2025 IEEE/SICE International Symposium on System Integration (SII)
January 21-24, 2025, Munich, Germany

Comprehensive Support for Dressing Bottoms in Hemiplegic Individuals Using a Branching Arm Robot

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Abstract— **This paper presents a robotic system designed to assist hemiplegic individuals in dressing, specifically focusing on the process of putting on bottoms. Assisting a hemiplegic patient with this task involves several complex actions, such as maneuvering through tight spaces and coordinating simultaneous movements with both hands. In this study, we analyze the assistive techniques used by caregivers and propose a branching arm robot equipped with two end-effectors to address these challenges. The proposed robot has a sufficient range of motion and torque, enabling it to assist in dressing while maintaining a compact design. Additionally, it includes a specialized end-effector capable of performing a multi-stage release of the bottoms, accommodating the intricate handling of clothing. Experimental results demonstrate that the robot effectively aids hemiplegic individuals in dressing, from threading the legs through the hems to pulling the bottoms up to the waist.**

I. INTRODUCTION

Wearing clothes is a daily activity that everyone performs and is a fundamental aspect of life. However, this essential task can be challenging for individuals with physical disabilities. In the field of robotics, various efforts have been made to provide support for these individuals [1-3].

The purpose of this study is to develop a system that assists hemiplegic individuals in putting on bottoms, specifically focusing on the process from a sitting position. Rather than addressing isolated actions, such as threading the legs through the hems or pulling up the waistband, we consider the entire sequence of movements involved in dressing support. Our goal is to construct a robot system capable of providing comprehensive and effective assistance throughout this process.

Assisting a hemiplegic patient in dressing requires numerous complex movements, such as lifting the patient's legs with the knees while simultaneously handling the bottoms with both hands. In this study, we begin by analyzing the key characteristics of these supportive actions performed by caregivers and identifying the essential elements involved. Based on this analysis, we propose a branching arm robot equipped with two end-effectors as a solution. These end-effectors work together to manipulate the bottoms and support the patient's body, enabling the robot to provide comprehensive assistance throughout the entire process of putting on trouser.

The contributions of this paper are as follows:

- We analyzed and systematically categorized the actions performed by caregivers when assisting hemiplegic patients in putting on bottoms.
- We designed and developed a branching arm robot to replicate these essential actions and introduced a novel motion sequence for dressing support based on these features.
- We conducted a series of experiments using the real robot, successfully demonstrating the complete dressing support process, from threading the hem through the legs to pulling the bottoms up to the waist.

The structure of this paper is as follows: The next section introduces related work, followed by Section III, which details the action analysis of caregivers and presents our proposed approach. Section IV introduces the flow of dressing assistance Section V introduces our hardware system and explains its characteristics. Section VI presents the experimental results and discussion, and Section VII concludes the study.

II. RELATED WORK

Several studies have explored dressing assistance for hemiplegic individuals. Erickson et al. [1] developed a fast and low-impact method for shirt dressing assistance by predicting the forces exerted by the garment on the human body. They utilized model predictive control informed by a model learned through simulation, incorporating tactile and other sensory data. Zhang et al. [2] proposed a method for probabilistically tracking a person's arm posture using the robot's hand position and force data. Zhu et al [3] developed a two-arm dressing assistance system that manipulates a person's arms and sleeves, drawing inspiration from the techniques used by medical professionals for helping patients put on jackets. Their system effectively estimates arm posture while minimizing the load on the user. Clegg et al [4] developed models for various body restriction patterns related to dressing and devised a method for assisting dressing within the limited range of arm motion using reinforcement learning. Yamazaki et al [5] employed model predictive control(MPC) to predict the forces applied to the arm, successfully implementing a sleeve-threading support system with minimal load. Unlike traditional studies on dressing support [6-9], which primarily focus on individuals with some degree of mobility, these studies address the unique challenges of assisting hemiplegic patients by considering joints with restricted range of motion and providing support for limbs that are difficult to move. This finding is significant for supporting hemiplegic patients. However, these studies primarily focus on upper garments, such as shirts. Applying these techniques to lower garments, such as bottoms, presents challenges due to their distinct characteristics. For example,

