BTS Gripper: Compliant Linkage-Based Gripper Design for a Busing-Table Service Application

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***Abstract*—In this article, we present an adaptive busing-table service (BTS) gripper. The BTS gripper is a mode-changeable three-fingered parallel gripper with compliant linkage-based finger mechanisms and has two modes: adaptive grasp and nongrasp modes (push/pull operation). For the BTS task, the gripper must be able to grasp dishes of various sizes, shapes, and weights. In addition, the gripper must have the capability to push and pull dishes so that there is sufficient space for holding the dishes. A compliant linkage-based finger mechanism using mechanical compliance and a stopper was developed to implement adaptive grasping. A mode-changing mechanism and rigid posture of the finger with a mechanical stopper were designed to achieve the nongrasp mode. A gripper prototype was designed, and the feasibility and effectiveness of the proposed gripper were verified through several experiments on various dishes and objects on a 1-DOF jig testbed and 6-DOF manipulator. Thus, this study contributes to the advancement of robotic manipulation technology by offering a novel gripper design for complex BTS scenarios.**

***Index Terms*—Adaptive grasp, busing-table service (BST) robot, compliant linkage mechanism, mode change, parallel gripper, underactuated robotic finger.**

I. Introduction

THE low birth rate and aging population have led to an imbalance in labor supply, making it necessary to secure a stable workforce. To solve this social problem, service robots are actively entering the market in various industries, such as electronics, logistics, distribution, and security, and it is highly likely that the service robot market will continue to grow rapidly. In particular, serving robots that deliver food at restaurants have been commercialized and are fully performing a practical serving support role. Collecting empty dishes after a meal is an area that requires urgent manpower in the restaurant's overall task, and tables are not cleared on time, resulting in additional damage due to longer waiting times. If the task of setting food on a table fails, it can be fatal to personal safety, but in the case of collecting empty dishes after a meal, there is freedom in that regard, so the possibility of commercialization is very high. Therefore, a busing-table service (BTS) robot supports the task of collecting dishes and workers can focus on improving the quality of service to customers. This is possible because object recognition and grasping technologies have advanced in various ways and collaborative robots with high stability and reliability have emerged. One of the most important technologies for realizing the BTS robot is the grasping technology of the gripper. The BTS gripper must be able to adaptively grip a wide variety of objects with a single gripper without changing the gripper tool, unlike robots that use industrial grippers specialized for gripping only a few types of objects. The grasping technology of the BTS gripper can be expanded to fields that require safe pick and place manipulation without damage to a variety of objects, such as nursing homes, hospitals, housekeeping, laboratories, and factories, other than the restaurant industry mentioned above.

Grasping is one of the most crucial functions of the human hand. A human hand can adapt to and grasp objects of various sizes and shapes in various environments. Adaptive grasping has long been one of the most important research fields for robotic hand or gripper researchers and is still being actively studied [1]. Various gripper types have been studied to implement compliant and adaptive gripping. Examples of gripper research include implementing compliance by introducing soft or flexible materials into the gripper [2], [3], [4], [5], [6], [7], [8], implementing compliance in the gripper actuator, such as series elastic actuator (SEA) [9], [10], [11], [12], [13], and tendon (wire)-driven methods utilizing wire elasticity [14], [15], applying compliance control, such as impedance control [1], [16], [17], [18], and implementing mechanical compliance by applying springs to the linkage-based gripper (underactuated robotic gripper) [19], [20], [21], [22], [23], [24], [25].

The human hand interacts with environmental constraints to grasp an object successfully by wrapping it around or sliding on the surface on which it rests. Therefore, inspired by the behavior of the human hand when grasping objects, several scientists have developed adaptive robotic hands and grippers that can grasp different types of objects using underactuated mechanisms that exploit mechanical compliance [19], [20], [26]. The underactuated gripper mechanism can be passively

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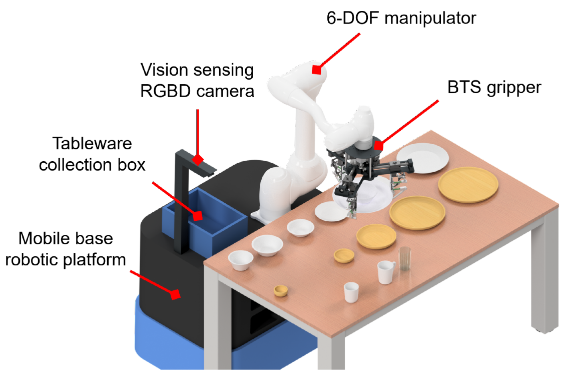

Fig. 1. Configuration of the BTS robot.

controlled and manipulated through physical contact with constraints [22]. Without using a complicated control algorithm, the mechanical compliance of the underactuated mechanism allows the robotic gripper finger to automatically enclose the object shapes [21]. The primary emphasis of these endeavors has been on implementing passive intelligence, including self-adaptation to diverse object geometries, interaction with environmental constraints, and manipulation of objects to establish a secure grasping position [24], [25].

As shown in Fig. 1, the BTS robot comprises a mobile base platform, a 6-DOF manipulator, a BTS gripper, an red, green, blue plus depth (RGBD) camera for vision sensing, and a tableware collection box. The BTS task of the robot is as follows. After the mobile-based platform moves toward the table with the dish to be collected through autonomous driving, it recognizes the dish on the table through the vision-sensing RGBD camera, and moves the 6-DOF manipulator equipped with the gripper to operate the gripper to grip the dish. The manipulator then moves to place the gripped dish into the tableware-collecting box.

The BTS task involves collecting dishes of various sizes, shapes, and weights, such as plates, bowls, and cups, that may or may not contain leftovers inside the dish placed on the table and may not have sufficient space for gripping between the dishes. It includes all the processes, from stably gripping the dishes to moving the manipulator equipped with the gripper without shaking the dishes and loading them. Thus, the BTS gripper should be designed such that it can grip not only tall bowls or cups, but also objects that are low in height and have only slightly raised edges, such as plates. The BTS gripper must satisfy the design requirements described in Section II-B, such as adaptability to various objects and BTS work characteristics and environments. However, the existing studies on various grippers have not fully met all the necessary design requirements for dish collection task. They have the limitation that there are many restrictions on the uncertainty of the object shape in the case of single-shape grippers, and the payload of multijoint grippers is limited compared with complex control due to the use of multiple actuators.

In this article, an adaptive BTS gripper, a mode-changeable three-fingered parallel gripper with a compliant linkage-based finger mechanism, is proposed by reflecting various design requirements and operation scenarios for the BTS task. By applying a compliant linkage-based finger mechanism based on an underactuated finger mechanism using fewer actuators [25], the BTS gripper can adaptively grip dishes of various sizes, shapes, and weights that are difficult for existing commercial grippers to grip with simple control of small number of actuators. This is possible even in the presence of vision-sensing errors by utilizing the passive adaptation movement and the three-fingered grasping strategy described in Section II-B. In addition, the BTS gripper is capable of performing nongrasp operations in the form of push/pull on objects as well as grasping through a mode-changing mechanism to secure the gripping space. The BTS gripper has a safe release technology that reduces the risk of object damage through a finger mechanism with passive environmental adaptability.

