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Design Consideration for Arm Mechanics and Attachment Positions of a Wearable Robot Arm*

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***Abstract*— This paper presents an experimental evaluation of a usability of a wearable robot arm in different combinations of arm mechanics and attachment positions. A wearable robot arm has been recently proposed as a new system concept for the assistance of activities of daily living. Wearable robot arms are expected to enhance our physical abilities and perform multiple tasks simultaneously. However, the usability study of a wearable robot arm has not been discussed sufficiently in the concept design phase. In particular, an experimental comparison of arm mechanics and attachment positions has not been verified in the previous work. We therefore conducted a usability evaluation with a hypothetical attached robot arm which performs a representative task of activities of daily living. The time required for the experimental task and score of NASA Task Load index was evaluated. Two design concepts of a wearable robot arm is suggested according to the usability analyses: shoulder attached articulated robot arm and chest attached spherical robot arm.**

I. Introduction

Robotic arms contribute to complement our capabilities and assist the activities of daily living. Assistive robotic arms have been introduced to achieve continuous assistance and care for people with upper extremity disabilities [1]. Robot assistance is constantly required to perform daily tasks such as moving objects, dressing, eating and drinking. In consequence, robotic arms are now used to perform everyday tasks in the human environment to improve general quality of life [2].

These changes led to develop various design concepts of assistive robotic arms. The design concepts of an assistive robotic arm are classified as the articulated arm mechanics and the spherical arm mechanics. For instance, the articulated arm mechanic has been widely provided as wheelchair mounted robotic arms [3], [4], [5]. The articulated arm mechanics is a joint configuration represented only by roll or pitch joints. Articulated robotic arms are applied in general purposes such as assistance of activities of daily living (ADL), prosthesis and human-robot interaction platforms [1]. In addition, spherical arm mechanics is also provided as an assistive robotic arm [6], [7]. The spherical arm mechanics is a joint configuration represented not only by roll or pitch but also with prismatic joints. Spherical robotic arms can extend the arm length and generate a different trajectory from human activities. The design concepts of assistive robotic arms are thus a subject of considerable discussion in terms of human-robot interactions.

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Fig. 1. The prototype design of a wearable robot arm; a spherical robot arm is attached to the chest position of the human

Wearable robot arms have been recently proposed as a new system concept of an assistive robotic arm not only to people with disabilities. In particular, wearable robot arms have been applied to perform wide range of human activities. Parietti et al. developed a robotic device which is named Supernumerary Robotic Limbs(SRL) [8]. Articulated robot arms are attached to the shoulder to assist its wearer in the execution of tasks in the overhead workspace such as aircraft manufacturing [9]. In addition, spherical robotic arms are attached to the lower back to assist the balance and reduce the joint load for human bipedal walking [10]. Kojima et al. developed a wearable robot arm called Assist Oriented Arm (AOA) [11]. An articulated robot arm is attached around the waist to hold the surrounding objects. Vatsal et al. presented a design of a wearable robot arm for close range human-robot collaborations [12]. A spherical robotic arm is attached at the elbow which supports wide variety of usage scenarios as a collaborative tool. As a consequence, attachment positions have been a novel design factor of an assistive robotic arm.

However, the usability of a wearable robot arm has not been discussed sufficiently in the concept design phase. In particular, an experimental comparison of arm mechanics and attachment positions of a wearable robot arm has not been verified in previous research. Arm mechanics and attachment positions are design factors which has a dominant influence on extensiveness and cooperativeness of a wearable robot arm [13]. A usability study on design factors is therefore necessary for discussions of the concept design of a wearable robot arm.

A design consideration for arm mechanics and attachment positions of a wearable robot arm is presented in this paper. The evaluation is based on the premise that the human perform multiple tasks of activities of daily living simultaneously. An experimental evaluation of the usability of a wearable robot arm is conducted in a hypothetical attached condition. The relation between the usability and the two design factors are suggested according to the usability analyses in this paper.