*This work was supported in part by JSPS KAKENHI 23H00492 and JST [Moonshot R&D], [Grant Number JPMJMS2034]

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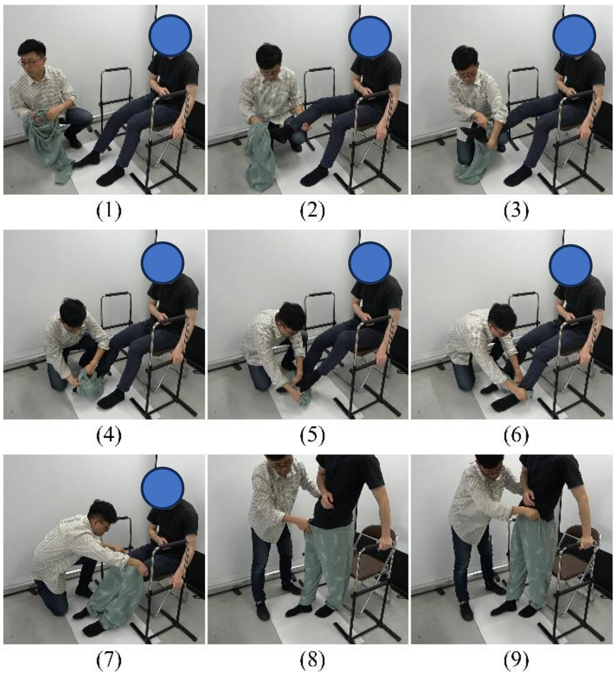

Fig.1 Dressing assistance procedure

unlike sleeves, bottoms cannot be managed one leg at a time, and legs are generally more difficult to maneuver than arms.

Yamazaki et al. [10] developed a method for detecting failures by estimating the shape of the cloth from a sequence of images, which was then used to assist in manipulating bottoms. They implemented this approach in a humanoid robot. Zhao et al. [11] introduced a failure detection method based on recognizing the boundary of the bottoms' waistband from images, with the assumption that the robot would be used in a restroom setting. In these studies, the focus was primarily on manipulating and pulling up the waistband of bottoms, with insufficient attention given to hemming process. For example, simplifying the task by starting with the legs floated or already hemmed. Hemming bottoms while the legs are on the ground is important not only for the dressing process but also for preventing falls [12]. Additionally, research on assisting with putting on bottoms is limited to a few case studies, resulting in a lack of comprehensive knowledge in this area.

III. Requirements and Approach

A. Caregiver Motion Analysis and Requirements

In this section, we analyze the characteristics of the assistive motions performed by caregivers and identify the factors that the robot must address based on these characteristics. Our study focuses on hemiplegic patients who can stand independently with the aid of a handrail or other support. We aim to develop a partially assisted method for putting on trousers for such individuals. Specifically, we concentrate on actions involving mutual interaction between the caregiver and the assisted person, excluding preparatory actions performed solely by the caregiver.

Figure 1 illustrates the flow of assistive motions performed by a caregiver, which includes the following characteristic steps [13].

A. Hold the affected side of the hemiparesis (Fig. 1(1)).

B. Lift the leg on the affected side and position the foot on the knee (Fig. 1(2)).

C. Thread the foot through the hem (Fig. 1(3)).

D. Lower the leg back down (Fig. 1(4)).

E. Spread the hem openings on the healthy side, allowing the patient to place their foot through the hem (Fig. 1(5), (6)).

F. Grasp the waist portion of the bottoms and pull them up to the knees (Fig. 1(7)).

G. Have the patient stand up and pull the waistband up to the waist (Figs. 1(8), (9)).

In step C, caregivers rotate the hem to prevent the cloth from catching on the heel. This adjustment ensures the cloth slides smoothly and passes over the heel at the point where it is gripped, avoiding any spread of the fabric. In step E, the caregiver holds and spreads both ends of the hem opening to facilitate easier leg insertion by the patient, akin to manipulating the cloth at multiple points simultaneously. Generally, the support procedure follows this sequence: threading the hem on the affected side first, then on the healthy side, and finally lifting the waistband. Threading the hem on the affected side before the healthy side minimizes the need to excessively bend the affected joint, thereby reducing the overall burden on the patient.