The rest of this article is organized as follows. In Section II, the concept of the BTS gripper, including the robot's BTS task and the gripper's operating scenarios, is described. Section III explains the kinematic design of the compliant linkage-based finger mechanism and the static analysis of the gripper in the grasp pose. The mechanism design of the BTS gripper is presented in Section IV, including the gripper configuration and driving mechanism, compliant linkage-based finger mechanism, and mode-changing mechanism between the grasp and nongrasp modes. An experimental evaluation was conducted to verify the feasibility and effectiveness of the gripper in Section V. Finally, Section VI concludes this article.

II. Concept of the Busing-Table Service Gripper

A. Busing-Table Service Task of the BTS Robot

The BTS gripper proposed in this study is designed with the goal of meeting various design requirements for dish gripping and collecting work from a BTS robot, as shown in Fig. 1. The BTS task involves vision sensing of various dishes placed on the table, motion planning and control of a robotic manipulator with a gripper mounted on its end effector based on the vision-sensing data, and manipulation of the gripper.

First, the mobile-based robotic platform autonomously moves and stops at the target location around the table where the dishes to be collected are located, using light detection and ranging (LiDAR) sensors. The vision-sensing RGBD camera mounted on the mobile-based robotic platform measures the position (center point location), size (diameter), and height (or depth) of all the dishes. Based on the visual-sensing data of the dishes on the table, the optimal dish collection order is determined by considering the type and location of the dishes. For vision sensing, an Intel RealSense depth camera D435 is adopted, and a deep-learning-based object detection algorithm is used. However, vision sensing using such an RGBD camera has the problem of vision-sensing errors, and it was found that vision-sensing errors occur up to 20 mm in the x, y, and z-axes directions. Thus, the gripper must be able to stably grasp the dish under operating conditions where vision-sensing errors occur.

After vision sensing is completed, the robotic manipulator (Doosan Robotics M1013 Manipulator) with the gripper is moved to the best place to grip the targeted dish, and the manipulator is lowered to grip the dish. The gripper holds the

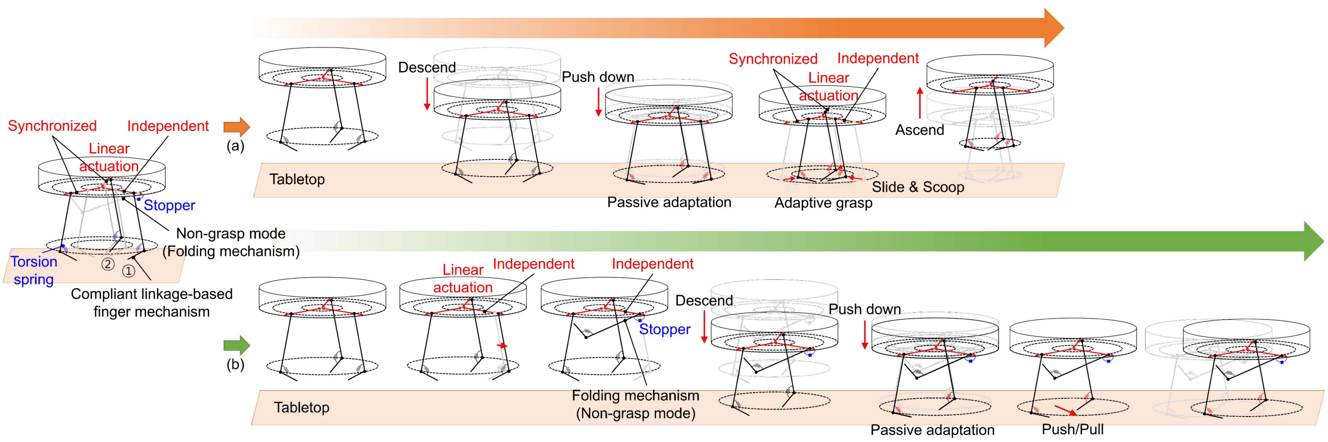

Fig. 2. Operating scenarios of the BTS gripper. (a) Adaptive grasp mode. (b) Nongrasp mode (Push/Pull mode).

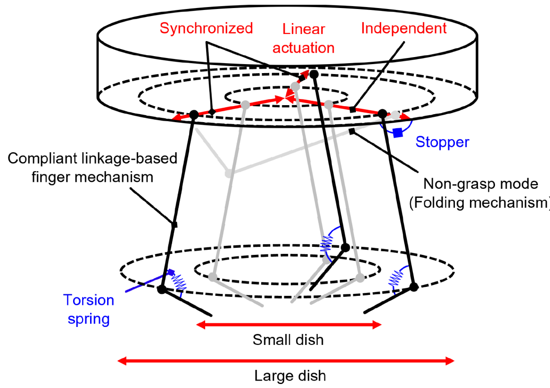

Fig. 3. Proposed conceptual gripper design, which satisfies the design requirements of the BTS gripper is a mode-changeable three-fingered parallel gripper with a compliant linkage-based finger mechanism.

dish. The gripper should be able to grip dishes of various sizes, shapes, and weights. However, there may be insufficient space between dishes for the gripper's fingers to grip. For this situation, a push/pull operation, which is a nongrasp operation, is devised and used to create a space between dishes by pushing or pulling the dishes with the gripper finger. When the gripper successfully grips the targeted dish, the manipulator rises with the gripper holding the dish and moves it onto a tableware collection box. The manipulator is then lowered to allow the gripper to place the dishes, and the gripper releases the dishes in the tableware collection box. After this series of processes, the BTS task is completed.

B. Operating Scenarios and Design Requirements of the BTS Gripper

To realize the busing-table task defined in the previous section, two types of operation scenarios are required: adaptive grasp and nongrasp operation (push/pull operation). The operating scenario of the BTS gripper is devised by considering its conceptual design of the BTS gripper in Fig. 3, which is designed to meet the design requirements of the gripper. Fig. 2 shows a specific operation scenario of the gripper for the busing-table tasks. To implement the proposed operating scenario, the design requirements of the BTS gripper are established as follows.

1) Adaptive grasp of dishes of various sizes (100 mm $< D <$ 300 mm), shapes (plate, bowl, etc.), and weights (Max 4 kg) by mechanical compliance in case of vision-sensing error.
2) Adaptation movement (detection of tabletop) using passive and compliant linkage mechanism.
3) Implementation of a rigid posture of the gripper finger for the push / pull operation.
4) Mode changing mechanism between the adaptive grasp mode (three fingers) and non grasp mode (two fingers).
5) Safe release of a dish.

As shown in Fig. 3, the proposed conceptual gripper design, which satisfies the design requirements of the BTS gripper, is a mode-changeable three-fingered parallel gripper design with a compliant linkage-based finger mechanism. The three-fingered shape of the gripper is inspired by the shape of dishes and the grasp taxonomy of the human hand. According to the grasp taxonomy of the human hand [27], [28], [29], [30], a three-fingered gripping strategy is used to grip round or spherical objects effectively. The gripper must be able to adaptively grasp dishes of various sizes, shapes, and weights. The size of the dish is classified based on its diameter, and dishes with diameters of 100–300 mm are selected. The shape of the dish is divided into plates and bowls according to height and is classified as round or square. In addition, in the case of the dish weight, a weight of up to 4 kg is considered, considering the weight of the dish from the normal weight to a heavy bowl containing leftovers. Table I lists the dishes used in this study. Most of the dishes considered in this study are circular, and it is judged that some square plates can be gripped equally using the gripping strategy of the three-fingered gripper for circular plates.

Since the BTS robot has vision-sensing errors, the gripper proposed in this study must be able to stably grip the dish even under operating scenario conditions where vision-sensing errors occur. Vision-sensor errors can be overcome by using the following gripper gripping strategies. Vision-sensor errors in the x- and y-axes directions can be resolved as follows.

