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Paper:

Wearable Robot Arm with Consideration of Weight Reduction and Practicality

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In this paper, we propose a wearable robot arm with consideration of weight and usability. Based on the features of existing wearable robot arms, we focused on the issues of weight and usability. The behavior of human hands during physical work can be divided into two phases. In the first, the shoulder and the elbow joints move before commencing the task by using the hands. In the second, the wrist joints move during the actual work. We found that these features can be applied to wearable robot arms. Consequently, we proposed hybrid actuation system (HAS) with a combination of two types of joints. In this study, HAS is implemented into the prototype wearable robot arm, assist oriented arm (AOA). To verify the validity of the proposed system, we implemented three types of robot arms (PasAct, Act, 6DOF) using simulation to compare the weight, working efficiency, and usability. Furthermore, we compared these simulation models with AOA for evaluation.

Keywords: wearable robot arm, hybrid actuation system, passive joints

1. Introduction

Practical use of a humanoid can been achieved through its ability to perform tasks performed by humans. Among humanoids, a type of robot that moves on two legs has high adaptability to human living environment because it performs bipedal walking similar to humans. However, there are two problems in this approach: (i) high cost of a humanoid and (ii) poor stability of bipedal walking. Particularly, such a robot often encounters falls while walking on a stepped surface or unstable ground.

In this context, the wearable robot has currently gained attention. In the works of Jo et al. [1] and Kearn et al. [2], a device, such as a robot, is attached to a human, and it is utilized for work assistance and cooperation. Advantages such as reduction of human burden and improvement of work efficiency seen in this approach have attracted attention in nursing facilities and work sites.

The wearable robot is attached to a human user and supports their work. Therefore, unlike a humanoid, it does not need to move autonomously and is relatively cheaper. Therefore, attempts for its practical use are being made.

Practical application of a powered suit (powered exoskeleton) that reduces workload and uses this wearable robot technology is underway [3]. Powered suits can be utilized by workers and elderly people to reduce workload and gain assistance for rehabilitation.

Wearable robots similar to that by Khodambashii et al. in [4], wherein a robot arm mounted on a human user performs cooperative work with the user, have also attracted attention. By mounting the robot arm on the user, works that cannot be executed by one person are possible and work efficiency can be improved. The robot arm's adaptability to the human living environment is high owing to its human-mounting, and the distance between the robot and the user during cooperative work can be easily maintained.

Consequently, the wearable robot arm is expected to be applied to work and daily activities. However, the following issues need to be addressed in the wearable robot arm: (i) its weight burden on the user and (ii) its user-operability.

The weight burden problem lowers the work efficiency and safety because an increase in the weight of the robot arm increases the burden on the user. In a robot arm that performs work requiring dexterity, a high-precision actuator is required, which makes the robot arm heavy. In other words, to control the joint angle dynamically by using the actuator, the actuator must output the torque that repels the weight of the robot arm. The output torque of the actuator increases towards the root joint of the robot arm; therefore, the actuator inevitably has a heavy root joint. This results in increased weight of the robot arm, thereby increasing the burden on the user.

To prevent accidents owing to user contact, the regulations for the industrial and other types of practically used robot arms are strict, e.g., the emergency stop devices and the entry prohibition for the user into the movable area of the robot arm. The regulations are imposed because the robot arm is heavy and the impact at the time of contact can be large. The wearable robot arm is no exception to this fact; therefore, weight reduction can lead to improved safety and usability.

Since user with both their hands engaged in work need to utilize the wearable robot arm as their third arm to perform the given tasks, how to operate the wearable robot arm in such a scenario constitutes the problem of operability.

Certain studies on operation methods have attempted to address this problem, e.g., the method of operating the robot arm using electromyography [5] by Morizono et al. and "face vector" by Iwasaki et al. [6] that shows a three-dimensional target position from the face direction vector of the human.

However, as described in [7] by Nimawat et al., this operability problem can prove dangerous to the user owing to an unexpected movement of the robot arm. In other words, the operation by UI (user interface) is difficult because all the joints of the robot arm are dynamically driven, which involves the dangers of human contact owing to the user's operational error or the UI's false recognition. Additionally, an increase in the weight of the robot arm increases the danger in human contact. Therefore, mitigation of both the weight burden and the operability problems has limitations in both weight and operation when the mechanism that dynamically drives all the joints is used in the robotic arm.

This research contributes in terms of weight reduction of the wearable robot arm without impairing the operability. Furthermore, the weight reduction improves safety because the impact during human contact is reduced. Moreover, the weight burden in mounting the robot arm to the user is reduced; therefore, we can use the robot arm mounted on the forearms and the shoulders. Consequently, various work supports can be expected.

In this research, to mitigate the weight burden and the operability problems, which are present in the existing wearable robot arms, we propose a mechanism of the robot arm in which two types of joints are combined. The objective of this research is to provide work support by attaching a wearable robot arm to the waist and the shoulder. Most of the tasks performed by conventional industrial robot arms assume a workspace in which the hand often moves greatly, e.g., holding and carrying an object to a target position. However, this research considers the task of supporting the user's task by holding an object.