Based on the above arrangement, we will develop a robot system designed to replicate these features. The summarized requirements are as follows.

1. The system must include a mechanism to prevent the cloth from snagging on the heel during hemming on the affected side.
2. The system must have a mechanism to lift and stabilize the leg on the affected side for efficient hemming.
3. The system must be equipped with mechanisms to operate at multiple points simultaneously, including supporting the legs, holding the hem, and gripping both ends of the hem.
4. The system must support the sequence: threading the hem on the affected side first, then on the healthy side, and finally addressing the waistband.

In requirement 1, the goal is to replicate the described foot movement, including its rotation, and the robot must be capable of moving the foot to the back of the leg. For requirement 4, the system must not only execute these actions in sequence but also provide the necessary degree of freedom for each phase. Additionally, since dressing assistance typically occurs in environments with handrails or walls near the bedside or toilet, the mechanism and motions must be compact to avoid interference with these structures.

B. Our Approach

Figure 2 illustrates the concept of the proposed robotic system, which features a large main robotic arm with smaller robotic arms attached as branches extending from the middle link. The main robotic arm is referred to as the Trunk Arm (T-Arm), while the smaller, attached robotic arms are known as the Branched Arm (B-Arm).

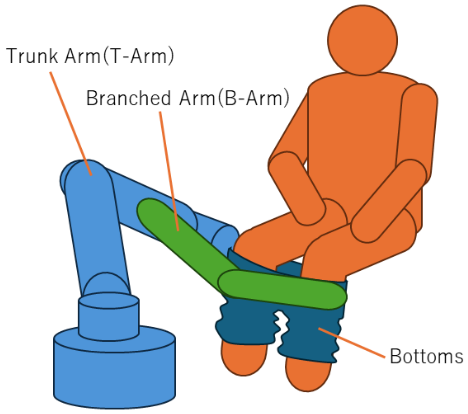

Fig.2 Assistance by branching arm robot

The B-Arm is responsible for manipulating the bottoms. Its end-effector grasps the hem or waistband of the bottoms and pulls them through or up. Because of its compact size, the B-Arm can position its end-effector underneath the heel without significantly raising the leg when hemming the bottoms on the affected side, effectively addressing the heel snag issue described in requirement 1.

The T-Arm serves three functions, switching roles based on the movement phase: (1) Lifting the affected leg: during hemming, the T-Arm lifts the affected leg, addressing requirement 2 from the previous section; (2) Spreading the hem opening: the T-Arm helps spread the hem opening on the healthy side while the B-Arm manages the hemming; (3) Pulling up the waist , after both legs have been hemmed, the T-Arm grips waistband to pull the bottoms up.

To address requirements 3 and 4 from the previous section, we propose the branching configuration shown in Fig. 2. This design features multiple end-effectors that allow simultaneous operation at different locations. The B-Arm's range of motion adjusts in tandem with the T-Arm's movements, enabling the B-Arm to be compact yet sufficiently maneuverable for the task. Unlike most conventional studies on dressing support using dual-arm robots [1][2][6][7][8], which focus solely on manipulating the cloth without direct interaction with the person, our solution includes direct assistance by physically engaging with the user. While dual-arm robots commonly used in dressing assistance studies, such as Baxter [14], offer a sufficient range of motion for tasks like those described, they risk interfering with the surrounding environment due to large arm movements around the legs or when spreading the hem of the garment. Although the proposed procedure could be feasible with a conventional dual-arm system, the complexity of the assistive motion, the intricacies of the hardware, and the need for precise insertion into narrow spaces highlight the advantages of the branching configuration. This design, featuring a small arm mounted on a long-reach arm, provides significant benefits in managing space and maneuverability.