Fig. 2. The first prototype of the wearable robot arm; an articulated robot arm is attached to the shoulder position of the human [17]

II. PRELIMINARIES

A. Previous Work

For example, we might wish to have an additional arm that can open a door when we carry something in both hands. These situations which we need an extra hand is common in our daily life. We therefore present a concept of a wearable robot arm which allows humans to extend their physical abilities and assist multiple tasks simultaneously in activities of daily living. The goal of this research is to develop a concept design of a wearable robot arm for idealized human-robot collaboration.

Prototype designs have been developed for the usability study on the design concept of a wearable robot arm. The initial prototype of the shoulder attached articulated robot arm is shown in Fig.2. A novel interface system for a voluntary and intuitive control of a wearable robot arm was also proposed as a previous work [14]. The accuracy of object instructions and adjustability of the face vector interface system is reported. We therefore aim to develop a wearable robot arm with a face vector interface and voice control as a final system concept.

B. Design Factors of the Wearable Robot Arm

A wearable robot arm has three main design factors: arm length, attachment positons and arm mechanics. The arm length of a wearable robot arm is preferred to be longer than a human body. In general, a wearable robotic device is aimed to enhance our physical abilities [12]. Furthermore, a wearable robot arm with short link lengths shares their workspace with the human and has high risk of collisions [13]. However, the moment loads of a robot arm will increase if the link length is too long. The arm length is therefore necessary to be optimized in the concept design phase.

Attachment positons are suggested to be on the torso based on previous ergonomics studies [8]. Shoulder and waist is especially described as a suitable position to support dynamic loads. In addition, a robot arm is preferred not to interfere with movement of either hands or feet to perform activities of daily living [1]. The attachment position is also required not to interfere with the head motion in order to apply the proposed interface system. The attachment position is therefore selected from a representative point on the torso.

Arm mechanics of a wearable robot arm is designed based on the analysis of activities of daily living [15]. The robot arm is designed to perform lifting tasks which is the most common activities in daily living. The lifting task is classified into positioning and rotation of an end effector about a threefold axis (4DOF). Joint configurations which satisfy this movement are vertically articulated or spherical coordinated mechanisms [16]. The arm mechanics is therefore suggested to be consisted of vertically articulated or spherical joint configurations.

C. Concept Design of the Wearable Robot Arm

Evaluation indexes for the design factors of a wearable robot arm were proposed in terms of extensiveness and cooperativeness [13]. The common workspace of the human and robot arm was calculated in the concept design phase. The example calculation of the workspace is shown in Fig. 3. Two design concepts were presented based on the evaluation indexes: shoulder attached articulated robot arm and chest attached spherical robot arm. The prototype design image of the chest attached spherical robot arm is shown in Fig. 1. The chest attached spherical robot arm indicated the highest extensiveness and expected to highly enhance our physical abilities. On the other hand, the shoulder attached articulated robot arm indicated high cooperativeness and expected to be suitable for the human-robot collaborative tasks. However, usability studies of these two presented design concepts have not been experimentally discussed.

Design evaluations of arm length and attachment positions were reported in terms of cooperativeness and collision safety [17]. The wearable robot arm was recommended to consist of an extended arm length as compared with human body. On the other hand, the attachment position did not have a dominant influence on collision safety according to the experimental results. However, experimental evaluations of arm mechanics have not been verified in previous woks. The usability of a wearable robot arm is expected to be varied according to the combination of arm mechanics and attachment positions. We therefore present an experimental design evaluation of the combination of arm mechanics and attachment positons. The usability of the two presented design concepts is discussed according to the experimental results of this paper.

