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A Robot System for Assisting Humans in Wearing Long-Sleeved Shirt

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***Abstract*–In this paper, we propose a robot system that can support humans, particularly those with a paralyzed half-body, in wearing a long-sleeved shirt. For this purpose, with advice from experts, we re-organize a wearing procedure assuming that it will be supported by a robot. The robot system aims to support the smooth passage of the sleeves while narrowing the movement range required for the healthy side arm. In the proposed method, the body posture of a person is estimated and then used for the motion generation of the robot. Hybrid control of the robot avoids unnecessary external force while following the movement of the person. Our experiments showed the effectiveness of the robot in supporting the human to put his arm through the sleeve, without excessive external force.**

Index Terms –Wearing support, long-sleeved shirts, trajectory generation, position- and force-based hybrid control

I. Introduction

People with physical disabilities often find it difficult to wear clothes by themselves. In such a case, they require the help of others to perform such essential tasks. In today's fast-moving and aging society, an increase in the number of people with physical disabilities is inevitable. Thus, having a serious labor shortage is not difficult to imagine. Therefore, countermeasures are being considered in various fields.

The intelligent robotics field can contribute to this situation by creating a mechanism that allows automated machines to help humans with physical disabilities easily wear clothes. Several efforts exist in this regard so far [1–5]. If these technologies are cultivated, such individuals may lead an independent life that does not require the help of others. Here we would like to emphasize the policy that robots should support the movement of individuals rather than entirely substituting robots for his/her wearing work. In other words, the person leads the wearing movement to his or her capacity, and the robot supports the part that is beyond the individual's capacity. Thus, this support can be expected to enhance self-efficacy [6] because one can wear clothes by oneself with only limited support from robots.

This study aims to construct a robot system that can support humans with physical disabilities to wear clothes by themselves with limited external support. As an example, consider a situation of a person with a paralyzed half-body who wants to wear a long-sleeved shirt. For this, the person has to make complete use of the healthy side arm to put the sleeve through the paralyzed side arm. This work requires a large range of movement, and it is difficult to pass the sleeve, which is extremely flexible, through the paralyzed arm while maintaining proper body posture. In such a case, it is preferred to be able to support the smooth passage of the sleeves through the paralyzed arm while narrowing the movement range required for the healthy side arm.

Robot systems can provide such support and are required to endow with several functions and closely link them. Specifically, the robot system requires a function to estimate the posture of the arm on the paralyzed side, a function to track the body movement on the healthy side, and a function to correct the support action according to the movement on the healthy side. In this study, we aim to create such a robot system that can assist people with physical disabilities to wear clothes, specifically long-sleeved shirts by themselves with minimal external support. We implemented each of the abovementioned functions, linked them, and verified them through the wearing task described above.

The contributions of this paper are stated below:

- Our proposed robot system will support the proposed flow of wearing a long-sleeved shirt assuming a case where half of the body is inconvenient.
- We will organize the technical elements necessary to realize the above flow and formulate methods for each.
- Our experiment using a real robot confirmed that putting an arm through a sleeve is possible via our proposed mechanism.

The structure of this paper is as follows. Section II presents related works. Section III explains the problem settings and the approach used in this study. Section IV introduces a method to estimate human posture, and Section V introduces motion generation of a robot arm and online motion modification. Section VI reports the experimental results, and Section VII concludes this study.

II. Related Work

Many research works have aimed at making automated machines such as robots to support humans in wearing clothes. Tamei et al. [7] expressed the phase relationship between a person and a cloth product in a low-dimensional state and successfully put a t-shirt through the head of a mannequin using reinforcement learning. Their main focus was to acquire a manipulation trajectory, assuming that the person getting dressed cannot move. Erickson et al. [3] estimated the force exerted by the cloth on a person during dressing via a neural network. They applied model prediction control to achieve dressing support without exerting any load on the person. They used hospital gowns for their experiments. Yamazaki et al. [8] proposed a method for online cloth state estimation. By visually detecting the stuck of the cloth at an early stage, they succeeded in preventing a large force from being applied to the wearer. They used a humanoid robot to put on the bottoms of the wearer to prove the effectiveness of their proposed method. All these abovementioned studies assume that a person sits still or does not move in a way that interferes with wearing. Therefore, these studies did not propose any mechanism to modify the moving trajectory on the spot to increase the success rate of wearing.