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TABLE I
TARGET DISHES AND OBJECTS

Type of dish and object	Specification (*D*: Diameter, *H*: Height, *W*: Width, *L*: Length, *a*: Semi-major axis, *b*: Semi-minor axis)
	
Plate	Circular plate (ceramic, wood, melamine) 1. D 171 mm $\times$ H 17.8 mm 2. D 216 mm $\times$ H 18.4 mm 3. D 260 mm $\times$ H 21.2 mm 4. D 280 mm $\times$ H 24 mm 5. D 300 mm $\times$ H 34 mm 13. D 149 mm $\times$ H 33 mm Square plate (melamine, ceramic) 12. W, L 150 mm $\times$ H 33 mm 15. W 225 mm $\times$ L 165 mm $\times$ H 25 mm 16. W, L 298 mm $\times$ H 37 mm
Bowl	Circular bowl (ceramic, glass, wood) 6. D 158 mm $\times$ H 49 mm 7. D 145 mm $\times$ H 100 mm 8. H 268 mm $\times$ H 93 mm Elliptical bowl (ceramic) 14. a 125 mm $\times$ b 85 mm $\times$ H 50 mm
Other objects	Square bottle 9. W, L 110 mm $\times$ H 205 mm Cylindrical object 10. D 150 mm $\times$ H 140 mm Soccer ball (spherical object) 11. D 210 mm Rectangular box 17. W 215 mm $\times$ L 115 mm $\times$ H 90 mm

The manipulator descends by spreading the three fingers of the gripper to the corresponding diameter and adding a possible vision sensor error to the diameter of the dish recognized by the vision sensor. The vision-sensor error in the z-axis direction can be overcome through passive compliance of the gripper finger in the vertical direction and contact recognition of the torque sensor of the manipulator with the tabletop. Subsequently, if the three fingers are brought together in a concentric circle, even if there is an error in the x- and y-axes directions in the location (center point coordinates) of the dish recognized by the vision sensor, the dish can be driven to the center point of the concentric circle while gripping it. The safe release of the dish can be implemented using the vertical compliance of the gripper, gradually descending the manipulator, and then safely putting down the dish while spreading the three fingers in the reverse direction when gripping the dish.

III. KINEMATIC DESIGN AND STATIC ANALYSIS

A. Kinematic Design of the Compliant Linkage-Based Finger Mechanism

As shown in Fig. 4, the compliant linkage-based finger mechanism consists of a base linkage with a seven-bar linkage shown in black and a synthetic linkage shown in red. The connection

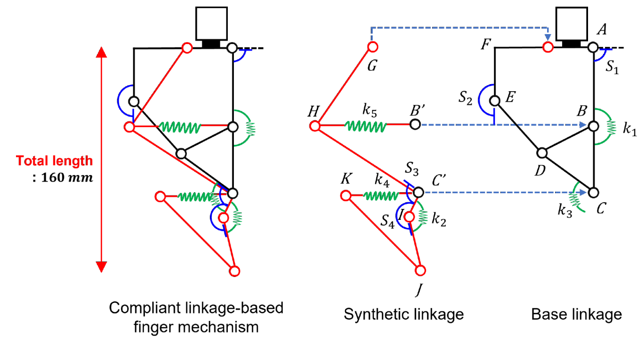

Fig. 4. Kinematic design of the compliant linkage-based finger mechanism.

mount marked with a square connecting the finger and the linear actuator of the driving (actuating) parts is located at the top of the base linkage of the seven-bar linkage structure shown in black. The base and synthetic linkages have mechanical springs (torsional springs and linear springs) installed at several joints, so that after gripping, the mechanically compliant joint restores the original shape of the finger prior to gripping.

The base linkage comprises of a seven-bar linkage structure with two mechanical stoppers marked in blue (S_1, S_2) and two torsional springs (k_1, k_3) marked in green. When it comes into contact with a bowl or cup with a high height, joint B is pressed (shape adaptation occurs), enabling physical constriction-type gripping. Torsional spring k_1 and linear spring k_5 provide a mechanical restoration (resilience) force for joint B to return to its original position after being deformed and gripped by an object in contact with joint B. Stopper S_1 maintains angle $\angle FAB$ vertically when the base linkage returns to its original state after gripping the object. Stopper S_2 restricts the base linkage from moving beyond the singularity through contact with link DE (l_{DE}) when joint B is deformed when pressed by an object.

The synthetic linkage consists of the upper three linkages [link GH (l_{GH}), link $B'H$ ($l_{B'H}$), and link $C'H$ ($l_{C'H}$)], and the lower four-bar linkage structure fingertip (linkage $C'IJK$). The four-bar linkage fingertip (linkage $C'IJK$) at the bottom of the synthetic linkage exhibits a passive adaptation movement in the vertical direction as joint C' rotates, and torsional spring k_2 and linear spring k_4 deform when the manipulator descends and the finger contacts the tabletop. Torsion spring k_3 provides a mechanical restoring force that allows joint C' to rotate when the manipulator ascends, allowing the four-bar linkage fingertip to return to its original position. In addition, when a dish with a low height, such as a plate, is in contact, joint I of the four-bar linkage fingertip is pressed and deformed, enabling physical constriction-type gripping. The stoppers S_3 and S_4 prevent the lower fingertip (linkage $C'IJK$) from bending backward through contact with link CD when an object contacts the lower fingertip of the synthetic link and joint C rotates, which is necessary for nongrasp operation (push/pull operation).

A compliant linkage-based finger mechanism is designed by setting the kinematic design parameters, as shown in Fig. 4. Each

TABLE II
KINEMATIC DESIGN PARAMETERS OF THE COMPLIANT LINKAGE-BASED FINGER MECHANISM

Linkage length						
l_{AB}	l_{BC}	l_{BD}	l_{CD}	l_{DE}	l_{EF}	l_{FA}
40 mm	45 mm	45 mm	45 mm	39.2 mm	30 mm	61 mm
l_{GH}	$l_{B'H}$	$l_{C'H}$	$l_{C'I}$	l_{IJ}	l_{JK}	$l_{C'K}$
56.9 mm	71 mm	84 mm	20 mm	40 mm	89.6 mm	70 mm
Stopper angle				Linkage angle		
S_1	S_2	S_3	S_4	$\angle AFE$	-	-
90°	180°	90°	135°	90°	-	-
Spring coefficient						
k_1	k_2	k_3	k_4	k_5	-	-
1 Nmm/deg	1 Nmm/deg	1 Nmm/deg	0.4 $N/$mm	0.4 $N/$mm	-	-

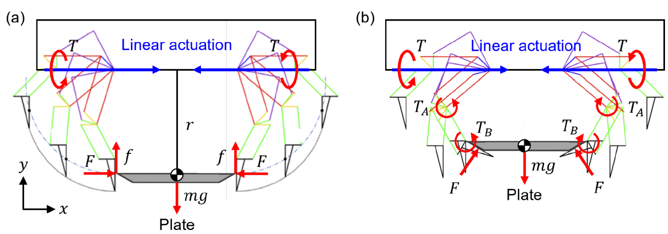

Fig. 5. Static analysis of the gripper in the dish gripping posture. (a) Gripping a plate using the frictional gripping method. (b) Gripping a plate using the physical constriction gripping method.

design parameter was selected as a design variable value that can perform the tableware collection scenario presented in Section II through a repetitive dish collection simulation for various dishes using the RecurDyn dynamic simulation tool [31], and the results are given in Table II.