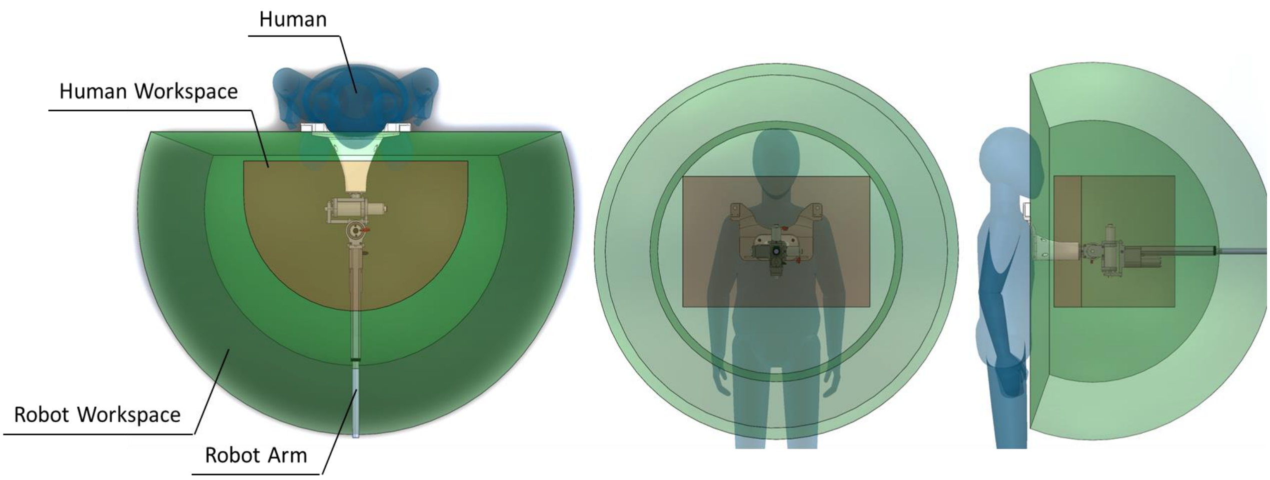

Fig. 3. Example of the visualization of reachable workspace (green) and approximate comfortable human workspace (red). [13]

III. Materials and Methods

A. Experimental Overview

We conducted a plastic bottle recycling task to evaluate the usability of a wearable robot arm with different arm mechanics and attachment positions. The overview of the experimental environment is shown in Fig.4. Plastic bottles are inside the human workspace and a recycle box is outside the human workspace. The participants throw away the plastic bottle caps to the recycle box with a robot arm which is clamped to a pole fastened to the floor. The mounting position of the robot arm on the pole is adjustable to compare the relative position with the human. The experimental task describes a hypothetical situation which performs a collaborative task with a wearable robot arm. Magnets were bonded to the end of robot arm and bottle caps in order to perform the task without the influence of end effectors. The human attracted magnets of the robot arm and caps to each other and the robot arm axially rotated to throw away the attracted bottle caps into the recycle box. The experimental task was therefore simplified in order to compare the design factors of the robot arm on the most basic level.

The plastic bottle recycling task was previously conducted to experimentally evaluate the cooperativeness and collision safety of a robot arm [17]. Taking off plastic bottle caps is a representative task which describes general movements in the activities of daily living [18]. An availability assessment in the previous work suggested that a wearable robot arm contributes to perform this task efficiently. The proposed experimental task is therefore appropriate to evaluate the usability of a robot arm for an assistance of activities of daily living.

The time required and score of NASA Task Load index (NASA-TLX) was evaluated in the experiment [19]. The total time to throw away caps of six plastic bottles was measured as an evaluation index of operation efficiency. The NASA-TLX is an assessment tool which is widely used in human factors research. The total score of the NASA-TLX was measured to assess cognitive workloads of task performances. The usability of the robot arm was assessed based on both quantitative and qualitative evaluation factors. A consideration of the design factors was therefore discussed according to these two indexes.

The experimental task was conducted in two steps. At first, the participants performed the task without the assistance of a robot arm. Next, participants performed a collaborative task with a robot arm in four different setups, which compares the combination of each of the two arm mechanics and attachment positions. The total time spent on the task with each robot arm conditions was measured and NASA-TLX score was assessed relative to the task without the assistance of a robot arm.