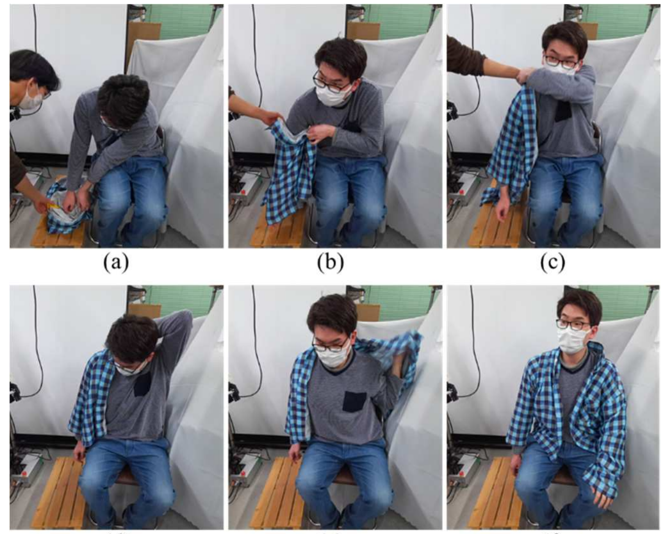
Pignat et al. [9] proposed a programming by demonstration method for obtaining clothing manipulations that match the individual's body structure. They tracked the movement of the human hand in real time via an augmented reality marker to demonstrate the effectiveness of their proposed method. Gao et al. [2] achieved the wearing of a sleeveless jacket by recognizing the posture of the upper body of a person in real time. Their study focused on the movement of a person while wearing clothes; however, it did not thoroughly examine the contact between the person and the robot. Jevtic et al. [10] achieved the task of putting on shoes by focusing on human-robot interaction. Their study used human posture estimation, dialogue, pointing, etc. for estimating the actions. Joshi et al. [1] applied imitation learning to acquire the manipulation trajectory for dressing clothes. They showed that an appropriate trajectory can be obtained even from a single demonstration. They assumed that the wearer provided cooperative movement when realizing the work of putting on a sleeveless shirt. The abovementioned studies allowed for flexible wearing support. In that respect, the direction of these studies is similar to our present study. In these studies, wearing trajectory generation is mainly the role of the robot as they have not assumed that the person will move independently. However, the task of our present study requires a high level of interaction according to the person's movement.

III. Approach

A. The Assumed Wearing Assistance

Generally, a healthy person takes the following steps to wear a long-sleeved shirt. As the first step, the collar is grasped with one arm, the fingertips of the other arm are put into a sleeve, and then the entire upper body is moved appropriately to path the latter arm through the sleeves.

As mentioned in Section I, this study targets those people who can wear clothes to some extent by themselves but find it difficult to complete the process of wearing clothes. Thus, people with half-body paralysis are included in this category. In this case, only one hand can manipulate the clothes. Although the person can wear clothes by himself, it takes a lot of time and physical hardship to complete the process. This can reduce the motivation for wearing clothes and lead to the choice of relying on others. Our goal is to prevent that. It is desirable to simplify the manipulation of clothes such that the time required for wearing clothes can be shortened.



(a) (b) (c) (d) (e) (f)

Fig. 1 A method for putting an arm through the sleeves of a shirt in the case of hemiplegic patients

Wearing a long-sleeved shirt with a front opening consists of several steps. For people with hemiplegia, the following efficient procedure is proposed. First, sit on a chair and (1) hang the paralyzed arm between both legs. After that, (2) grasp the collar of the shirt near the sleeve hole with the healthy hand. Then, (3) put the paralyzed hand in the sleeve and pull it up to the shoulder. (4) Release the healthy hand and grab the clothes again from behind the shoulders. (5) Bring the remaining sleeves to the healthy side and let pass the arm through the sleeves. (6) After adjusting the position of the shirt, fasten the buttons to finish.

Of the above steps, the major obstacle is faced when performing step 3, i.e., passing the arm on the paralyzed side through the sleeve of the shirt. In this step, the cloth often gets caught in the paralyzed arm and requires frequent pulling up the stuck cloth with the healthy hand. Robotic assistance can reduce this action and lead to smooth wearing. Therefore, we focus on this step and aim to design a mechanism that will support the movement of pulling up the sleeve on the paralyzed side with the hand on the healthy side.