As described above, assuming that all the joints of the robot arm need not be driven dynamically in the case of supporting task, for which the hand work space does not move greatly during the work, we focused on the movement of the human arm during the work. Based on this, we propose a mechanism in which the joints of the robot arm are divided into passive and active joints.

2. Related Studies

Various studies have been conducted on the wearable robot arm that performs human work support by acting as a third arm. The specifications of an existing wearable robot arm are provided in **Table 1**.

The main support mechanisms of these wearable robot arms include object retention and user assistance. Parietti et al. in [8] and Llorens-Bonilla et al. in [9] use a backpack-type mounting device to attach a robot arm to a human. By using the arm as a work support, it is possible to maintain the balance of the user by grasping an object and a column.

Table 1. Features of existing wearable robot arms: MP denotes mounting position. DOF denotes degrees of freedom.

Reference	MP	DOF	Weight
Parietti et al. [8]	Waist	6	18 kg
Parietti et al. [10]	Waist	3	9 kg
Baldin et al. [11]	Shoulder	5	4.5 kg
Vatsal et al. [12]	Elbow	3	2 kg
Nakabayashi et al. [13]	Shoulder	5	unknown
Saraiji et al. [14]	Waist	6	9.6 kg
Sasaki et al. [15]	Waist	7	unknown

Parietti et al.'s work [10] comprises a robotic arm, which is an improvement over [9] to support the user's posture during work. The degrees of freedom (DOF) of this arm is three; therefore, it can be said to have achieved weight reduction in comparison with [9].

Furthermore, Llorens-Bonilla et al. proposed a wearable robot arm that is attached to the shoulder to support ceiling panel installation work [11]. The robot arm with five DOF supports the ceiling panel based on the input to the inertial measurement unit (IMU) sensor mounted on the user's hand. This allows the user's hands to be free, thereby allowing them to concentrate on the installation work. Vatsal et al. in [12] researched a robot arm that is mounted on the elbow instead of the waist or the shoulder to perform work for the user whose both hands are engaged.

These aforementioned types of wearable robot arms are expected to improve the work efficiency of users by supporting their main tasks. However, the heavier the retainable weight, the more the weight of the robot arm; consequently, more the weight burden on the user. Therefore, it is necessary to study the mounting to a position with less burden. Further, studies on the mounting position evaluated with the working space and cooperativity include [13] by Nakabayashi et al.

Apart from the abovementioned wearable robot arms, studies on the wearable robot arms that interact with humans include [14] by Saraiji et al. and [15] by Sasaki et al. The work in [14] involves a wearable device, in which a robot arm is integrated with a camera, and a partner located at a remote place uses a head-mounted display (HMD) and a controller to operate the robot arm mounted on the user. The partner and the user can interact in the same workspace by using the camera and the robot arm. The work in [15] involves a wearable robot arm with seven DOF that is in synchronization with a human leg by using motion capture. The arm can perform intuitive interaction just as a third arm would because it is synchronized with the user's leg.

The common point of these researches is that these wearable robot arms need to perform dexterous works. Furthermore, to interact with the user, the robot arm must ensure sufficient space for operation. Therefore, a multi-DOF robot arm such as one with six DOF is required. However, this gives rise to the following issues: the problem of the weight burden on the user owing to the increase in the weight of the robot, the operation method of the UI, and the danger of user contact.

3. Assist Oriented Arm (AOA)

3.1. Idea Behind Designing Lightweight Robotic Arm

To mitigate the weight burden and the operability problems of the wearable robot arm, we focused on the human working method.

Abe et al. described in [16] that human work is characterized by separate independent movement of the arm group such as the elbow and the wrist and the trunk group such as the head and the shoulder. Based on the observation of the movement of the human hand during various works, we consider that the two types of joint groups have different roles in the given work. We apply these two joint groups to the wearable robot arm and study its mechanism.

When a user performs drilling work by using a solder or a drill, fixation work, etc., they move the entire arm using their shoulder and elbow joint before they commence the work, and then move their hand to the work area. Subsequently, they perform the work using their hand joint; therefore, the root joint does not move greatly during the work unless the work area changes.

With the assumption that all the joints of the robot arm do not necessarily have to be driven dynamically, it is possible to divide them into two independently moving groups: the root joint, which moves before the work is commenced and the hand joint, which moves during the work.

However, in the case of a redundant robot arm such as one with seven DOF, the posture of the robot arm is not uniquely determined by the positioning of the hand. Owing to this, a control algorithm in consideration of the redundancy is required to determine the work area of the hand using the root joint before performing the work; consequently, the calculation time increases. This requires the processing performance of a large computer that is difficult to mount on a human. The control of this redundancy has been researched in [17] by Qin et al. as a significant problem in the robot arm.

The human arm has seven DOF, and redundancy is considered for it because a natural joint angle that is reasonable for the work is judged and controlled. Additionally, Al-Faiz et al. in [18] presented a relational expression by using the kinematics of the wrist position and the shoulder joint based on the human arm. It can be said that the angle of the shoulder joint is uniquely determined with respect to the wrist position by a control in consideration of this relational expression and the natural joint angle that is reasonable for the work.