B. Design Overview of the Prototype

Two prototype of a robot arm mechanics were developed for the usability assessment. First, an articulated robot arm was developed for the previous experimental evaluation [17]. The articulated robot arm mechanics consists of four rotatory joints that recreate the movement of the upper limbs of a human. Next, a spherical robot arm was additionally developed for the usability assessment. The device overview of the spherical robot arm is shown in Fig.4.The spherical robot arm mechanics consists of three rotatory joints and one prismatic joint that change the arm position and extend the arm length to reach the outside of the human workspace. Degrees of freedoms of the two prototypes were both a total of 4 DOF, which compares arm mechanics under uniform conditions. Besides, the arm length of the each arm mechanics (800 mm) was designed according to the result of the previous experiment [17].

Two types of actuators were mounted to the each prototype. Maxon DCX 35L motors with Maxon GPX 42 gearboxes were used for the rotatory joints of each of the arm mechanics [20]. Progressive Automations PA-14P with a stroke size of 203 mm was also used for the prismatic joint of the spherical mechanics. The selected prismatic actuator is composed of a common rotatory motor and a threaded shaft drive that transforms rotatory into a linear motion. The rotatory actuators were operated by PTP (point-to-point) movements and the prismatic actuator was controlled independently with a potentiometer during the experiments. The motion of each arm mechanics was registered in advance and controlled by the voice of the participants. Furthermore, the velocity and acceleration of the actuators were defined to prevent the unexpected collisions between the human and robot arm. The prototype of two arm mechanics were therefore developed for the experimental comparison the design factors of a wearable robot arm.

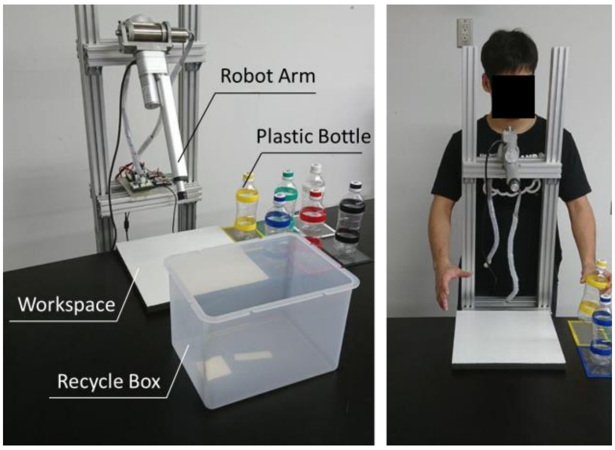

Fig. 4. The experimental overview; a robot arm is clamped to a pole fastened to the floor; the participants take off the plastic bottle caps and attract to the magnet bonded to the robot arm which is placed close together

IV. Results and Discussion

A. Experimental Results

The experiment was conducted with participants including adult male and female (N=7). A two-way analysis of variance was analyzed to define the relation between the evaluation indexes and design factors. The results of the time required and NASA-TLX total score are shown in Fig.9 and Fig.10. Statistical interaction was not detected between the arm mechanics and attachment position. Significant differences in the time required and NASA-TLX score were shown between two arm mechanics in shoulder attached positions. Significant differences in time required and NASA-TLX score were also shown between two attachment positons in the articulated arm mechanics. On the other hand, a difference in time required and NASA-TLX score was marginally significant between two arm mechanics in chest attached positions. Significant differences in the NASA-TLX score was not shown between two attachment positions in spherical arm mechanics.

B. Consideration of the Design Factors

The shoulder attached articulated robot arm is suggested to be applied in a collaborative task according to experimental results. The fastest completion times and highest NASA-TLX scores were obtained with the shoulder attached articulated robot arm. An articulated robot arm mechanics which is attached to a shoulder generates a trajectory approximated to the movement of a human arm. The generated trajectory of a shoulder attached articulated robot arm is considered to be easier to perceive for the human compared with the other arm mechanics or attachment positions. Reduction of the cognitive loads is therefore related to increase the operation efficiency of a wearable robot arm according to the experimental result.

The articulated robot arm is suggested to be attached on the shoulder position compared with chest position. The visibility is considered to be a dominant factor which influence to the cognitive loads of the human. The collaborative task might become complicated when the view of the human is obscured by the robot arm attached in front of the body.