B. Assistance Method and Technical Requirements

Figure 1 shows the flow of the proposed steps of wearing clothes. When considering support by robots, the concerned person should take a posture that is easy to observe with the sensor. Therefore, we make one change from the wearing method described in the previous subsection. The arm through which the sleeve is passed is hung vertically on the side of the body. Such a position allows the sensor to observe the fingertips of the arm until just before wearing. This change is in line with the opinions and suggestions of researchers who specialize in experimental psychology and occupational therapy.

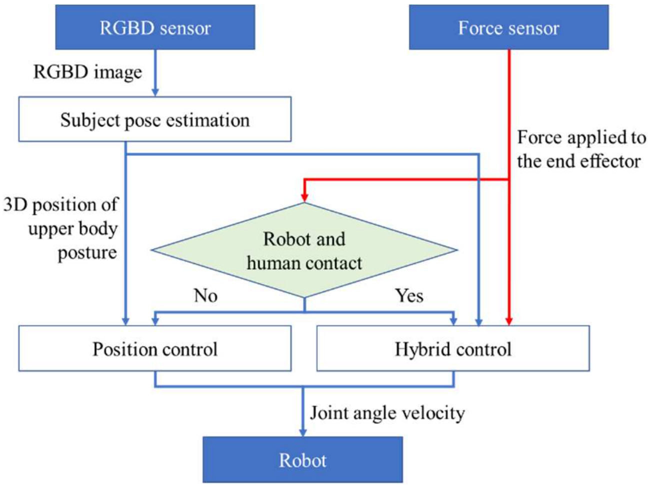


Fig. 2 Functional configuration of the proposed system

The rest of this paper defines the person's arm that manipulates the sleeve of a shirt as the wearing arm (WeA) and the other arm as the worn arm (WoA). The proposed robot system has the below main functions to support wearing clothes under the above method.

(a) A function to estimate the movement of WeA and WoA. Particularly, the WeA's hand position and WoA's shoulder position are tracked online.
(b) A function that supports the manipulation of sleeves using a method that does not allow the cloth to get stuck during the wearing process.
(c) A function to adjust the movement of the robot online. This is because the position of the paralyzed arm may change while wearing clothes, and the human trunk may lean during the wearing movement. Such a change in positions may result in an unexpected situation such as WoA hitting the robot.

C. *Our Approach*

Figure 2 shows the functional configuration of the robot system constructed in this study. This system includes a function to estimate the posture of the upper body of a person and functions to control the motion of the robot arm. There are two modes of motion control: position-based control and hybrid control based on position and force.

Based on the configuration, functions (a), (b), and (c) are materialized as follows:

(a) Pairs of a color image and a depth image obtained from a three-dimensional (3D) range image sensor is used to estimate the posture of the upper body of a person. A human bone model extracted from the color image is made in 3D via the depth image. The above processing is performed on the time-series data, and the movement of the person is tracked online.
(b) The support of wearing is performed via a serial link manipulator. To reduce the number of times the cloth gets caught by WoA, the robot grips the opposite side of the sleeve held by the healthy-side hand and pulls up the sleeve in synchronization with the movement of the WeA's hand using position-based control.

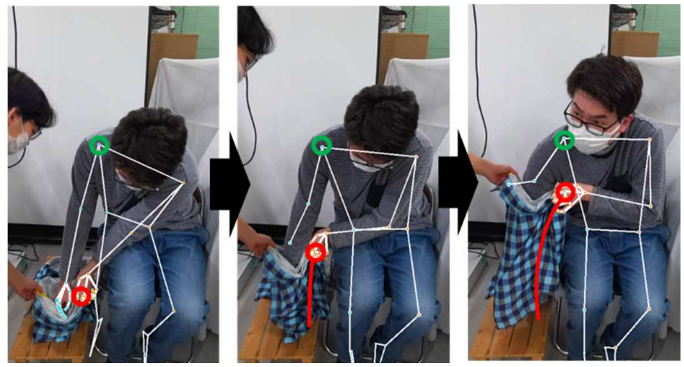


Fig. 3 Posture tracking during putting an arm through the sleeve of clothes with MediaPipe Holistic

(c) When there is a contact between the robot and the person, the end-effector position is controlled along the given end-effector trajectory while giving priority to force control based on the force data obtained at the wrist of the robot.