B. Static Analysis of the Gripper in the Gripping Posture

A gripper uses two main methods of grasping: physical constriction and friction [32]. A physical constriction method is a method of grasping an object by the physical contraction of the inner part of a finger, in which a finger encircles the part to some extent and changes the contact surface of the finger to approximate the shape of the part. The friction method is a gripping method, in which an object is fixed by friction between a finger and an object, and the finger must apply sufficient force so that the friction required to grip the object acts against gravity acting on the weight of the object. For the friction method, the gripper must be designed to exert force based on the weight of the part, the friction coefficient of the fingertip, and release acceleration. In this study, we conducted a static analysis of the gripper's performance for both grasping methods.

As can be seen in Fig. 5, we tried to find the motor torque required to grip the dish by performing static analysis when the gripper gripped the dish according to each gripping method. Fig. 5(a) shows the case of grasping a plate by the friction method. Fig. 5(b) depicts the case of gripping a plate by the physical constriction method. In the case of Fig. 5(b), the force acting on the plate through the fingers required to hold the plate is trivially smaller than the force of Fig. 5(a), which is required to hold the plate only by friction. This is because of the force acting on the plate by the torque acting on the springs and the area between the plate and the finger contact surface, which is increased by deforming the finger composed of links of several joints to fit the shape of the plate to some extent because of the springs. Thus, the minimum torque required to hold the dish is obtained by calculating the required torque in Fig. 5(a).

The gripper is a three-fingered parallel-type gripper that uses a linear actuation method. Fig. 5 shows the three fingers gripping the dish through the linear actuation drive. The two fingers move in synchronization with one motor (motor 1) and only one finger moves independently of the other motor (motor 2). Because the driving mechanism of the gripper is a linear actuation type, the torque from the motor is transmitted as the torque of the ball screw, and the rotational motion of the ball screw is converted into the translational motion of the finger connected to the ball screw. Thus, based on the free-body diagrams of Fig. 5(a), the torque acting on the ball screw T by a motor has the following relationship with the force acting on the plate by one finger F:

$$T = r \times F \tag{1}$$

where r is the distance from the center of gravity where the weight of the plate acts to the ball screw and where the torque T acts. f represents the frictional force generated by F against the weight of the plate, and mg is the force owing to the weight of the plate. The friction coefficient μ acting between the finger and plate is assumed to be 0.9 considering the friction coefficient between the plate and the silicone pad to be attached to the finger, and r is assumed to be 0.12 m considering the length of the finger. m is set to 4 kg, which is the maximum dish weight according to the gripper design requirements described in Section II. Because three fingers grip the plate, the force equilibrium equations shown in Fig. 5(a) can be obtained as follows:

$$\Sigma F_y = f - \frac{mg}{3} = 0, \quad f = \mu F. \tag{2}$$

The motor torque T required to grip the dish can be calculated as

$$T = \frac{mgr}{3\mu}. \tag{3}$$

Therefore, the torques of motor 1 (T_1) and motor 2 (T_2) should satisfy the following inequality:

$$T_1 \geq \frac{2mgr}{3\mu}, \quad T_2 \geq \frac{mgr}{3\mu}. \tag{4}$$

IV. MECHANISM DESIGN OF THE BUSING-TABLE SERVICE GRIPPER

A. Configuration and Driving Mechanism of the Gripper

In this study, a mode-changeable three-fingered parallel gripper design with a compliant linkage-based finger mechanism, which satisfies all the design requirements of the dish-collecting gripper established in Section II, was designed to stably grip dishes of various sizes, shapes, and weights considering the vision sensing error. Fig. 6 shows the configuration of a compliant

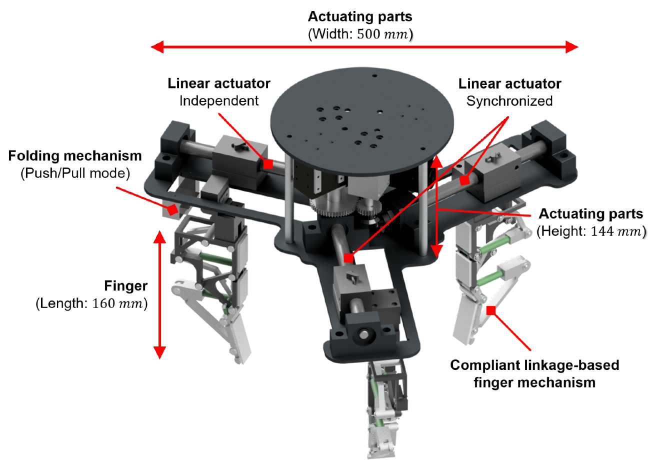

Fig. 6. Overall configuration of the BTS gripper.

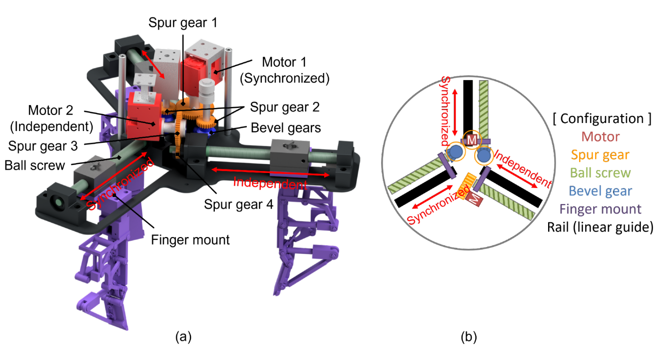

Fig. 7. Driving mechanism of the gripper. (a) 3-D design model. (b) 2-D configuration diagram of the actuating parts.

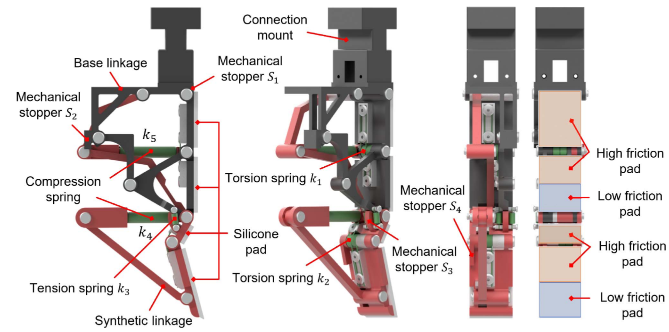

Fig. 8. Configuration of the compliant linkage-based finger mechanism.

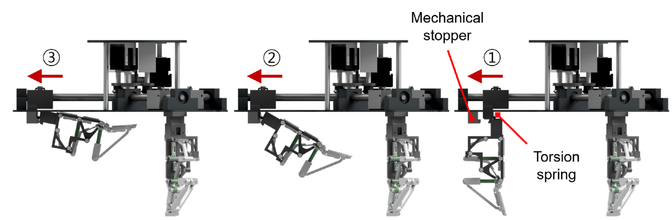

Fig. 9. Mode changing mechanism (finger folding mechanism) between grasp mode and nongrasp mode.

linkage-based gripper for the BTS robot. The gripper consists of an actuating part with a width of 500 mm and a height of 144 mm and three fingers with a length of 160 mm. The total weight of the gripper was designed not to exceed 6 kg considering that the payload of the robot manipulator is 10 kg and the maximum tableware weight is 4 kg.