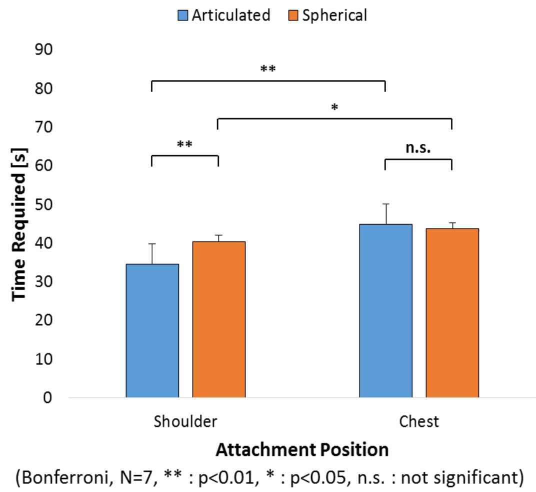

Fig. 5. Evaluation results of the time required;

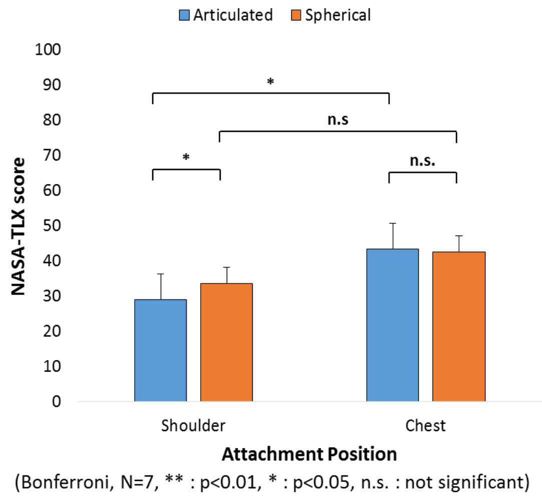

Fig. 6. Evaluation results of the NASA-TLX score

However, the chest is an attachment position which most increases the reachable workspace according to the previous simulation [13]. The workspace of a robot arm is expanded to horizontal direction symmetric when the origin is at the center of the body. The chest attachment position is appropriate in enhancements of physical ability compared with the shoulder.

The spherical arm mechanics takes higher cognitive loads than a shoulder attached articulated arm, but has versatility of attachment positions. The cognitive load was not significantly different between two attachment positions in spherical arm mechanics. Furthermore, the efficiency and workloads of the task were marginally significant between two arm mechanics in chest attached positions. On the chest position, a spherical robot arm is suggested to be attached according to the results.

In summary, a design tradeoff between the reduction of the cognitive load and expansion of the reachable workspace is suggested. In particular, the shoulder attached articulated robot arm is suitable for collaborative tasks inside the human workspace and the chest attached spherical robot arm is suitable for independent tasks outside the human workspace.