The design of branching robots has been explored in the field of continuum robotics [15, 16], sharing the same concept of balancing workability and compactness as in this study. However, these designs are typically tailored for scenarios where the trunk arm and branched arms assist each other in complementary tasks. They do not address applications like ours, where multiple branching arms work simultaneously on the same object.

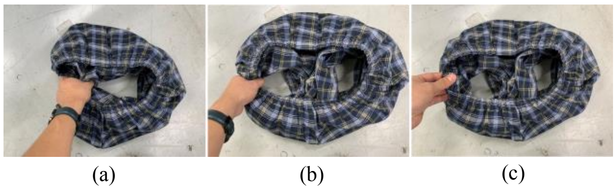

Fig.3 Grasping states of the end-effector of the Branched Arm

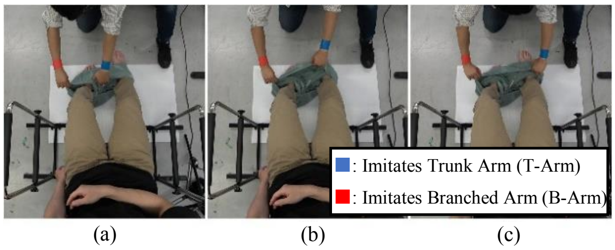

Fig.4 Procedure of manipulating waist portion of the bottoms by the Trunk Arm. Right side is assumed to be paralyzed side.

IV. Flow of Dressing Assistance

This section outlines the robot's assistive motion, which is designed to replicate the procedures described in Section III-A through B-G. The B-Arm end-effector sequentially adopts the grasping states of (a), (b), and (c) shown in Fig. 3:(a) grasping the leg part and crotch of the healthy side of the bottoms while keeping the hem opening of the affected side exposed, (b) grasping the leg part of the healthy side with the hem openings of both sides exposed, (c) grasping only the waistband of the healthy side. Initially, the end-effector secures the bottoms, and the grasping state is then transitioned sequentially from (a) to (c).

As illustrated in Fig. 2, the robot is positioned in front of the seated subject and operates from this frontal position. This setup minimizes the width of the work area, enabling the robot to function effectively in confined spaces such as toilets and bedsides areas. The procedure for assistive motion is as follows. (1) Initial Grasping: In the configuration shown in Fig. 3(a), the B-Arm grasp secures the hem of the leg part in advance. (2) Leg Support: The T-Arm lifts and holds the leg on the affected side. (3) Hemming: The B-Arm threads the hem while simultaneously rotating the hem opening. (4) Lowering the leg: The leg is lowered and the hem opening on the affected side, which was held by the B-Arm, is released, transitioning to the state shown in Fig. 3(b). (5) Spreading and Grasping the Healthy Side: The T-Arm spreads and grasps the hem opening on the healthy side, as held by the B-Arm. After the subject passes their foot through, the hem opening is adjusted to the state shown in Fig. 3(c). (6) Grasping the Waist: Both sides of the waistband are grasped by the T-Arm and B-Arm. (7) Pulling Up to the Knees: The waistband is pulled up to the knees. (8) Final Adjustment: Once the patient stands up with the aid of the handrail, the waistband of the bottoms is pulled up to the waist. Note that when grasping the waistband on the affected side with the T-Arm in step (6), the end-effector should be inserted into the waistband, which is stretched in a straight line between the legs, as shown in Fig. 4(a). It should then be slid into the grasping position as illustrated in Fig. 4(b) and (c). This operation can be performed without precise cloth recognition if the leg position is approximately known, thus eliminating the need to

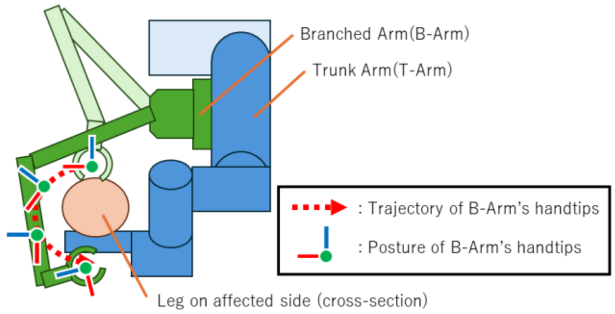

Fig.5 Motion of the Branched Arm without interference with the leg

manually adjust the cloth for grasping. The hardware required to achieve this functionality is detailed in the next section.