We first explain the function for (a) in Section VI and then explain the functions for (b) and (c) in Section V.

IV. Human Pose Estimation and Tracking

In this study, the minimum requirement for the human posture estimation function is the 3D position of WeA's hand and WoA's shoulder. The former is used to determine the end of sleeve wearing support, the latter is necessary for the position control of the robot's end-effector.

First, the posture of the whole body is estimated by applying the human bone model to a color image obtained from a 3D range image sensor. The pixel coordinates of WoA's shoulder and WeA's hand are calculated and then converted to 3D using the depth value of the paired depth image.

Various methods have been proposed for fitting bone models using images [11-13]. We chose Google's MediaPipe Holistic method [14] because of its lightweight and fast processing and high detection accuracy of the hand. The OpenPose method [11] also meets our requirements, but we experimentally confirmed that the MediaPipe has better estimation performance in terms of processing speed. MediaPipe Holistic first detects skeletons other than fine skeletons such as fingertips. Then, it detects the hand by creating an ROI based on the wrist detection result. This method assumes that the subjects do not move significantly at consecutive frames. Thus, it uses the previous estimation result for the estimation at the current frame so that the processing can be completed in a short time.

Figure 3 shows the mechanism involved in MediaPipe Holistic in tracking posture during the sleeve-wearing task. The red circle is WeA's hand, and the green circle is WoA's shoulder. When the person's hand and the robot's end-effector grip the shoulder part of the shirt, the subject's hand is tracked. The sleeve-wearing work is continued to the vicinity of the armpit. When the distance between WoA's shoulder and WeA's hand gets closer than the predefined threshold, the work is terminated.

V. Assist Motion Generation

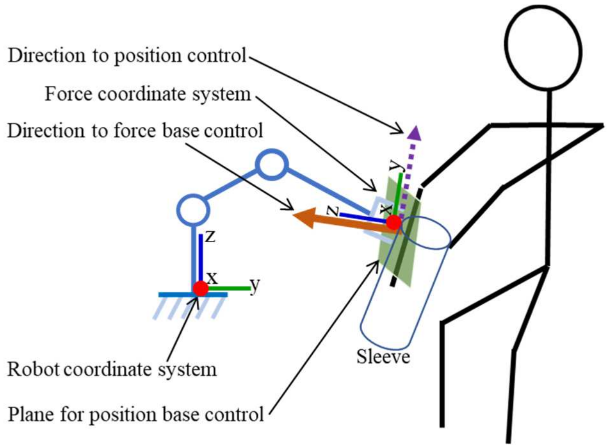


Fig. 4 Switching from position control to hybrid control during putting an arm through the sleeve of clothes

A. Outline of the Wearing Motion Generation

The robot arm in the proposed system is required to move in synchronization with the healthy hand and in the direction of escaping from external force. Some studies have proposed a method to enable robots to provide conventional wearing support by robots. This method uses hybrid control of force and position. Among these studies, the method proposed by Fan et al. [15] has a high affinity with our study. Therefore, we adopt their method and modified it as per our problem setting. This section explains the modified method used in this study.

Fan et al. achieved wearing support for a sleeveless jacket using a manipulator with seven degrees of freedom. In their method, the robot's trajectory was modified online in response to an unexpected contact during wearing movement. This was possible because of the trajectory generation method that used hierarchical multitasking control. The outline of their method is as follows. First, prioritize the wearing work and divide it into two subtasks. The first subtask is trajectory generation that does not impose a burden on humans. This is of the highest priority. Here, the external force applied to the end-effector is estimated from each joint torque of the manipulator, and the desired end-effector speed is calculated by damper control. The second subtask is trajectory generation to put the sleeve through the human arm. Based on the posture estimation result of human WoA, motion for wearing is executed in the order of hands, elbows, and shoulders.