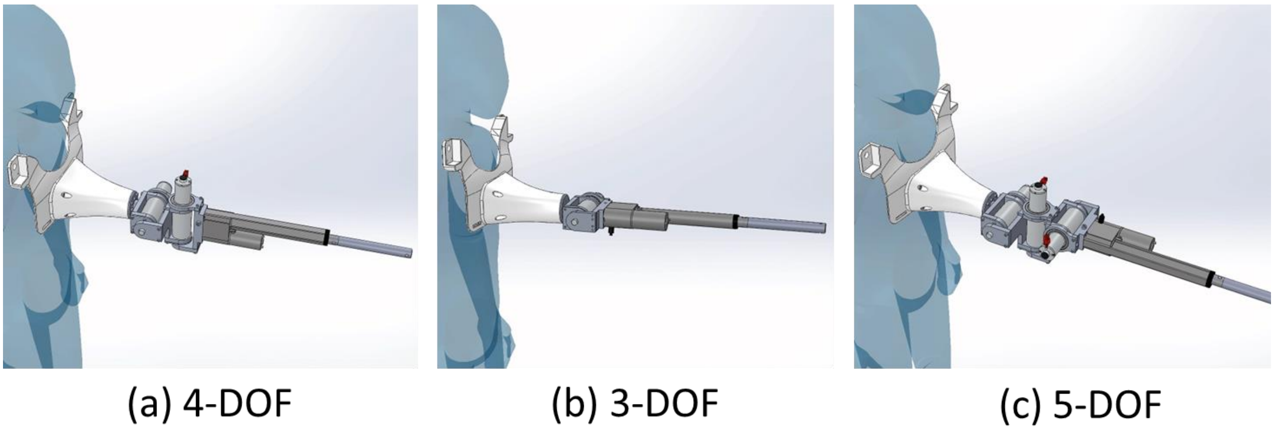

Fig. 7. Changing the degree of freedom; (a) Standard set-up with three rotatory actuators and one prismatic actuator. (b) Reduced set-up with two rotatory actuators and one prismatic actuator. (c) Extended set-up with four rotatory actuators and one prismatic actuator.

C. Future Work on the Chest Attached Spherical Arm

As a result, the chest attached robot arm is suggested to be applied to increase the reachable human workspace compared with the shoulder attached articulated robot arm. However, design issues remain to develop the chest attached robot arm. The design issues of the chest attached spherical robot arm are categorized into joint configurations and attachment comforts.

Due to the fact that this design has never been built before, it is not trivial to predict how many degrees of freedom are actually needed to successfully accomplish various tasks in activities of daily living. The prototype of the spherical arm mechanics is therefore designed flexible to change the joint configurations; the standard setup can be easily modified and less or more degrees of freedom are possible with minor construction changes (Fig. 7 a, b, c). The construction change of the joint configurations also influences overall length, mass and controlling complexity of the robot arm.

The task performance is not only the factor for convenient usage, but also the robot arm has to be comfortable to wear. Although the mentioned experiment was performed without actually attaching it to participants, there are some general characteristics that should be considered. The mass of the robot arm is an important factor of the wearing comfort. The mass of the experimental robot arm with three rotatory actuators and one linear actuator is 6 kg, which might be heavy for long usage periods. The heaviness is strongly influenced by the weight of the linear actuator, whose metallic shaft makes it heavier than the rotatory actuators.

The weight distribution is another factor which influences the wearing comfort. For a shoulder attached robot arm, a balanced equilibrium in the idle joint configuration is only achievable if two robot arms are used meaning one attached on each shoulder. This is not the case for a chest attached robot arm, which has an intrinsically balanced equilibrium in the idle joint configuration due to its symmetry. The occurring momentums during the robot arm movement though cannot be compensated with the chest attached robot arm, but at least partly with two shoulder attached robot arms via contrary movements of the respective other robot arm.

The change of the center of mass causes discomfort for the user for the chest attached robot arm. The center of mass is located in front of the human without considering mass and position of components needed for controlling and power supply. The center of mass is located inside the human when two wearable robot arms are attached slightly above each shoulder, making it more comfortable to wear.

The chest is a suitable attachment position for men, because the costae are a good substructure for attaching the wearable robot arm. In contrast, the pressure on the breasts can cause discomfort or even injuries for women. Either the attachment position has to be moved to the upper belly or the attachment components have to be redesigned, that the occurring forces and momentums get absorbed by other body parts (Fig. 1).

V. Conclusion

In this paper, we presented an experimental evaluation of usability of a wearable robot arm in different combinations of arm mechanics and hypothetical attached positions. A design tradeoff between the reduction of the cognitive load and expansion of the reachable workspace is suggested according to experimental results. We therefore recommended designing two concept designs of a wearable robot arm: the shoulder attached articulated robot arm for collaborative tasks inside the human workspace and the chest attached spherical robot arm for independent tasks outside the human workspace. An additional experiment at higher velocities of the actuator is expected to discuss the design consideration in more depth

The results of the usability analyses are considered to be applied to not only for the concept design of a wearable robot arm but also for assistive robotic arms in general. For example, the cognitive load and reachable workspace might be a subject of a discussion on wheelchair mounted robotic arms which is widely provided for people with upper extremity disabilities.

The design issues of the chest attached spherical robot arm are remained as a future work. The comfortableness of the attached components is especially an important issue for the development of a wearable robot arm. Design considerations of a wearable robot arm are still an unexplored field of study.

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