There are two general driving methods for robotic grippers: parallel (linear) and rotary (angular). In this study, a parallel driving method was used. This is because the gripper uses a compliant linkage-based finger mechanism, and linear actuation results in consistent compliance regardless of the translated finger position [21]. This facilitates the design of the finger mechanism because it allows the passive finger mechanism to have a relatively predictable finger trajectory. As shown in Fig. 7, motor 2 is designed to be able to move only one finger independently by being connected to one ball screw through spur gears to implement nongrasp operation. Motor 1 is connected to two ball screws through spur gears and bevel gears and is designed to synchronize the movement of the two fingers. Based on the motor torque values obtained in Section III-B, ROBOTIS Dynamixel XH540-W150-R is used as motors 1 and 2. The spur gear is designed with a gear ratio of 2:1 for motors 1 and 2 to increase the movement speed of the finger by increasing the rotational speed of the ball screw.

B. Compliant Linkage-Based Finger Mechanism

For an adaptive grasp of the gripper, we can implement compliant and adaptive gripping using various methods, such as introducing soft or flexible material, adopting an actuator (SEA), which incorporates a series of elastic elements in itself for compliance, a tendon (wire)-driven method utilizing the elasticity of the wire, compliance control including impedance control, and mechanical compliance by applying springs to the linkage mechanism. In this study, a compliant linkage-based mechanism using mechanical compliance and a mechanical stopper was adopted for the finger mechanism of the gripper for adaptive grasp and nongrasp operations, considering control simplicity and durability for the target payload.

Fig. 8 illustrates the compliant linkage-based finger mechanism of the gripper. The base linkage with a seven-bar linkage is shown in black and the synthetic linkage is shown in red. The finger is connected to the ball screw through a connection mount at the top of the finger and is designed to move in parallel using the ball screw. Interlink force sensing resistors (FSR) UX 408 tactile sensors are installed on the four phalanxes of each finger, and silicon pads are attached to the top. This is to measure the gripping force of the fingers to safely grip the dishes without damaging them and to stably grip the dishes by securing a sufficient frictional force. For the friction pads attached to the first and third phalanges, low- and high-friction pads are attached to the bottom and top, respectively, to ensure smooth sliding and scoop motion of the plate and bowl when gripping the dish.

A compliant linkage-based finger mechanism was designed based on the kinematic design parameters listed in Table II. However, the proposed finger mechanism was designed with different types of springs and stiffness coefficients to consider

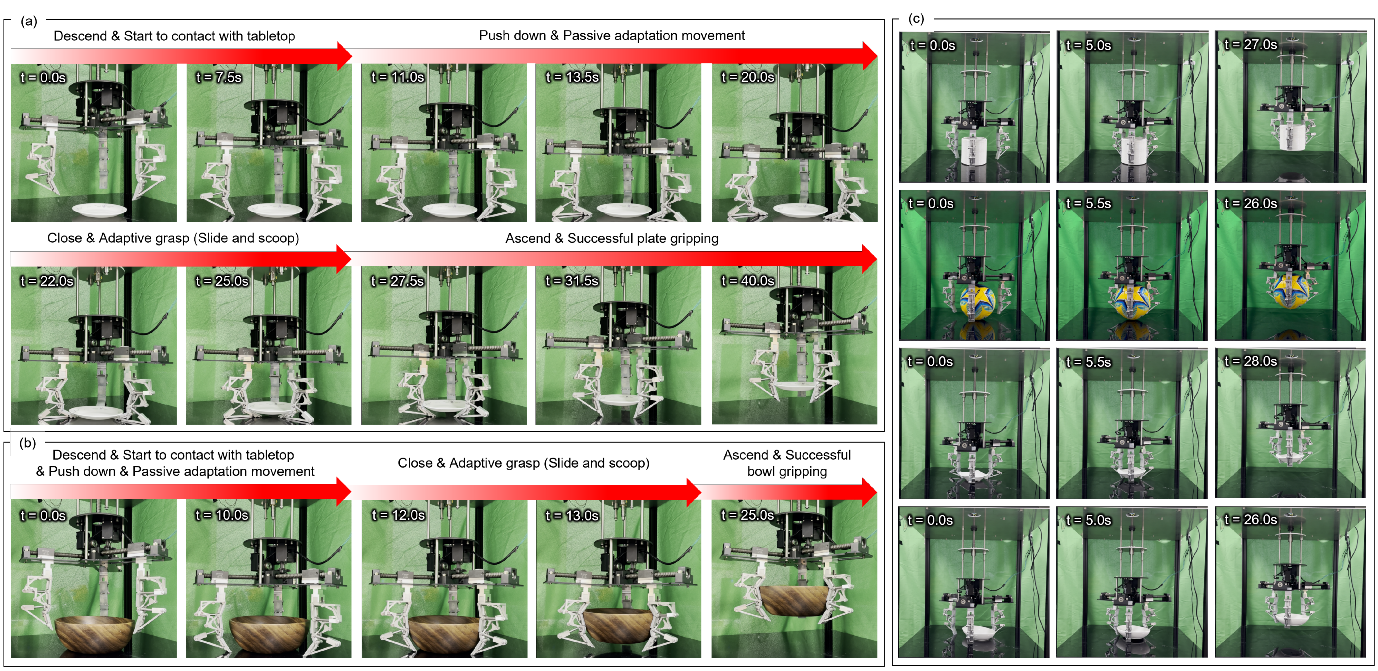

Fig. 10. Detailed sequence of adaptive grasping according to dish type. (a) Plate (Dish ② of Fig. 12). (b) Bowl (Dish ⑧ of Fig. 12). (c) Various dishes and objects (Dish and objects ⑩, ⑪, ⑫, and ⑭ of Fig. 12) have been successfully gripped. Gripping videos of all the dishes and objects in Fig. 12 used in the experiment can be found in the Supplementary Material (experiment videos).

the space efficiency of the mechanical design and installation characteristics of springs and to use commercially available components. Torsional springs k_1 and k_2 were designed by arranging two torsional springs (each 0.43 $\mathrm{N{\cdot}mm/^\circ}$) with similar stiffness in parallel to a total of $k_1 = k_2 = 0.86$ $\mathrm{N{\cdot}mm/^\circ}$. The torsional spring k_3 was designed by arranging two tension springs (each 0.406 $\mathrm{N{\cdot}mm/^\circ}$) with similar stiffnesses in parallel to a total of $k_3 = 0.912$ $\mathrm{N{\cdot}mm/^\circ}$ between links $l_{C'H}$ and $l_{C'I}$. The stiffness of the linear springs was selected to have a joint torque aspect similar to that of the torsional spring, with $k_3 = 1$ $\mathrm{N{\cdot}mm/^\circ}$. Linear springs k_4 and k_5 were designed to have values similar to the original design spring coefficient of 0.4 N/mm using compression springs with a spring coefficient of 0.49 N/mm.

C. Mode Changing Mechanism Between Grasp Mode and Nongrasp Mode

For nongrasp operation (push/pull operation), the gripper has a mode-changing mechanism from a three-fingered adaptive grasp mode to a two-fingered nongrasp mode. As shown in Fig. 9, the mode-changing mechanism from three to two fingers becomes possible when one of the three fingers, which is independently linearly actuated, is folded using a mechanical spring and stopper. One of the three fingers of the gripper is designed to perform linear drive independently through a ball screw connected to motor 2. The finger is designed to have a connection mount composed of a hinge with a torsion spring and a mechanical stopper for folding, unlike the other two synchronized fingers. After the independent fingers are folded, the other two fingers can be used to perform the nongrasp operation of pushing and pulling when there is insufficient gripping space between the dishes.