The abovementioned method has fundamental elements to realize the function (c) of Section III-C. However, when unpredictable changes occur in the moving orientation of the end-effector, the manipulator may come in contact with the person. In addition, the end-effector may vibrate when trying to follow the movement of the WeA. In addition, the estimation accuracy of the external force is low due to the restrictions of the hardware used in their experiment, and therefore the person may feel uneasy about the robot. In the present study, we aim to create a wearing assistance system that people can use with confidence while incorporating countermeasures for these issues.

B. Motion Generation Method

Figure 4 shows coordinates systems for force-based control and position-based control in hybrid control. The force-based control is directed on a specific axis that is defined to coincide with the direction of force applied to the end-effector. The position-based control is in the direction of a plane orthogonal to the axis. Hereafter, we refer this coordinate system as the force coordinate system shown in Fig. 4. The force applied to the robot is measured by a force sensor built into the wrist. This is because the force sensor method to measure the external force applied to the end-effector is highly accurate compared with the joint torque method [15].

The wearing work is performed only by position control unless the external force applied to the end-effector is above the threshold value. In other words, the contact between the robot and the person is examined based on whether or not the threshold value is exceeded. Accordingly, the two control laws are switched based on the result. The output of each control is calculated by the following formula.

$$\dot{\boldsymbol{q}} = \begin{cases} \dot{\boldsymbol{q}}_{pos} & \text{if } h_m < h_t \\ \boldsymbol{J}_c^{\dagger}\boldsymbol{v}_{force} + \left(\boldsymbol{I}_{6\times6} - \boldsymbol{J}_c^{\dagger}\boldsymbol{J}_c\right)\dot{\boldsymbol{q}}_{pos} & \text{otherwise} \end{cases} \tag{1}$$

$\dot{\boldsymbol{q}}$ is the target angular velocity output to the manipulator's joints. h_m is the amount of force applied to the end-effector. h_t is a predefined threshold. $\boldsymbol{v}_{force}$ is the target end-effector velocity calculated from the force-based controller. $\dot{\boldsymbol{q}}_{pos}$ is a target angular velocity for putting an arm through a sleeve, and the detail is explained later when we introduce Eq. (6). $\boldsymbol{J}_c^{\dagger}$ is a pseudo-inverse matrix of $\boldsymbol{J}_c$. Then

$$\boldsymbol{J}_c^{all} = \begin{bmatrix} {}^{force}\boldsymbol{R}_{base} & \boldsymbol{O}_{3\times3} \\ \boldsymbol{O}_{3\times3} & \boldsymbol{I}_{3\times3} \end{bmatrix} \boldsymbol{J}, \tag{2}$$

$$\boldsymbol{J}_c = [\boldsymbol{O}_{4\times2} \quad \boldsymbol{I}_{4\times4}]\boldsymbol{J}_c^{all}. \tag{3}$$

$\boldsymbol{J}_c^{all}$ is a transformed matrix from the original Jacobi matrix $\boldsymbol{J}$ based on the force coordinate system. $\boldsymbol{J}_c$ is a matrix extracted from $\boldsymbol{J}_c^{all}$. It corresponds to four degrees of freedom of the axis for force-based controls and the direction of the end-effector. $\left(\boldsymbol{I}_{6\times6} - \boldsymbol{J}_c^{\dagger}\boldsymbol{J}_c\right)$ is a null space of $\boldsymbol{J}_c$, and its working degrees of freedom is a two-dimensional plane where it is defined for position-based control. ${}^{force}\boldsymbol{R}_{base}$ is a rotational matrix from the force coordinate system to the robot coordinates. The identification matrix $\boldsymbol{I}_{3\times3}$ is used to prevent the coordinate conversion of the end-effector direction at the time of coordinate conversion.

The first term in the lower part of Eq. (1) is used to generate movements that avoid putting a load on the person to the extent possible. A damper term is introduced to generate movement in the same direction as the force applied to the hand. Specifically, the target end-effector velocity is calculated by the following formula.

$$\boldsymbol{v}_{force} = [v, \boldsymbol{O}_{3\times1}], \tag{4}$$
$$v = Dh, \tag{5}$$

where v presents a target end-effector velocity on the force coordinate system (scalar). $\boldsymbol{O}_{3\times1}$ is a 3D zero vector added to the end to maintain the orientation of the end-effector. D is a damper coefficient for adjusting escape sensitivity. h is the external force applied to the end-effector and is the value on the force coordinate system.