V. Hardware of Branching Arm Robot

A. Design and Overview of T-Arm

The requirements for the T-Arm are primarily determined by its payload capacity and range of motion. Specifically, the T-Arm must be capable of lifting the leg on the affected side. Based on statistical data on leg dimensions and mass [17, 18], the T-Arm needs to support a minimum load of approximately 2.5 kg. Additionally, the robot must be able to reach the waist of a standing person, which is the furthest point from the robot's installation position. Meanwhile, the base position of the T-Arm is assumed to be fixed at the same height as the knee, extending slightly beyond the knee joint of the leg to avoid interference with the lifted leg. Given the statistical dimensions of hip height and width, the T-Arm would need a reach of approximately 800 mm. Additionally, to operate effectively in three-dimensional space, the T-Arm must have at least 6 DOFs.

To meet these requirements, the UR5e [19] from Universal Robotics was chosen for the T-Arm. The 6-axis serial link manipulator offers a payload capacity of 5 kg and a reach of 917 mm. It is mounted on a platform with a height of 340 mm.

B. Design and Overview of B-Arm

The requirements for the B-Arm are dictated by its range of motion and the need to avoid interference with the human body. The B-Arm must be capable of reaching the far side of the waist from the T-Arm at both ends when the waist is lifted. To achieve this, the B-Arm is positioned at the midpoint of the forearm link of the UR5e T-Arm. Based on statistical measurements of waist width, the B-Arm needs a reach of approximately 450 mm or more. When the patient's leg is being hemmed, the B-Arm rotates the end-effector to position it behind the leg. During this movement, it is crucial that the arm does not interfere with the leg. To prevent interference, the moving components must be compact, and the end-effector must follow a precise trajectory and orientation, as illustrated in Fig.5. Interference can be avoided if the hand tip moves along the calf side of the leg, with the wrist joint positioned on the opposite side of the trajectory, as shown in Fig.5.

To meet the specified requirements, a new 6-DOF serial link manipulator was designed as the B-Arm. Fig. 6 illustrates the outline and joint configuration. A parallel drive mechanism is used for the second and third joints, with the motors that drive these joints are positioned at the base. This

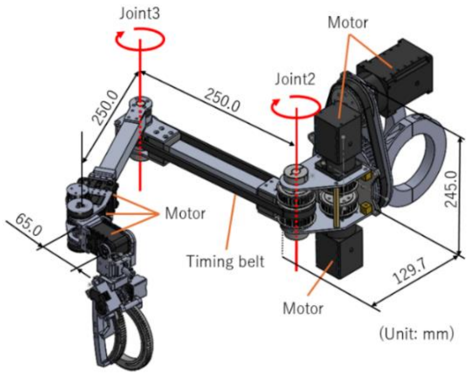

Fig.6 Overview of Branched Arm

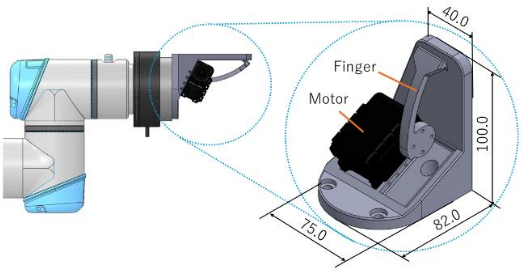

Fig.7 Overview of end-effector for the Trunk Arm

design minimizes the size of the moving unit. The length of each link was determined through inverse kinematics calculations for the trajectory and orientation of the end-effector, as shown in Fig. 5, ensuring that the chosen link lengths allow for feasible solutions. The actuators selected for each joint are as follows: the Dynamixel PRO H54-100-S500-R from BestTechnology is used for the first joint, the Dynamixel PRO H42-20-S300-R for the second and third joints, and the Dynamixel AX-18A for the fourth, fifth and sixth joints.