Therefore, it may be possible to uniquely determine the posture of the robot arm by determining the hand position by using the root joint even in the wearable robot arm with multi-DOF. With this assumption, an independent operation is performed by using the joints of the robot arm, which are divided into two: the root joint, which moves before commencement of the work and the finger joint, which moves during the work, and the mitigation of the weight burden and the operability problems is studied.

Using these two types of independent joint operation methods, we design the work support by using the wearable robot arm as follows.

1. The hand position of the robot arm is adjusted to the work area by using the root joint of the wearable robot arm before the work is commenced by the user.
2. During work, the joint angle of the root joint of the wearable robot arm is fixed, and the work area is not moved greatly.
3. Angle control is performed dynamically for the hand joint of the wearable robot arm by using an actuator to support the work of the user.

This operation method allows a simple lightweight brake mechanism that statically fixes the joint angle to be substituted for the conventional heavy actuator for the root joint of the wearable robot arm, and the weight reduction of the entire wearable robot arm can be expected.

Furthermore, the user directly grasps the body of the robot arm and operates the root joint without using devices such as the UI for the operation method of the root joint; therefore, an intuitive operation that is related to the operability problem becomes possible, thereby reducing the danger in human contact through an erroneous operation.

Based on the aforementioned idea, we propose a prototype of AOA by considering weight reduction and usability.

3.2. Design of AOA

We refer to the static joints of the root, which is the most important feature of the prototype, AOA, as the passive joints, and the dynamic joints of the hand as the active joints. We propose and implement the mechanism: hybrid actuation system (HAS), in which the passive and the active joints are combined. In the implementation of the HAS, selection of the DOF of the passive and the active joints is the most important factor. If the DOF of the passive joint is increased, the robot arm becomes lighter and safer; however, the assist force of the work is reduced. On the contrary, if the DOF of the active joint is increased, the assist force of the work increases; however, weight reduction and safety are compromised.

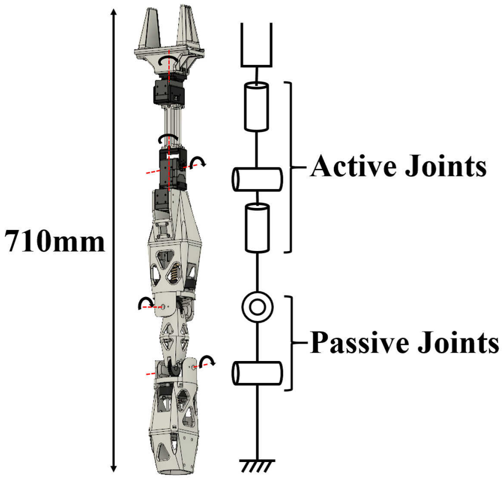


Fig. 1. Mechanism of assist oriented arm (AOA).

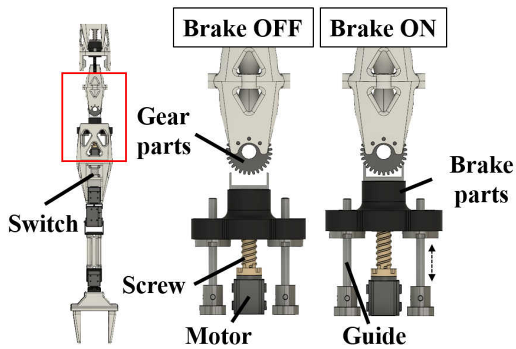


Fig. 2. Brake mechanism in passive joints.

Therefore, based on the work task, it is necessary to determine the number of DOF from the root as the passive joint and the hand as the active joint. In this research, with the aim of implementation of a wearable robot arm that can move over the work area as a prototype, we determined the minimum DOF configuration that allows the tip coordinate in the passive joint. The active joint of the HAS must move in the right, left, up, and down directions. The configuration is presented in **Fig. 1**.

In the proposed configuration, an independent drive is necessary for both the passive and the active joints. Therefore, a spherical coordinate robot (R-P) and a rectangular coordinate robot (R-P-P) are considered as the configuration of the DOF that can flexibly access the user's workspace by avoiding any obstacles. The R-P-P has three DOF, and when it is applied to the passive and the active joints, the entire robot arm except the gripper has DOF exceeding six. Therefore, in this research, the R-P with two DOF is applied to the passive and the active joints.

However, for the passive joint, the user directly grasps and operates the robot arm; therefore, in the R-P configuration, the user needs to twist their arm. This makes the operation difficult when the user operates the roll rotation of the root joint. For the passive joint, by using the combination of P-Y instead of R-P, the user can operate without twisting their arm.

Therefore, the HAS configuration is implemented with a six DOF, i.e., four DOF of the passive (P-Y) and the active joints (R-P) and two DOF of the gripper.