The second term in the lower part of Eq. (1) is used for position-based control. It generates the joint angular velocity to move in synchronization with WeA's hand. As mentioned in the previous section, the WeA hand is estimated using the posture estimation method. The robot's end-effector may vibrate due to the estimation error of the bone model or the original irregular movement of the WeA. Therefore, a low-pass filter is used to suppress them. However, note that this filtering is not applied to the first term to avoid any delays in the force control due to the low-pass filter. The target joint velocity is calculated according to the position control law that is given by the following equation.

$$\dot{\boldsymbol{q}}_{pos} = \boldsymbol{J}^{\dagger} f_{lp}\left(\frac{([\boldsymbol{p}_{goal}, \boldsymbol{O}_{3\times1}] - [\boldsymbol{p}_{now}, \boldsymbol{O}_{3\times1}])}{dt}\right) \quad (6)$$

where the function f_{lp} indicates a low-pass filter. Considering the real-time property, the transfer function of the first-order lag system is used. $\boldsymbol{p}_{goal}$ is the target 3D position of the end-effector, and $\boldsymbol{p}_{now}$ is its current position. dt is set to the time required for bone model estimation.

VI. Experiments and Discussion

A. Experimental Method

To verify the efficiency of the proposed clothing support system, the UR5e robot [16], manufactured by Universal Robots Inc., was used in the experiments. This robot has six rotational joints and has up, left, right, left, up, and left orientations of the axes in order from the root. A six-axis force sensor (PFS080YA501U6 manufactured by Leptrino Co., Ltd.) having an acquisition frequency of 200 Hz was incorporated into the wrist of this robot.

Azure Kinect [17] was used to obtain the pairs of color images and depth images at a frame rate of 15 fps. The posture estimation by MediaPipe Holistic also showed stable performance when the frame rate exceeded 15 s/frame. Hence, the first term of Eq. (1) was updated at 200 Hz, and the second term was updated at 15 Hz. A total of two PCs were used. One PC was for robot control and was an Intel Core i9-10980 (2.40 Hz × 12) CPU, 64 GB memory, and NVIDIA Quadro RTX5000 (8GB memory) GPU. The other PC was for posture estimation and was a Xeon (R) Silver 4216 (3.60 Hz × 12) CPU made by Intel, a 64 GB memory, and an NVIDIA Quadro RTX4000 (8 GB memory) GPU.

The camera was installed in a position facing the person to capture the whole body of the person. The elbow and shoulder of the WoA were equipped with movement-restricting devices. Figure 5 shows the arrangement at the experiment.

The clothes used in this experiment included a long-sleeved shirt that was 100% cotton and had a thickness was 0.4 mm. A yellow color marker was attached at the base of the sleeve and was used as the gripping target position for the robot. At the beginning of the wearing process, the root of the sleeve was placed by WeA so that the camera could capture the color marker. The color markers were extracted via HSV color processing. The 3D position of the marker was calculated as the average value of the 3D point cloud of the marker part. The robot gripped the position. Since this method involved automated processing, proper gripping may fail. These failures can be prevented or recovered from by appropriate intervention by WeA.

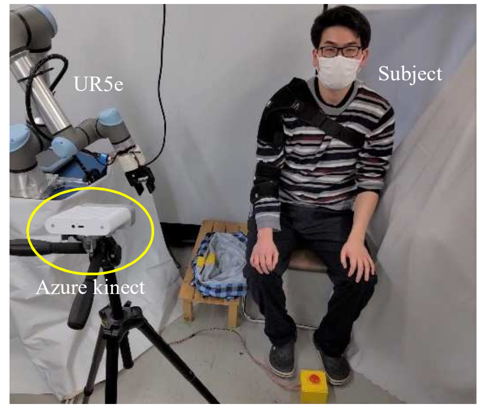


Fig. 5 Arrangement of robot and sensors in the experiment.

In the evaluation of the proposed wearing support system, one subject shit on a chair and asked to lose his posture during the wearing. We also ensured that the subject was not subjected to heavy load when the force was applied to the robot's end-effector. To compare and analyze the effectiveness of the proposed method, we also conducted an experiment in which the wearing support was performed only by position control. This comparison was required to investigate the extent to which the wearing can be carried out without imposing a load on the person in the case of hybrid control. For safety purposes, the robot was designed to stop cloth manipulation when a large load was applied to the robot's end-effector. The threshold value for this load was set to 10 N, and if this threshold value was exceeded, the task was considered a failure. Note that the threshold value of 10 N was determined in the preliminary experiment where the authors began to feel uncomfortable. This value is defined as wearing failure in related works [3, 8].