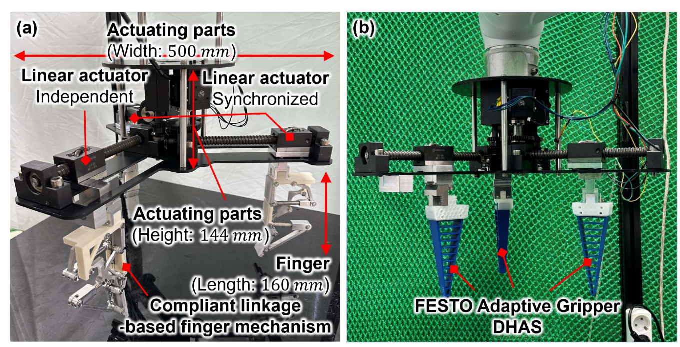

Fig. 11. Grippers used in the experimental evaluation. (a) Prototype BTS gripper fabricated for experimentation. (b) FESTO adaptive gripper DHAS.

V. Experimental Evaluation

A. Gripping Experiments on 1-DOF Jig Testbed

1) Adaptive Grasp of Various Dishes and Objects: As shown in Fig. 11(a), a prototype of the BTS gripper was fabricated to verify its feasibility and effectiveness. The BTS gripper was designed to grasp various dishes through adaptive grasping, and the experimental results shown in Fig. 10 illustrate the gripping strategy (sequence) of the gripper according to the type of dishes and the successful grasping of different types of dishes and objects by the gripper. As shown in Fig. 11(b), for comparative evaluation between the BTS gripper and the existing gripper, the FESTO adaptive gripper DHAS, which implements soft

Fig. 12. Variety of dishes and objects were used in gripping experiments. Gripping success rate of the (a) BTS gripper and (b) FESTO gripper for various dishes and objects was expressed as N/10 (N: number of successful gripping).

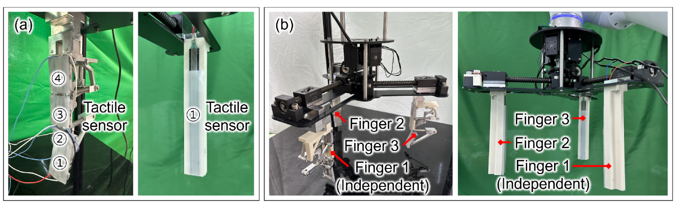

Fig. 13. Experimental conditions of the gripping force evaluation using a tactile sensor. (a) Tactile sensors were mounted on the fingers of the BTS gripper and the three-fingered parallel gripper. (b) Gripping force of each gripper was measured with tactile sensors attached on three fingers.

and flexible gripping with the fin ray effect derived from the movement of a fish's tail fin, was used. To evaluate and compare the gripping success rate of the grippers, the grippers were mounted on a 1-DOF jig testbed and a 6-DOF manipulator, and 10 replicate gripping experiments were performed for each dish and object from Table I. Fig. 12 presents the grasping success rate for each dish and object for the BTS and FESTO grippers. The grasping success criteria for the gripper were determined based on its ability to lift dishes or objects by 100 mm after gripping and maintaining its position for 10 s.

Although the BTS gripper was designed to be able to grip a variety of dishes and objects, the gripping success rate of dish ⑬ and ⑮ is lower than that of other dishes. The reasons for this are the strict gripping success criteria, which assumes that the grip is successful only if the plate is gripped horizontally without being tilted or twisted, and the control method in the grasping mode, in which the three fingers are synchronized and move at the same position and speed. This can be solved by controlling the position and speed differences between the three fingers.

In addition, to assess the adaptive gripping performance of the gripper, a payload experiment was conducted to measure the maximum weight of an object that the gripper can grip. It was confirmed that the BTS gripper can reliably grip and lift up to 10 kg for the bowl and up to 6 kg for the plate. The FESTO gripper was able to stably grip and lift up to 2.2 kg for bowls and 1 kg for plates. The experimental videos can be found in the Supplementary Materials.

2) Evaluation of Gripping Force: Gripping force evaluation was conducted using a tactile sensor to measure the force required for gripping dishes, such as a plate or bowl. An interlink FSR, UX 408, was used for this purpose. Fig. 13 compares the

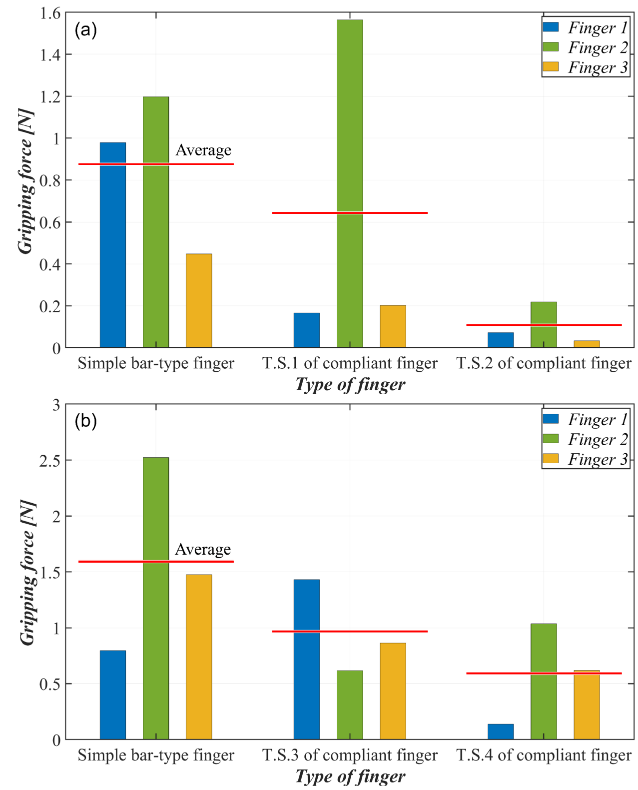

Fig. 14. Gripping force measured when gripping (a) a plate (Dish ② of Fig. 12) and (b) a bowl (Dish ⑧ of Fig. 12) with a simple bar-type finger gripper and a compliant linkage-based finger gripper (T.S.: Tactile sensor).

gripping force of the BTS gripper with compliant linkage-based fingers to a three-fingered parallel gripper with simple bar-type fingers when gripping dishes. The gripping force was measured as the minimum gripping force required to grip the dish reliably. The minimum required gripping force was defined and measured as the grip force immediately before the instant when the number of contact points was lower than the number of contact points with the gripped object. The gripper was judged to be a stable grip by checking the instant when the grip force read by the tactile sensor became zero, while gradually opening the three fingers of the gripper with a stable and firm grip on the dish.

Kok and Low [23] defined and quantified grasping ability using the total force grasp surface pressure. In a parallel gripper, the gripping force is determined by the reaction force of the gripper finger in contact with the object, against the force of the actuator moving the gripper finger in the translational direction. Given the same force moving the finger through the actuator, the more the points of contact between the finger and the gripping object, the more distributed and smaller the force on the object per point of contact. Therefore, when gripping fragile objects, such as dishes made of glass or ceramics, a higher number of contact points allows for higher-quality grasping.