3.2.1. Passive Joint

The passive joint requires a mechanism for statically fixing the joint angle instead of the angle control by using an actuator. Therefore, we implemented a brake mechanism using a gear shape as shown in **Fig. 2**. The gear part is used for fixing the joint, and it is integrated with the body part. The gear part is driven simultaneously with the rotation of the body part; therefore, the rotation angle of the joint is fixed by fixing the gear part. The brake part that is paired with the gear part is linearly driven by the actuator so that it meshes with the gear part; the gear is fixed, and the joint angle is retained. Furthermore, the user directly grasps and operates the body of the robot arm. Therefore, a switch is attached to the body of the robot arm, and the opening and closing of the brake is operated so that the brake can be easily switched on and off with one hand.

The force to fix the joint angle depends on the fixing strength of the guide part; therefore, the torque required for the actuator of the passive joint is merely the force to rotate the screw in **Fig. 2**. Therefore, the actuators in the passive joints do not need to consider the torque to fix the joint angle, and we can use lightweight low-output actuators for the passive joints.

3.2.2. Active Joint

The active joint has four DOF, i.e., the rotation joint with three DOF and the gripper with one. One of the three DOF is used for the posture rotation of the gripper; therefore, the rotation joint related to the position of the tip coordinate is the two DOF of R-P.

Moreover, the active joint is driven dynamically by using the actuator; therefore, the tip coordinate is operated by using kinematics and inverse kinematics. The kinematics and inverse kinematics of the active joint are shown by Eqs. (2) and (2).

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} l_1 + l_2 \cos\theta_2 \\ l_2 \sin\theta_2 \cos\theta_1 \\ l_2 \sin\theta_2 \sin\theta_1 \end{bmatrix} \quad \text{. . . . . (1)}$$

$$\begin{bmatrix} \theta_1 \\ \\ \theta_2 \end{bmatrix} = \begin{bmatrix} \tan^{-1}\dfrac{z}{y} \\ \tan^{-1}\dfrac{y}{x-l_1} \end{bmatrix} \quad \text{. . . . . (2)}$$

To operate the tip coordinate of the spherical coordinate robot in the up, down, left, and right directions, the tip coordinate of the robot arm in the active joint is expressed by using r, θ, ϕ of the polar coordinate shown on the right in **Fig. 3**. The tip coordinate is obtained by increasing or decreasing θ, and ϕ is converted into the rectangular

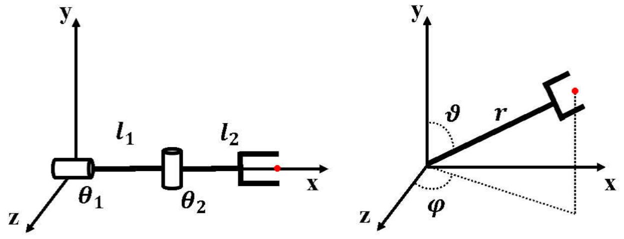


Fig. 3. Rectangular and spherical coordinates in active joints.

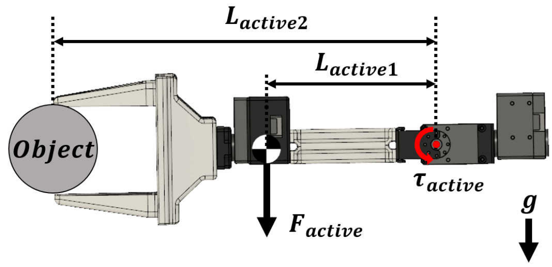


Fig. 4. Definition of torque calculation in active joints.

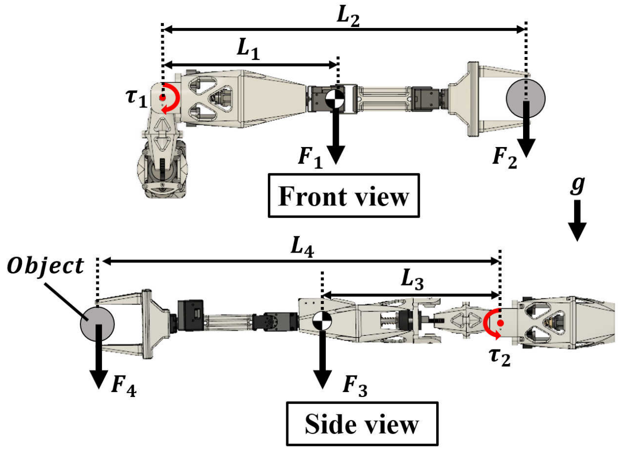


Fig. 5. Definition of torque calculation in passive joints.

coordinate shown on the left in **Fig. 3**, and it is obtained as a joint angle by inverse kinematics. The conversion from the polar to the rectangular coordinate is given by Eq. (3).

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} r\sin\theta\cos\phi \\ r\sin\theta\sin\phi \\ r\cos\theta \end{bmatrix} \quad \text{. . . . . (3)}$$

In this manner, the tip coordinate of the active joint on the spherical coordinate is controlled in the up, down, right, and left directions by using θ and ϕ.

