. This force generates friction torque on the contact surface S with area A [m^2], altering the stiffness of the

[1]It should be noted that all pulleys in the ”soft gripper” are free to rotate about their axes. Pulleys continue to rotate until all joints make contact with the object.

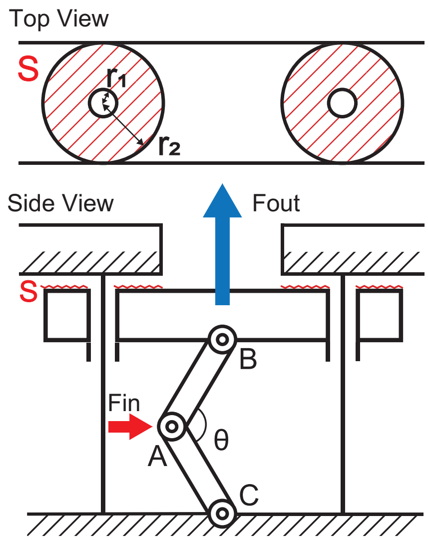

Fig. 5. Schematic diagram of the proposed toggle-linkage-based variable stiffness mechanism. Some parts are omitted for clarity.

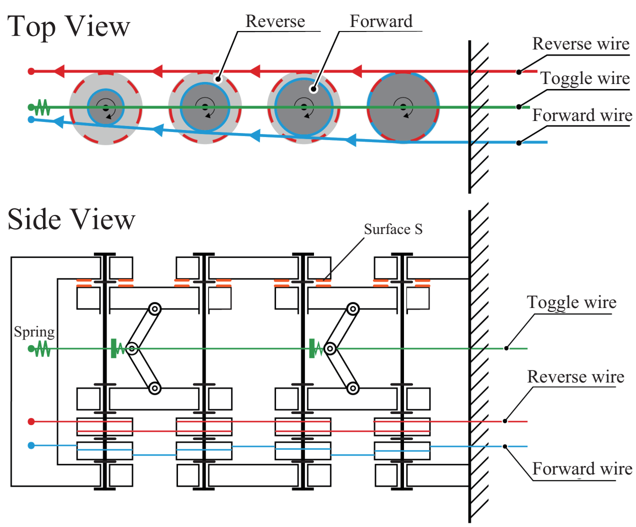

Fig. 6. Schematic diagram of the integrated overall configuration.

joint. As a result, this structure provides a variable stiffness mechanism without variations in the inter-axis distance. Furthermore, the toggle structure with nonlinear characteristics tends to maintain high rigidity even with a weak F_{in} due to its singular posture.

Let the pressure acting on the contact surface S be denoted as P [Pa],

$$P = \frac{F_{out}}{A} = \frac{\frac{1}{2}\tan\frac{\theta}{2}F_{in}}{2\pi(r_2^2 - r_1^2)}. \tag{1}$$

Therefore, the holding torque τ [Nm] due to friction at each joint is given by,

$$\tau = \int_{r_1}^{r_2} \mu P \pi r^2 dr, \tag{2}$$

$$\tau = \frac{\mu \tan\frac{\theta}{2}(r_3^2 - r_1^3)}{6(r_2^2 - r_1^2)} F_{in}. \tag{3}$$

Here, when the singular attitude $\theta = 90$[degree], theoretically $\tau = \infty$[N]. Although there are actually limitations due to the Young's modulus of the material, these characteristics provide mechanical advantages.

D. Integration of Shape Adaptation and Variable Stiffness

To ensure the compatibility and realization of both shape adaptability and variable stiffness, several design considerations are necessary.

Firstly, it is essential that the wires driving the toggles pass through the neutral line of the multi-joint link in the top view. This ensures that the force driving the variable stiffness mechanism does not adversely affect the theory.