Fig. 14 shows the gripping force measurements. A three-fingered parallel gripper achieved 3-point contact grasping, with each finger contacting the dishes at one point, as confirmed by the gripping force from tactile sensors. In contrast, the BTS gripper accomplished 6-point contact grasping, with each finger

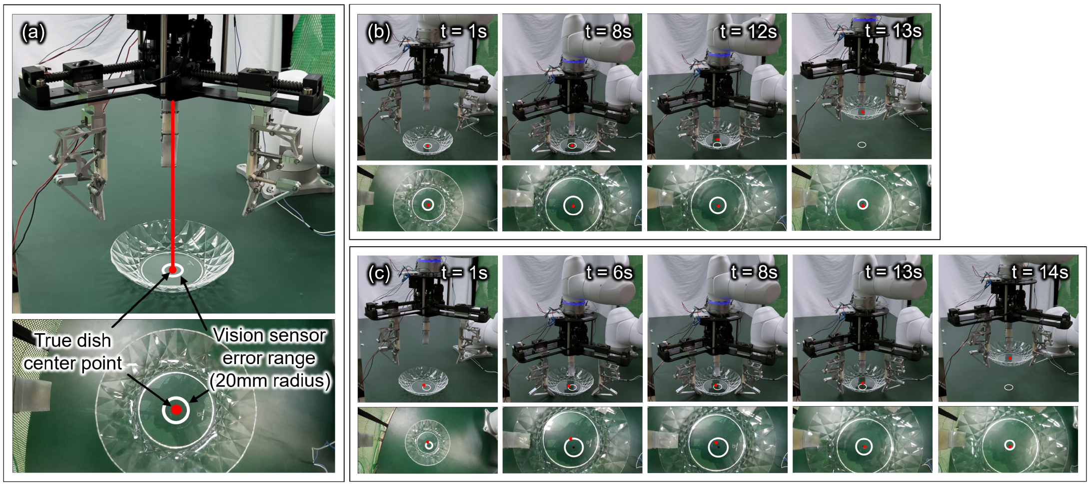

Fig. 15. (a) Experimental conditions for evaluating whether it is possible to grip dishes when there is a vision sensor error. Red point shows the center point of the dish. White circle around the red point represents the vision sensor error range of a 20 mm radius. Experimental results of adaptive grasp (b) without vision sensor error and (c) with vision sensor error of 20 mm radius. Experimental video can be found in the supplementary materials.

making 2-point contact with the dishes. The gripping force of the plate was measured using tactile sensors 1 and 2 on the compliant linkage-based finger, confirming the 2-point contact with the first and second phalanges of the finger. For the bowl, the gripping force was measured using tactile sensors 3 and 4, confirming a two-point contact with the third and fourth phalanges of the finger. The minimum required gripping force was determined by calculating the average of the minimum required gripping force measurements for each phalanx of the three fingers. Notably, the average gripping force of the compliant linkage-based fingers was lower than that of the simple bar-type fingers. Therefore, the BTS gripper, having double the contact points of simple bar-type fingers and applying lower forces to each point, achieve a higher-quality grasp for fragile objects, such as glass or ceramic dishes.

B. Gripping Experiments on 6-DOF Manipulator

1) Adaptive Grasp of a Dish in Case of Vision Sensor Errors: As mentioned in Section II-A, the vision-sensing camera of the BTS robot has a maximum error of 20 mm in the x-, y-, and z-axes directions. Therefore, the BTS grippers were designed to reliably grip dishes even with these vision-sensing errors. The BTS gripper overcomes the vision-sensing error, as described in Section II-B to grip the dish. To validate this, experiments were conducted as shown in Fig. 15, where the gripper's ability to grasp a plate was tested under two conditions: one with no vision-sensing error and the other with vision-sensing error (maximum error radius of 20 mm). These experiments verified that the BTS gripper is capable of successful grasping even when there is a vision-sensing error, confirming its effectiveness under such circumstances.

2) Stability Evaluation of Adaptive Grasp: To assess and compare the adaptive grasping stability of the grippers, the BTS and FESTO grippers were mounted on a 6-DOF manipulator, as shown in Fig. 16(a) and (b). The evaluation involved moving

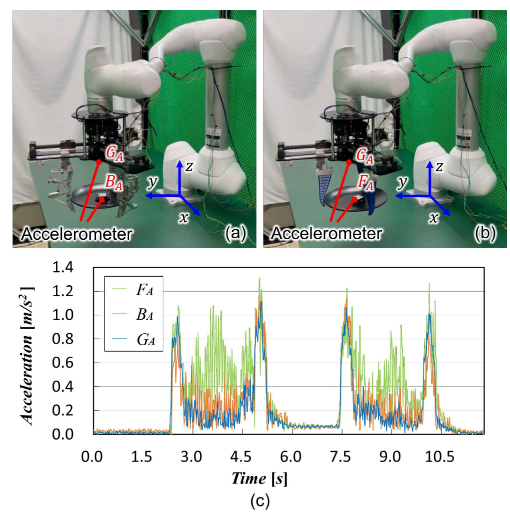

Fig. 16. Experimental conditions for the stability evaluation of adaptive grasp of the (a) BTS gripper and (b) FESTO gripper. (c) G_A, B_A, and F_A represent the measured accelerations of the dish and the two grippers, respectively.

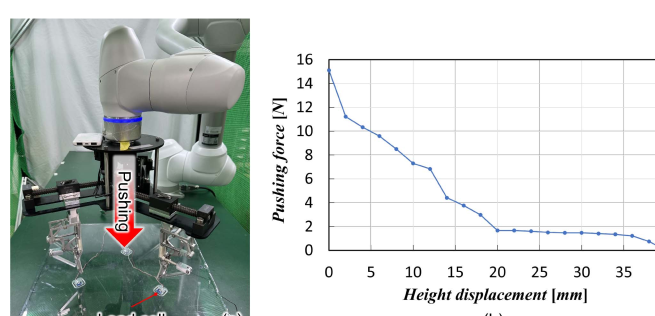

Fig. 17. (a) Pushing force activated by deformation of the compliant linkage-based finger mechanism based on height displacement was measured using a load cell. (b) Measurement result of pushing force by one finger according to height displacement.

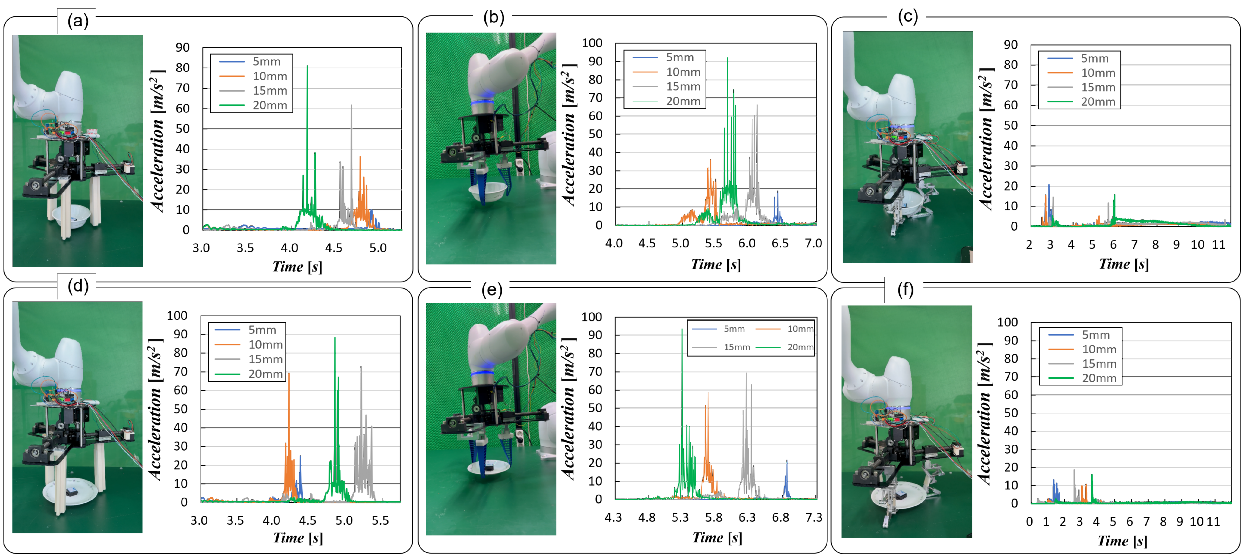

Fig. 18. Experimental results of the evaluation of safe dish release: Measured accelerations of a bowl and plate released by the (a) and (d) simple bar-type three-fingered parallel gripper, (b), (e) FESTO gripper, and (c), (f) BTS gripper at release heights of 5, 10, 15, and 20 mm.