4. Weight Comparison

We verify how much weight reduction is achieved by using the HAS, which is the feature of the wearable robot arm proposed in this study.

However, because the purposes, the DOF, and the length of the existing wearable robot arms and our purposed wearable robot arm are different, we cannot compare the weight of these robot arms directly. Thus, as a comparison target, we use a robot arm that is applied with a joint that performs angle control by using an actuator in the passive joint part of the AOA. Henceforth, this robot arm is referred to as all active (AAct).

We now consider a selection method of the actuator for use in the root joint of the AAct. The active joint of the AOA is used for the hand part of the AAct; therefore, we obtain the limit retaining weight of this active joint, obtain a torque value necessary for the root joint of the AAct based on the weight, and select the actuator.

The active joint of the AOA was implemented by using the XM540-W270-R of ROBOTIS Co. The output torque of this actuator is 10.6 Nm. As shown in **Fig. 4**, τ_{active} is the retaining torque of the active joint. Using a value of 10.6 Nm, which is the maximum output torque of the actuator, we obtain the limit retaining weight of the active joint.

Let the mass, M_{active}, and distance, $L_{active2}$, from the rotation shaft to the hand of the τ_{active} be 0.45 kg and 0.27 m, respectively, and the distance from the rotation shaft to the center of gravity of τ_{active} be $L_{active1} = 0.135$ m, then the limit retaining weight, M_{limit}, is obtained by Eq. (4) using $F_{active} = M_{active} * g$, where g is the gravitational acceleration.

$$\begin{cases} \tau_{active} = M_{limit} g L_{active2} + M_{active} g L_{active1} \\ M_{limit} = \dfrac{\tau_{active} - F_{active} L_{active1}}{g L_{active2}} \\ \qquad = 3.8 \text{ kg} \end{cases} \quad . \text{ (4)}$$

τ_1 and τ_2 shown in **Fig. 5** are calculated by using this limit retaining weight.

First, τ_1 is calculated. Let the mass from the rotation shaft of τ_1 to the hand be M_1, and the distance to the position of the center of gravity be L_1. The distance from the rotation shaft of τ_1 to the object is L_2. With the hand grasping the M_{limit} obtained earlier, τ_1 can be expressed by Eq. (5) by using F_1 and F_2 as follows.

$$\begin{aligned} \tau_1 &= F_1 L_1 + F_2 L_2 \\ &= M_1 g L_1 + M_{limit} g L_2 \quad \text{. . . . . (5)} \end{aligned}$$

where $g = 9.8$ m/s^2, $M_1 = 0.5$ kg, $L_1 = 0.27$ m, and $L_2 = 0.52$ m, then τ_1 becomes

$$\tau_1 = 20.6 \text{ Nm} \quad \text{. . . . . (6)}$$

We selected the H54-100-S500-R(A) of ROBOTIS Co. that is capable of outputting the torque value of τ_1. The output torque is 0.732 kg at 25.3 Nm. We calculate τ_2 by considering the weight of the actuator.

Let the mass from the rotation shaft of τ_2 to the hand be M_2, the distance to the position of the center of gravity be L_3, and the distance from the rotation shaft of τ_2 to the object be L_4, then τ_2 can be expressed by Eq. (7) by using F_3 and F_4 as follows.

$$\begin{aligned}\tau_2 &= F_3L_3 + F_4L_4 \\ &= M_2gL_3 + M_{limit}gL_4 \quad \dots \dots \dots \quad (7)\end{aligned}$$

where $g = 9.8$ m/s^2, $M_2 = 0.55$ kg $+ 0.732$ kg, $L_3 = 0.25$ m, and $L_4 = 0.643$ m, then torque τ_2 becomes

$$\tau_2 = 27.2 \text{ Nm} \quad \dots \dots \dots \quad (8)$$

We selected the H54P-200-S500-R of ROBOTIS Co. that is capable of outputting torque value τ_2. The output torque is 855 g at 44.7 Nm.

These results indicate that when the angle control was performed by using the actuator for all the joints of DOF of four, the weight of the robot arm (AAct) was 0.45 kg in the active joint, 0.732 kg in the τ_1 actuator, and 0.855 kg in the τ_2 actuator. Therefore, the total weight of the AAct was approximately 2.0 kg, which means that weight reduction of approximately 40% was achieved in comparison with the weight of the AOA, which was approximately 1.2 kg. Additionally, in the case of the joint that performs the angle control by using the actuator, the more the DOF and the link length of the hand joint part, the more the values of torques τ_1 (required) and τ_2 (obtained), and more the weight of the actuator. Therefore, by using the HAS, the effectiveness of the weight reduction is further improved.

Therefore, the wearable robot arm, AOA, while using the HAS, can be said to have a possibility of weight reduction equal to or more than approximately 40% compared to that without the HAS.