C. The End-Effector for T-Arm

Figure 7 shows the overview of the T-Arm end-effector. The end-effector consists is composed of a flat plate positioned perpendicular to the tip of the T-Arm tip, fingers designed for grasping the fabric, and a motor for drivingthat drives the fingers. A Dynamixel AX-18A from BestTechnology is used utilized to drive power the fingers movement.

D. The End-effector for B-Arm

Figure 8 provides an overview of the B-Arm's end-effector. As shown in Fig. 8(b), the end-effector features three movable fingers and one fixed finger. The spaces between these fingers (grasping area 1, 2, and 3) are designed to securely hold the bundled cloth. Movable fingers 1 and 2 are driven in an arc by a motor, while movable finger 3 is actuated by a gear system that meshes with part of the circumference of fingers 1 and 2. This configuration generates the necessary gripping force. By driving the three fingers with two motors, the design reduces size and facilitates the motion required to bring the hem around the leg. Grasping areas 1, 2, and 3 are designated to hold the fabric at the crotch, leg, and waist of the bottoms, respectively. The Dynamixel XL330-M288-T from BestTechnology is used to drive these fingers.

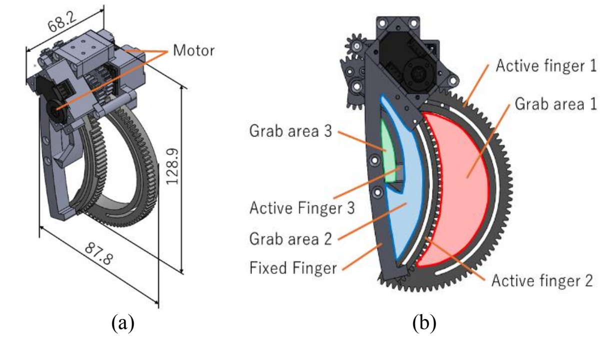

Fig.8 Overview of end-effector for the Branched Arm

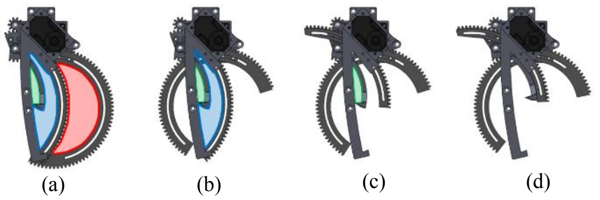

Fig.9 Movement of the end-effector for the Branched Arm

Figure 9 illustrates the transition between the movements of each finger and the corresponding grasping areas. Starting from the state shown in Fig. 9(a), where all movable fingers are closed, moving only movable finger 1 releases grasping area 1, leading to the state shown in Fig. 9(b). If movable finger 2 is then moved, grasping area 2 is released, resulting in the state depicted in Fig. 9(c). Finally, by moving both movable fingers 1 and 2 and opening movable finger 3, all grasping areas are released, as shown in the state depicted in Fig. 9(d). The states in Fig. 9(a), (b), and (c) correspond to the grasping states (a), (b), and (c) shown in Fig.3, respectively, and these grasping states are realized in turn by moving the movable fingers as shown in Fig. 9. When the end-effector is used to grasp bottoms, Fig. 9(a)-(d) are moved in the reverse order.

VI. Experiment and Discussion

An experiment was performed using the constructed robot to assist a hemiplegic patient with dressing. Fig. 10 shows the hardware setup and the arrangement of the person and robot during the experiment. The B-Arm was positioned 122 mm from the third joint of the T-Arm, with the robot placed 1100 mm in front of the subject and 160 mm to the right. The configuration of the robot is such that the B-Arm extends to the healthy side. The subject was seated on a chair with a seat height of 420 mm, and handrails were installed on either side to assist in standing.

The participant, an adult male standing 170 cm tall, and was asked to move under the assumption of hemiplegia in the right hemisphere of his body. The robot followed the pre-programmed trajectory. The bottoms used were made of a thin fabric consisting of 70% polyester, 20% cotton, and 10% rayon, with a loose hem circumference of 460 mm.