Secondly, there is the equalization of force distribution in the toggle wire due to the elastic spring component. Directly connecting the wire to point A of the toggle linkage may introduce biases in the operation of the toggle linkage due to wire tension-induced elongation and manufacturing and assembly errors. Therefore, inserting a relatively stiff elastic spring component between them helps prevent stiffness variations due to displacement errors.

Lastly, there is the element for retraction of the toggle wire. At the singular points of the toggle linkage, it is not possible to obtain the force needed to deactivate the high stiffness mode. Therefore, providing a weak tension spring component at the leading end of the wire facilitates wire retraction, enabling a transition to the flexible mode.

E. Grasping Behavior and Manipulation

For a more precise understanding, this section describes the grasping operation of the proposed gripper. The main capabilities mentioned so far are as follows.

- Enveloping the object from the base.
- Grasping with equal pressure.
- Increasing stiffness

This section elaborates on when these capabilities are activated. Here, we assume the use of a pair of grippers based on the proposed idea.

First, the gripper in a horizontal orientation approaches the object. Subsequently, driven by antagonistic tendons, the gripper enveloping around the object with relatively weak force. Then, while the reverse drive is disabled, the forward drive is strengthened to achieve equal-pressure grasping. Finally, the variable stiffness mechanism increases the stiffness of the gripper. When releasing the object, the reverse process occurs. This process realizes enveloping, equal-pressure grasping, and variable stiffness.

III. Prototyping

To validate the effectiveness of the proposed gripper, a second prototype based on the principle was fabricated (Fig. 1, Fig. 7). The body was fabricated using an acrylic-based stereolithography 3D printer, while off-the-shelf components were adopted for shafts and other parts. The specifications can be found in Tab. I. Furthermore, in this paper, only one set of grippers has been prototyped. However, there are plans to develop a symmetrical pair of grippers in the future.

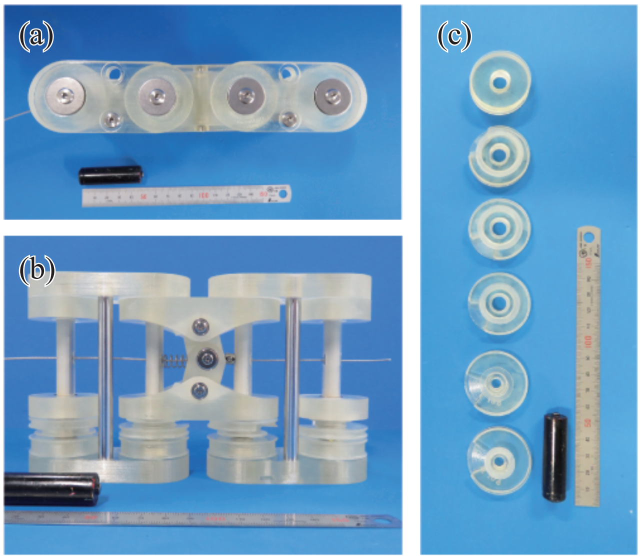

Fig. 7. Detailed photograph of the prototype principle model: (a) Top View, (b) Side View, (c) Forward pulleys.

TABLE I
SPECIFICATIONS OF PROTOTYPE

Total size	395x40x110	mm
Total weight	1.6	kg
Inter-axis distance	50	mm
Wire diameter	Approx. 1	mm
Length AB(BC)	20	mm
Number of joint	6	-
Surface S	$r_1 = 7, r_2 = 20$	mm
Static friction coefficient μ	0.427	-
Body Material	Acrylic (Agilista,AR-M2)	-
Wire	Kevlar	-