5. Experiment

5.1. Objective

The conventional robot arm performs angle control by using an actuator for all the joints; therefore, the joint of the robot arm is dynamically driven when the hand target coordinate of the robot arm is input, and the hand moves to the target coordinate that is inputted. However, the AOA proposed in this research uses the HAS that moves the hand to the approximate work area by using the passive joint and dynamically performs the work in the active joint. This can affect the robot arm's operability, operation difficulty, work efficiency, etc. Therefore, we evaluate whether the work efficiency and the operability would be affected in the following cases: (i) all the joints are dynamically driven and (ii) when the HAS is used.

During the evaluation of the HAS, it is difficult to implement a robot arm that dynamically performs angle control by using the actuator for all the joints as a comparison target, into the actual machine. Therefore, we perform the implementation through simulation by using Unity, followed by the evaluation.

We implemented three types of robot arms with different operation methods as the comparison targets of the AOA using HAS on the simulator. The characteristics of each type are outlined as follows.

- PasAct (Passive-Active): AOA of the actual machine was implemented on the simulator. The two joints at the root are operated as the passive joint, whereas the two joints at the hand are operated as the active joint. The active joint is operated using the aforementioned polar coordinate conversion and inverse kinematics.

- Act (Active): The configuration of this robot arm is the same as that of PasAct; however, all the joints are operated as the active joint. Similar to an existing robot arm, all the four DOF are controlled and operated as a joint that performs angle control by using the actuator. As long as the tip coordinate is within the operation range of the robot arm, the tip position is translated on each of the axes x, y, and z.

- 6DOF: This is implemented as a joint that performs angle control by using the actuator for all the 6 DOF, and it is operated as a robot arm having the work range of the experimental environment in this study as its operation range.

The aforementioned simulations were operated by using keyboard input. The operation method of the actual machine (AOA) is different for the active and the passive joints. In the operation method of the active joint, four switches correspond to the up, down, right, and left directions, and the tip coordinate of the robot arm is operated. This operation method is the same as that of the keyboard input in the simulation. The passive joint is different from the simulation only in the operation of the passive part because the user directly grasps and operates it. We evaluate the operability with different operation methods of the passive joint. Similar to the AOA of the actual machine, the joint rotation speed of all the robot arms was implemented at 45 rpm.

The following is the scope of the evaluation experiment. First, we evaluate whether there is a difference in the operability and the work efficiency of the actual AOA and PasAct in the simulation. If there are no significant differences between the AOA and PasAct in the simulation, the comparison between the simulation and the actual robot arm is considered to be appropriate. Next, we compare the work efficiency and the operability of PasAct and Act. If there are no significant differences between PasAct and Act, then, there is no effect on the work efficiency and the operability even while using the HAS. Additionally, we compare the 6DOF type with the highest operability and PasAct and evaluate the positioning of PasAct in terms of work efficiency and operability.

5.2. Procedure

We evaluate whether there is a significant difference in the work efficiency and the operability of the four types of robot arms – three types are implemented on the simulation and one on the actual machine.

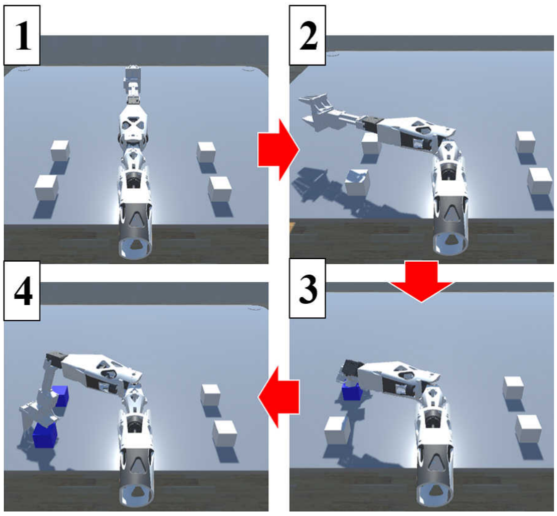


Fig. 6. Experimental environment of simulation and state of movement.

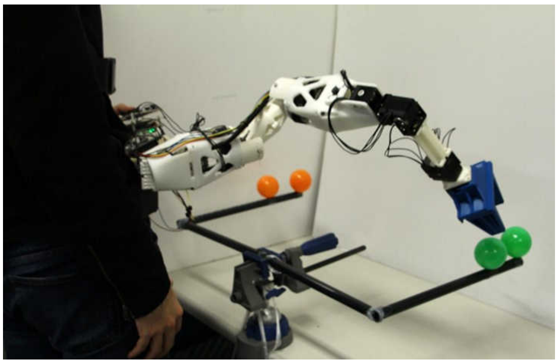


Fig. 7. Experimental environment of AOA.

The hand position of the robot arm of each of the types – PasAct, Act, and 6DOF is operated to the position of a cube by the procedure shown in **Fig. 6**. In this figure, let the left two comprise Task A and the right two comprise Task B. Then the time required to match the tip position of the robot arm to the two cubes is termed as working time, and the average working time is calculated. The subjects comprised six males in their twenties, who randomly performed the four operation methods. They were allotted three minutes of learning time for each method. As shown in **Fig. 7**, in the AOA of the actual machine, the distance of the target position was the same as that in the simulator, and a task similar to that in the simulator was performed. The standing positions of the subjects were fixed, and they were instructed to maintain their position as far as possible to reduce the drastic shake of the robot arm caused by human motion. Subsequently, we performed the simulation and comparison. Assuming that there is no difference between Tasks A and B, we calculated the average working time by using two types of working times per subject.