Figure 11 provides a snapshot of the experiment: (1) shows the initial state; (2) and (3) illustrate the process of threading the hem on the affected side. In (2), the T-Arm has lifted the leg, and in (3), the B-Arm has rotated the hem's grasping point and moved it to the back of the leg. In (4), the leg on the affected side is lowered, and the hem is released from the

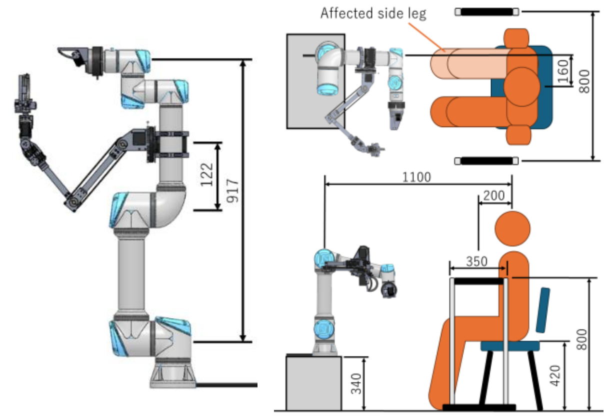

Fig.10 Structure of the robot and its positional relationship with humans.

B-Arm's grasp. In (5) and (6), the hem is threaded on the healthy side. In (5), the hem opening on the healthy side is extended by T-Arm and B-Arm, and in (6), the subject's foot passes through the extended hem opening. In (7), the end-effector of the T-Arm is inserted between the legs and slid across the waistband, and in (8), both ends of the waist are grasped by the T-Arm and B-Arm. In (9), the waist is pulled up to the knee, and then the subject stands up at (10). At (11), the subject begins to pull up the waist again, and at (12), the subject completes pulling up to the waist, finishing the task. At this final stage (12), the bottoms are hemmed away from the legs, demonstrating that the hemming on both the healthy and affected sides could be completed without snagging the fabric. In addition, the waist of the bottoms is successfully pulled up. These results indicate that the proposed system is sufficiently capable of assisting with dressing.

Figure 12 shows the end-effector paths of each robot during the assistive motion. The robots operated within a width range of 1 m, which is sufficiently small compared to the 1.6-meter width of an assisted-use toilet, indicating the system's feasibility for assisting with dressing in confined spaces like a toilet.

Furthermore, although this configuration assumes that the right side is the affected side, it is thought that the left side can also be supported by rotating the joint at the base of the T-Arm.

VII. Conclusion

This paper describes a robotic system designed to assist hemiplegic patients in putting on bottoms. We analyzed the assistive motions typically performed by caregivers and proposed a branching arm robot that replicates these movements. The branching arm robot combines workability and compactness, allowing it to perform complex tasks, such as threading the hem of bottoms while lifting the legs more easily than a dual-arm robot. In our experiments, we demonstrated the system's feasibility in performing a complete dressing sequence, from threading the hem to pulling the garment up to the waist, even in a confined space.

In the future, we aim to enhance cooperative dressing assistance by using human posture estimation and control via force sensors. Additionally, while this paper required, it was necessary to have the end-effector to grasp the bottoms in