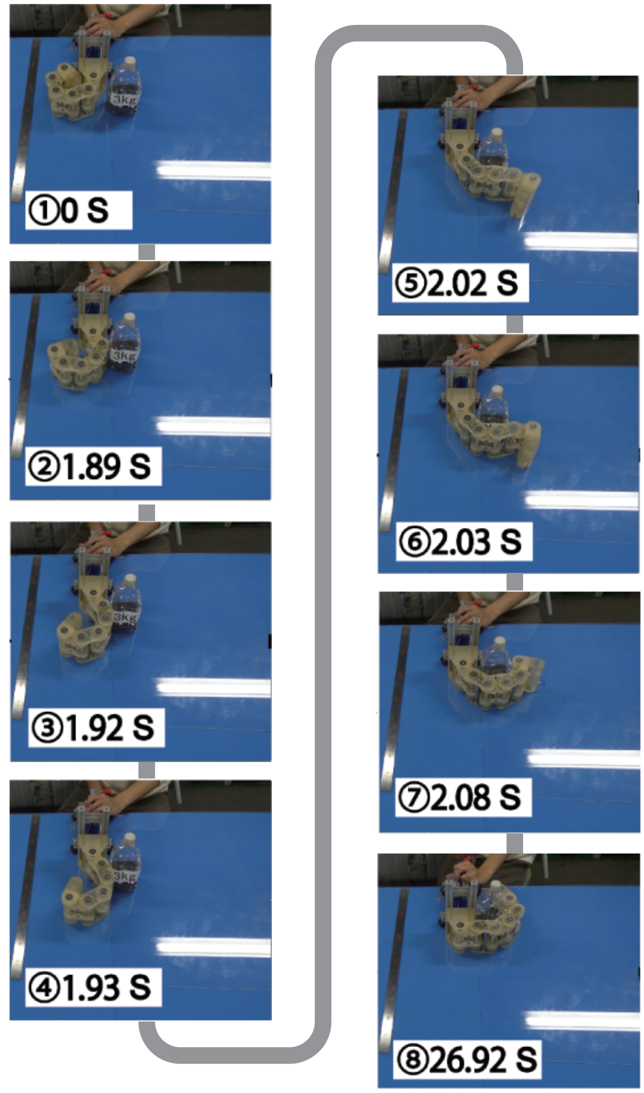

Fig. 8. Behavior of the prototype holding a 3kg object from the stored position. While applying a constant tension to the reverse pulley, the tension on the forward pulley was gradually increased. The prototype gripped the object by wrapping around it. However, the motion of the tip link was somewhat awkward, resulting in a longer gripping time.

The prototype is driven by three wires: one for toggle jamming, one for adaptation through foward rotation, and one for antagonistic through reverse rotation. The toggle wire is operated manually by a lever, while the other two wires are driven by adjustable weights. Notably, due to the weight of the prototype, sufficiently smooth ball rollers are installed at the bottom of each link. This allows horizontal alignment on a smooth floor.

This prototype has lower joint density compared to the ”Soft Gripper,” this is attributed to the enlargement of the toggle linkage to ensure strength. To address this issue, it is believed that utilizing high-strength resin parts and accurately calculating strength will allow for sufficient downsizing. This applies similarly to weight reduction considerations.

IV. Experiment and Discussion

In this section, we investigate shape adaptation and variable stiffness, revealing their respective performances and compatibility. First, we confirm the realization of the ”Soft gripper” theory, then proceed to validate the variable stiffness with the toggle linkage. If both are found to be feasible, it confirm the validity of the proposed idea.

A. Adaptive and Enveloping Behavior

In this experiment, we verify the enveloping behavior proposed in the ”Soft Gripper” theory. With a constant tension applied to the reverse wire, the tension of the forward wire is gradually increased. This should result in grasping objects from the base of the gripper and enveloping them. Note that toggle jamming is disabled.

Figure 8 shows the prototype gripping a 3kg object from its stored position. It can be observed that grasping proceeds sequentially from the base where the highest torque is required. Hence, it can be inferred that strategic antagonistic driving is successfully implemented as per the theory.