B. Experimental Result

Experiments were conducted with each method until 10 success data were collected. In the case of only position control, 10 data were collected after five failures. In the hybrid control method, no failure was observed. In this experiment, the threshold value to switch between two control laws was set to 3 N. This value was set based on the findings of the preliminary experiment where the authors did not feel uncomfortable when the force was smaller than 3 N. After collecting the data, the magnitude of the external force, the accumulated amount of the external force, and the number of time steps were compared.

Figure 6 shows the experimental results when the force exceeded 3 N in a boxplot. Based on the magnitude of the external force, the maximum force was around 5 N in the hybrid control and around 10 N in the position-based control. This

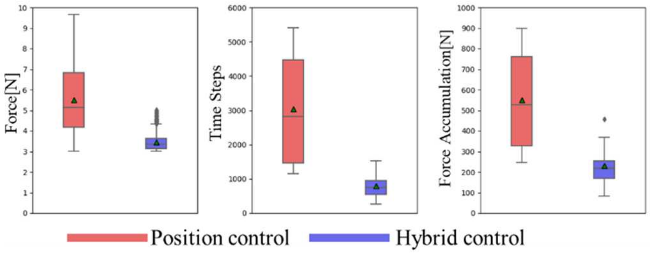


Fig. 6 The boxplot pictures of experimental results. The green triangle is the average value. The rhombus is outlier.

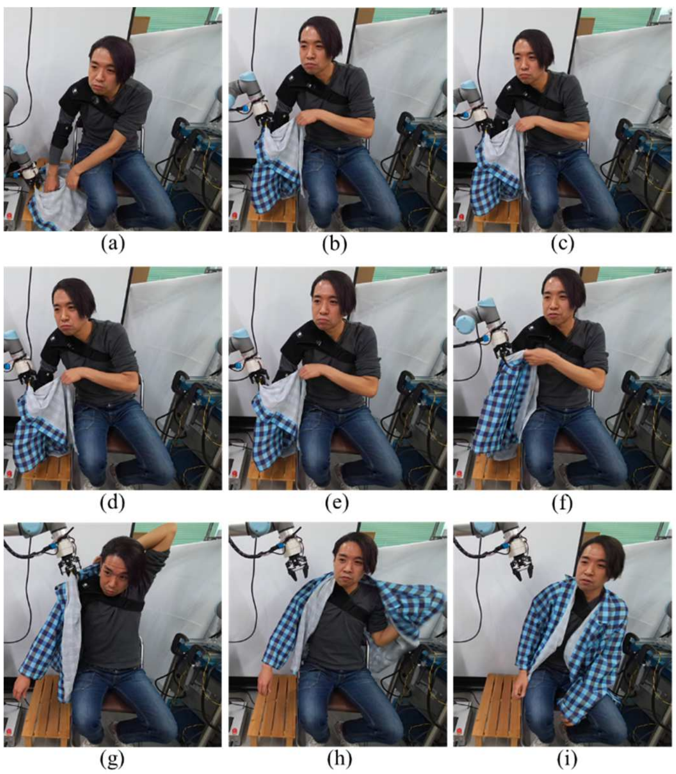


Fig. 7 Examples of putting an arm through the sleeve of shirt by an autonomous robot at the time of contact

finding shows that the proposed method could manage to not put a load on the subject with a certain margin. The number of time steps and the amount of accumulated external force in the proposed method were found to be smaller. This indicates that the proposed method has a shorter time to put a load on a person and that subjected load is smaller. These results suggest that the damper control of the proposed method worked to control the escape from the applied external force.

In the case of position-based control, the average time taken for the wearing task was 13.8 s and the standard deviation was 2.25. In the case of hybrid control, the average time was 12.6 s and the standard deviation was 3.62.