After the subjects executed the operations of the robot arms, we distributed a questionnaire to each of them to evaluate the work efficiency and the operability on a five-

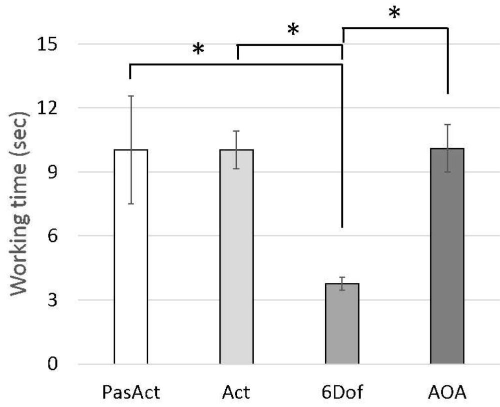


Fig. 8. Average working time ($*: p < 0.05$).

point scale. The questionnaire was as follows.

- Question 1: Were you able to move the robot hand position as desired?
- Question 2: State the difficulty level of the operation.
- Question 3: State the work efficiency compared to PasAct.

5.3. Results

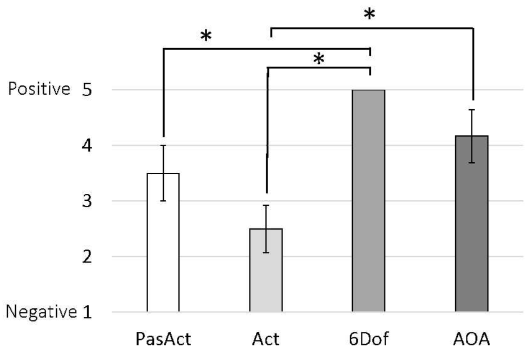
The results of the average working time of Tasks A and B in each of the robot arms evaluated by using multiple comparison and the standard error are shown in **Fig. 8**. In each of the tasks, the average working time of the four types of robot arms was compared, and it was evaluated whether there was a significant difference in the six pairs; the evaluation was performed by using the t-test assuming an equal variance.

The result in **Fig. 8** indicates that significant differences are seen, i.e., the following three pairs: PasAct and 6DOF ($p = 0.012$), Act and 6DOF ($p = 0.004$), and AOA and 6DOF ($p = 0.033$) in the average working time.

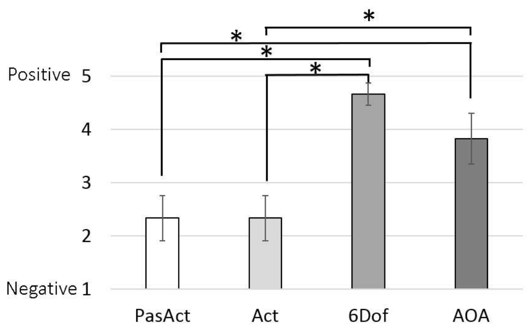
Figure 9 provides the results of the t-test corresponding to the questionnaire. **Fig. 9(a)** provides the result of Question 1 (“Were you able to move your hand position as desired?”), which indicates that there are significant differences of $p < 0.05$ between PasAct and 6DOF ($p = 0.013$), Act and 6DOF ($p < 0.01$), and Act and AOA ($p = 0.026$).

Figure 9(b) provides the result of Question 2 (“State the difficulty level of the operation”), which indicates that there are significant differences of $p < 0.05$ between PasAct and 6DOF ($p < 0.01$), PasAct and AOA ($p = 0.04$), Act and 6DOF ($p < 0.01$), and Act and AOA ($p = 0.04$).

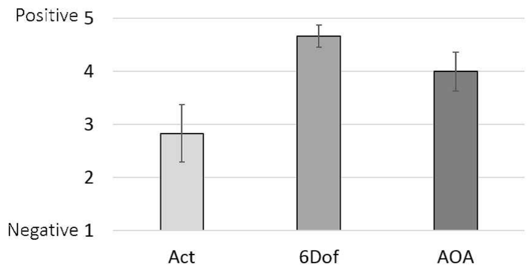
Figure 9(c) provides the result of Question 3 (“State the work efficiency compared to PasAct”). Here, it was evaluated whether there is a difference between the AOA value of the actual machine and the intermediate value of 3. It was seen that, $p = 0.04$, i.e., $p < 0.05$, This means there are no significant differences between the AOA and PasAct in their work efficiency.



(a) Q1: Were you able to move your hand as intended?



(b) Q2: State the difficulty of control



(c) Q3: State the work efficiency compared to Pas-Act

Fig. 9. Result of questionnaire ($*$: $p < 0.05$).