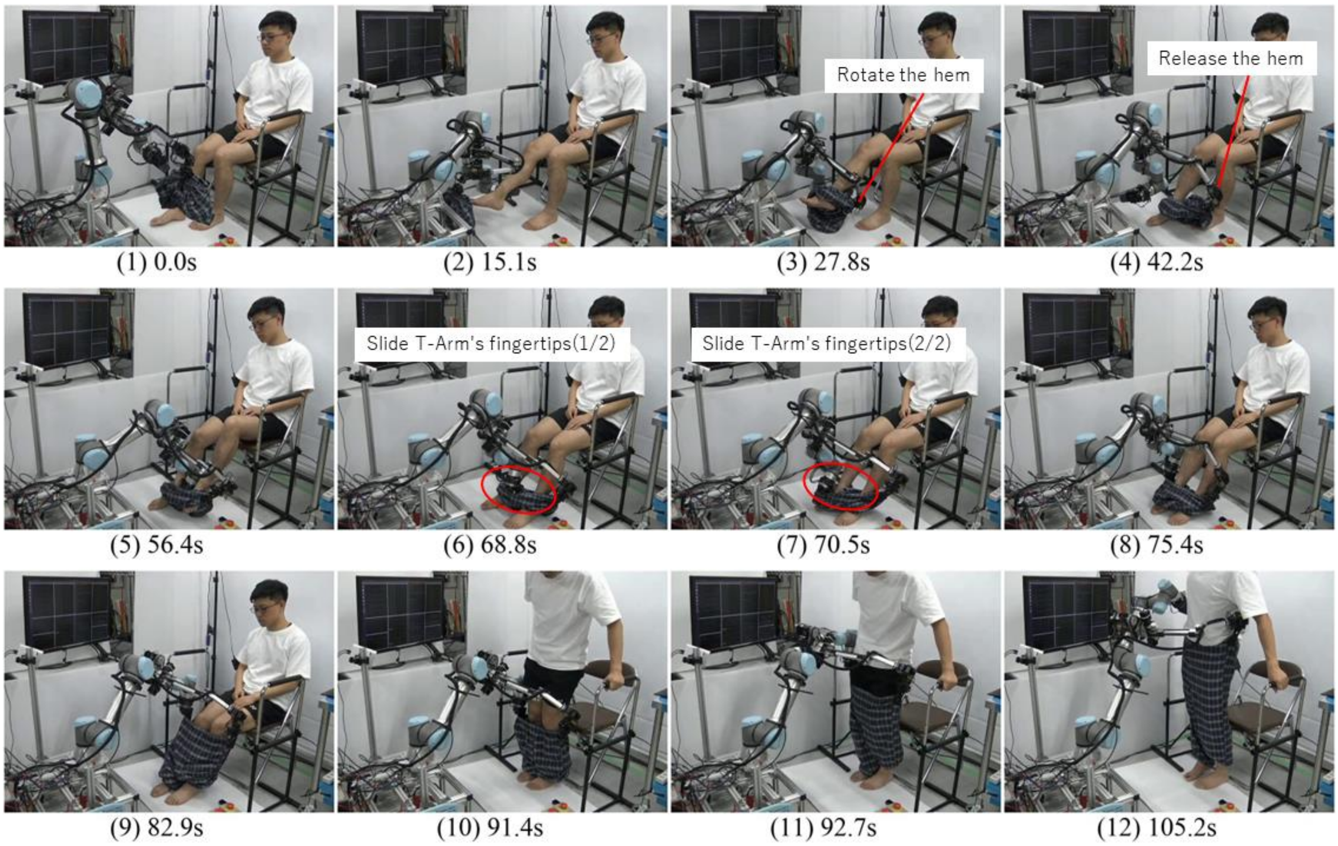

Fig.11 Dressing assistance by the branching arm robot

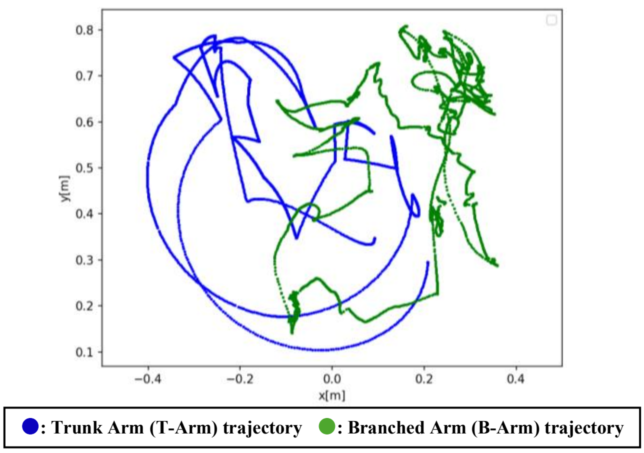

Fig.12 Robot end-effectors' trajectory

advance, we plan to simplify this preparatory step in future iterations.

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