Figure 7 shows the situation when the robot and the person come into contact under the hybrid control. (a)–(d) are images of a situation that which the robot is escaping in a direction that does not apply a load. (e) and (f) are images of the subject regaining his appropriate posture and continuing to wear

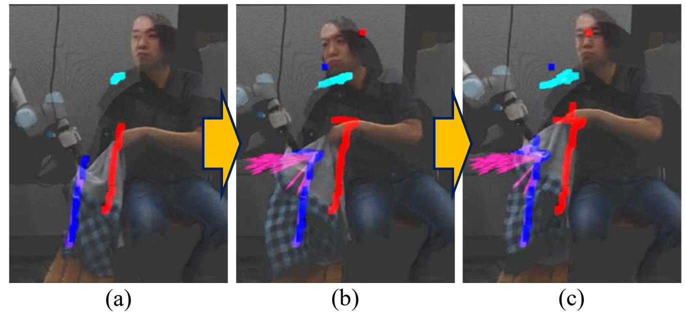


Fig. 8 A visualization result of control inputs for hybrid control during putting an arm through the sleeve.

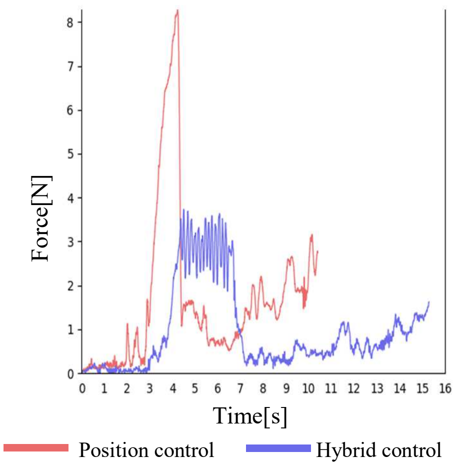


Fig. 9 Applied force comparison between only position-based control and hybrid control

clothes. After the wearing support by the robot was finished, the subject was succeeded to wear the other sleeve on healthy side as shown in (g) to (i). As illustrated in the figure, the wearing task is performed while switching between position control and hybrid control.

Figure 8 shows an example of control input for the proposed hybrid control. The trajectory shown in red is WeA's hand position. Light blue Points is the positions where WoA's shoulder have existed. The trajectory shown in blue was the target end-effector positions calculated from position-based control. Purple points almost overlap there. These are the positions where the robot's end-effector actually passed through. Pink arrows indicates the direction of force applied by the subject.

Figure (a) in Fig. 8 shows the state of wearing until just before contact. Up to this point, the robot was controlled only with the position-based law, and it was moving along the target trajectory calculated from WeA's hand trajectory. In (b), the subject's arm is in contact with the robot's end-effector. Note that when the subject's posture leans a certain direction, the WeA's hand position also moves in the same direction. Therefore, it was found that a certain level of load could be avoided by position-based control alone, depending on how the subject's posture collapsed. However, hybrid control was still necessary to properly avoid the load. Due to the proposed control policy, the subject was able to continue wearing clothes after returning to the proper posture as shown in (c). Here, the hybrid control was switched to the position control, and the robot generated the trajectory according to the position control law.

Figure 9 shows an example of force data applied to the force sensor embedded in the robot's wrist. The value of the contact force while the position control suddenly increased. On the other hand, in hybrid control, the force value at the time of contact oscillated around 3N. This is because the damper control moved in the direction of escaping from the external force, but the contact and non-contact were repeated while the subject was get out of the shape. In addition, on both control laws, the force value gradually increases in the latter half of the wearing work. It is considered that this is because the arm parts such as the elbow and the upper arm were caught by the cloth to the extent that the work were not affected.

VII. Conclusions

In this paper, we reported a robot system that can support the wearing of clothes in collaboration with humans. We focused on the situation of a person with a paralyzed half-body who intended to wear a long-sleeved shirt. Accordingly, we organized the technical elements necessary to realize the above policy and formulated methods for each. Based on the combination of human posture estimation and hybrid motion control, we constructed a unified robot system to support wearing. Our experiments using an actual robot confirmed that our robot system successfully supported in wearing of a long-sleeved shirt with a small number of time steps and a small accumulation of external force.

Future work should focus on quantitative evaluation with the cooperation of many subjects. Additionally, both the force load and the mental load should be investigated. We intend to extend our research work to introduce online cloth state estimation and improve the robot system to support wearing even in more complicated situations.

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