However, only the most distal joint exhibits sluggish behavior in its forward rotation. This is attributed to the relatively greater attenuation of forces due to flexure in 3D-printed materials, owing to the small pulley diameter relative

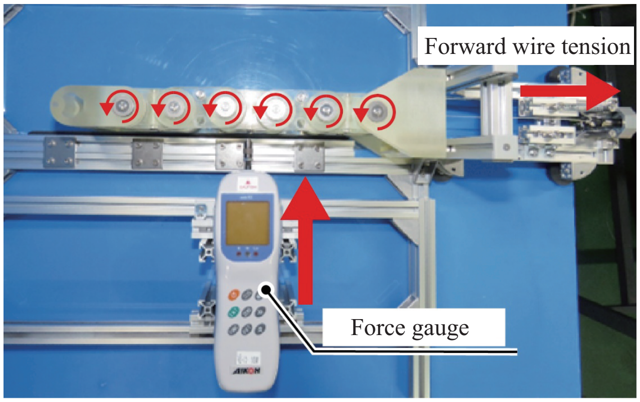

Fig. 9. Experimental setup for equi-pressure grasping. The link under measurement is lightly pressed by the force gauge, while the other links make contact with the aluminum frame. Measurements are conducted for all links except the tip.

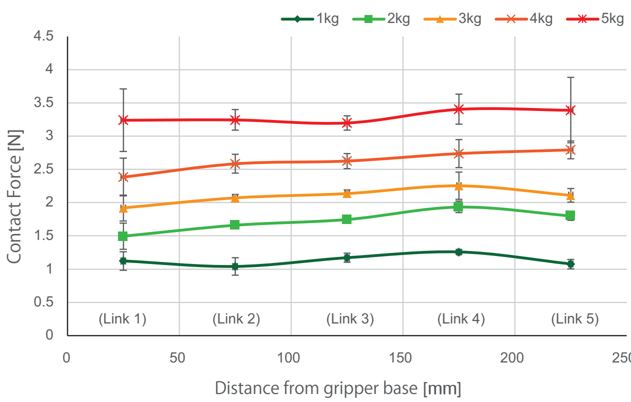

Fig. 10. Graph of the measurement results for equi-pressure grasping. The horizontal axis represents the distance[mm] from the base, and the vertical axis represents the contact force[N]. A consistent value was obtained for all cases with weights attached.

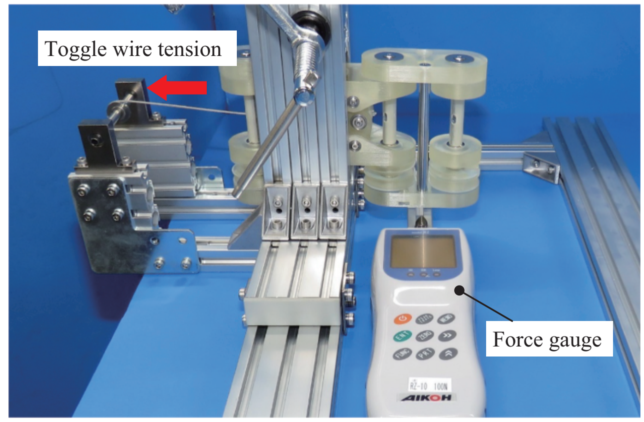

Fig. 11. Setup for measuring the holding torque of the toggle-linkage-based variable stiffness. The peak holding torque is measured and calculated by pressing the force gauge at each toggle wire tension.

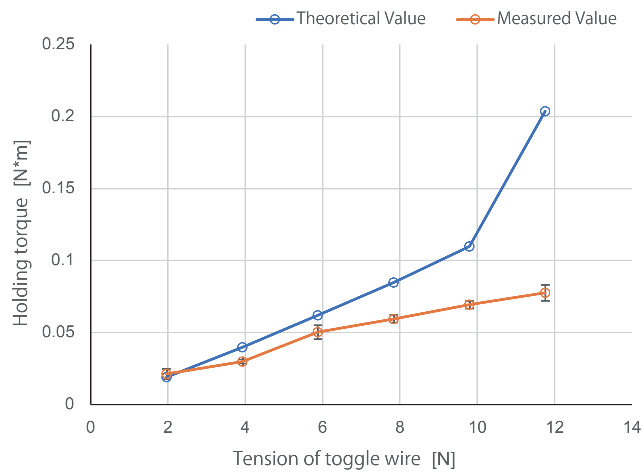

Fig. 12. Graph of the holding torque measurement results. The horizontal axis represents the tension[N] of the toggle wires, while the vertical axis represents the holding torque[Nm]. Although the results deviated from the theoretical values near the singular points of the toggle linkage, overall, the results exhibited a similar trend to the theoretical values.