5.4. Discussions

To evaluate the work efficiency and the operability of the AOA in this evaluation experiment, we compared the AOA (PasAct) implemented on the simulator, the robot arm (Act) that dynamically performs angle control by using the actuator to all the joints with DOF similar to that of AOA, and the 6-DOF robot arm (6DOF). First, we evaluated whether there was a large difference between the AOA (PasAct) implemented on the simulation and the actual machine (AOA).

The result of comparison of the working time (**Fig. 8**) indicates that there was no significant difference in the average working time of PasAct and AOA; therefore, it can be confirmed that no large difference is seen in the working time.

Furthermore, the results indicate that a large difference was not seen in the simulation (PasAct) of AOA and the actual machine (AOA), thereby confirming that the comparison between the robot arm implemented with the simulation and the actual machine was valid. Therefore, we evaluated and considered the work efficiency and the operability of the HAS by comparing the simulator with the actual machine.

The Act dynamically performed the angle control by using the actuator in all the joints, which is similar to the existing robot arms. However, there was no significant difference in the average working time of PasAct and AOA operated by dividing the joints into passive and active, as proposed in this research. Therefore, it is confirmed that there is no significant difference in the working efficiency of the robot arms that are operated by the active-passive joint division and those without the division.

From the point of view of operability, the result in **Fig. 9(a)** indicates that there was no significant difference between PasAct and AOA, whereas the result of operation difficulty in **Fig. 9(b)** indicates that there was a significant difference between PasAct and AOA. Furthermore, the result in **Fig. 9(c)** indicates that AOA shows improved work efficiency than that of PasAct. The reasons for this could be attributed to the following. Although the operation with the active-passive joint division is the same throughout, the operation of the passive joint on the simulation is performed by using the keyboard. Therefore, it lacks intuitiveness compared to the actual machine that the user operates by directly grasping the robot arm. This is considered to have caused the difference in the operation difficulty and the work efficiency.

These results indicate that there is no significant difference in the work efficiency of the wearable robot arm using the HAS, which is capable of achieving weight reduction compared to the robot arm configured to have the same DOF that performs angle control by using the actuator.

Furthermore, in the case of simulation, it can be concluded that there is no significant difference in the operability of the wearable robot arm using the HAS compared to the case in which all the joints are dynamically driven and operated and there is no large effect on the operability.

Therefore, it is confirmed that the use of the HAS does not affect the work efficiency and the operability of the robot arm, and the lightweight intuitively-operable wearable robot arm can reduce the weight burden and the operability problems.

6. General Discussion

By combining the passive and the active joints, one can expect weight reduction equal to or more than approximately 40% compared to the case in which all the joints are implemented with the active joint. The weight reduction of the robot arm reduces the weight burden on the user; therefore, an improvement in the work execution time can be expected. Moreover, the weight burden in the user-mounting is reduced; therefore, the robot arm can be mounted even in the mounting positions where the user burden is large, e.g., the forearm and the shoulder, thereby supporting various works. This would expand the width of the tasks that can be supported. Furthermore, safety would be improved because the impact caused by contact with the robot arm would be reduced owing to the weight reduction.

The influence resulting from the active-passive joint division in terms of the operation was a point of concern. However, large influence was not seen because there was no significant difference compared to the case in which all the joints are implemented with the active joint. Therefore, it can be concluded that the adoption of HAS does not affect the operability significantly and weight reduction is possible. However, the mounting position varies depending on the work support target; therefore, it is necessary to study the work target and the mounting position in future work.

Moreover, in the combination of joints, the more the passive joint increases, the more the robot arm's intuitiveness and operability. However, dynamic work support is not possible, and the work assist force is reduced. On the contrary, when the active joint increases, it is necessary to examine the interface (UI) that operates the robot arm. The user has both their hands engaged in work; therefore, a UI that performs the operation by using a position other than the hand is necessary. However, the DOF is small in a position other than the hand, and the operation becomes difficult as the active joint increases.

As a result of examining the balance on the basis of the motion of the human arm during work, this research successfully achieved weight reduction without significant influence on the operability and the work efficiency by using the passive joint for the two joints of the elbow and the shoulder that correspond to the root joint.

7. Conclusions

In this research, we focused on the motion of the human arm during work and examined a design by considering the weight reduction and usability of the wearable robot arm while performing independent motions in the root and the hand joints. We implemented the prototype robot arm, AOA, where the joint corresponding to the root joint of the human was considered as the passive joint, and the joint corresponding to the hand joint as the active joint. We successfully achieved weight reduction equal to or greater than approximately 40% compared to the robot arm for the case where all the joints are implemented as the active joint. Additionally, the influence of the active-passive joint division on the operability was small, and the evaluation experiment indicated that the proposed system has lightweight intuitive operability.

In future, we plan to study the mounting method and position for which the user does not feel burdened for the wearable robot, AOA. Our development efforts related to this are ongoing with reference to the existing wearable robot arms and wearable devices. Additionally, we plan to study the control method of the active joint in which the hand does not move from the given position because the entire robot arm moves owing to the user motion. The robot arm implemented in this study is a simple prototype; in future, we plan to use an optimum DOF in the passive and the active joints.

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