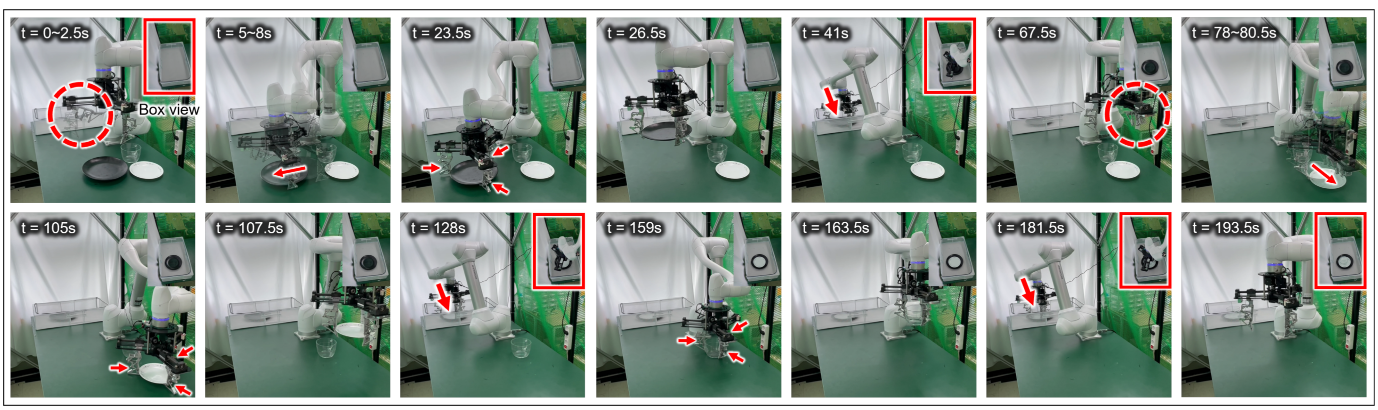

Fig. 19. Demonstration of the BTS gripper's operations, including adaptive grasping, nongrasping actions (push/pull operations), and safe dish release, in the entire BTS scenarios. Video footage of the mentioned experiments can be found in the supplementary materials (experiment videos) for reference.

the manipulator while the gripper held the dish to determine how securely and firmly the gripper maintained its grasp on the dish during motion. When the manipulator reciprocated a certain distance in the x-axis direction while the gripper grasped the dish, the acceleration values were measured and compared by attaching accelerometers to the BTS and FESTO gripper (B_A, F_A) and dish (G_A), respectively, as shown in Fig. 16(a), (b). The smaller difference between B_A (F_A) and G_A implies that the gripper has a firm grip on the bowl to prevent it from shaking as the manipulator moves. Thus, Fig. 16(c) shows that the difference between B_A and G_A is small, which is even smaller when compared with the difference between F_A and G_A, verifying the stability of the adaptive grasp of the BTS gripper.

3) Evaluation of Passive Adaptation Movement: The compliant linkage-based finger mechanism of the BTS gripper exhibits passive adaptive movement when in contact with the tabletop. To evaluate this passive adaptability, the range of adaptive movement of the compliant linkage-based finger in the vertical (z-axis) direction and the pushing force owing to the deformation of the finger along the vertical movement were measured, as shown in Fig. 17(a). As illustrated in Fig. 17(b), the finger could undergo deformation of up to 40 mm in the vertical direction, and the pushing force against the vertical deformation displacement was determined.

4) Evaluation of Safe Dish Release: The BTS gripper was designed not only to grasp dishes securely through adaptive grasping but also to safely release them when placing them down. To evaluate and compare safe dish release quantitatively, accelerometers were attached to the dishes (a plate and bowl). This allowed a comparison of the impact on dishes during the release process between the simple bar-type three-fingered parallel gripper, FESTO gripper, and BTS gripper. The acceleration of the dish was measured as each gripper released the dish. The vision sensor of the BTS robot has an error of up to 20 mm in the vertical (z-axis) direction. To conduct a comparative evaluation considering the limitations imposed by the error range of the vision sensor, dishes were released at different heights of 5, 10, 15, and 20 mm. During the release process at these heights, the acceleration of the dishes was measured and compared between the simple bar-type three-fingered parallel gripper, FESTO gripper, and BTS gripper. The results presented in Fig. 18 reveal that the measured acceleration values for both the plate and bowl were significantly lower for the BTS gripper compared with the simple bar-type three-fingered parallel gripper and FESTO gripper. This outcome verifies the substantial reduction in impact during the dish release process achieved by the BTS gripper and validates the safe dish release capability of the BTS gripper.

5) Demonstration of Adaptive Grasp, Nongrasp Operation, and Safe Dish Release in the Busing–Table Scenarios: The BTS gripper was designed to fulfill both the BTS task defined in Section II and the corresponding design requirements. Consequently, as illustrated in Fig. 19, the demonstration of the BTS gripper's operations, including adaptive grasping, nongrasping actions, and safe dish release, confirms its capability to execute the entire BTS scenario. This includes tasks, such as picking up dishes and placing them in a tableware collection box.

VI. Conclusion

In this study, a compliant linkage-based gripper capable of gripping dishes of various sizes, shapes, and weights has been proposed for BTS applications. The concept of the BTS gripper was established by analyzing the BTS task of the BTS robot and the operating scenario of the BTS gripper. Accordingly, the design requirements of the gripper were defined. A kinematic design and static analysis were performed to design the gripper and finger mechanisms. A three-fingered parallel gripper with a compliant linkage-based finger mechanism, which has two operating modes—an adaptive grasp mode and a nongrasp mode—was presented and designed with the aim of fulfilling the design requirements of the BTS gripper. To verify and confirm the effectiveness and feasibility of the BTS gripper, various experimental evaluations were conducted. The adaptive grasping capability based on the grasp success rate and payload test on various dishes and objects of the gripper was evaluated using a 1-DOF jig testbed. The adaptive grasping capability under vision sensor errors, stability of adaptive grasping, passive adaptability of the compliant linkage-based finger mechanism, and safe dish release were evaluated by mounting the gripper on a 6-DOF manipulator. In addition, a full busing-table scenario involving adaptive grasping, nongrasping actions, and safe dish release was demonstrated using a 6-DOF manipulator.

In future work, a study on simplifying the compliant linkage-based finger mechanism will be conducted using a flexible material, such as a belt, that shows similar or better performance to the gripper developed in this study.

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