to the link size. To address this, appropriate changes in material or fabrication methods, or doubling the diameter of all pulleys to increase relative pulley size, could be considered.

B. Equi-Pressure Grasping

In this section, we elucidate the equi-pressure grasping behavior proposed in the ”Soft Gripper” theory. Tension is applied to the forward wire, and the contact forces generated on each joint are measured. If the theory holds, the obtained results should be proportional to the tension and remain constant regardless of distance.

Figure 9 shows the experimental setup, while Fig. 10 presents the graph of the measurement results. A force gauge (FGP-100, Nidec, Japan) is lightly pressed against the center of each link, and the forward wire is driven. During this process, all links except the one under measurement are adjusted to contact the aluminum frame. The contact forces are measured 11 times each, and their averages and standard deviations are plotted. Wire tensions are generated using weights of 1, 2, 3, 4, and 5 kg . The results show that the contact forces remain constant, indicating that a certain degree of equi-pressure grasping is achieved.

C. Variable Stiffness Capability

Finally, we validate the effectiveness of toggle-linkage-based variable stiffness. With tension applied to the toggle wire, we measure the holding torque by pushing the link with a force gauge and compare it with the theoretical formula to assess effectiveness and model validity.

Figure 11 illustrates the experimental setup, while Fig. 12 shows the graph of the results. The peak value of friction holding torque is calculated from pressing a force gauge against a representative single joint. The tensions of the toggle wire are approximately 2, 4, 6, 10, and 12 N, respectively. Each measurement is performed 11 times, and their average values and standard deviations are plotted.

The graphs of the results demonstrate that stiffness variation is achieved, and the prototype and theoretical values exhibit similar trends. However, the increased force effect due to the toggle linkage singularity is hardly observed. This is attributed to the conversion of toggle-induced force into strain energy due to the low strength of the body material. Improvement is expected with the adoption of metallic materials.

D. Grasping Behavior and Manipulation

An integrated experiment demonstrating all functionalities is depicted in the attached video. The gripper is shown enveloping around, grasping, and finally manipulating a 3kg object by increasing its stiffness. Note that, note that the actions on the right and left sides of the video are comparable. Further enhancements are expected to be realized through future development efforts.

In conclusion, the experiments with this prototype demonstrate that both variable stiffness and shape adaptation are compatible. Thus, the validity of the proposed gripper is sufficiently supported.

V. Conclusion

In this paper, we introduced the novel gripper that combines shape-adaptive grasping and variable stiffness. This is achieved through the integration of the "Soft Gripper" principle, which enables equi-pressure grasping and enveloping shape adaptation of objects, with a toggle-linkage-based variable stiffness mechanism that does not inhibit these capabilities. As a result, it becomes possible to grasp objects independently of their shapes and to ensure secure manipulation and transportation. We first describe the theory and construction method of the proposed gripper and then highlight the need to consider the variation in inter-axis distances based on observations from the first prototype. Next, focusing on the compatibility of shape-adaptive grasping and variable stiffness with the principle prototype, we experimentally verify its feasibility. The results revealed new challenges in the rigidity of constituent components while sufficiently supporting the proposed idea.

Future work will involve improving the design for miniaturization and densification of the device, as well as aiming for automation of the driving system. This will contribute to the realization of multi-fingered hands and elongation with proposed mechanism, facilitating further advancements.

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