Proceedings of the 27th IEEE International Symposium
on Robot and Human Interactive Communication,
Nanjing, China, August 27-31, 2018

Experimental Evaluation of Cooperativeness and Collision Safety of a Wearable Robot Arm

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***Abstract*—This paper presents an experimental evaluation of a collaborative task for a design assessment of a wearable robot arm. Wearable robotic devices have been recently proposed as a new concept of the human robot collaboration. In particular, wearable robot arms have been expected to complement our physical capabilities and perform multiple tasks simultaneously. However, a design principle of a wearable robot arm based on the cooperativeness and collision safety has not been discussed sufficiently. The design factors of the wearable robot arm are considered to have a dominant influence on the cooperativeness and collision safety. We therefore conducted an experiment to evaluate time required for a collaborative task and number of collisions with a robot arm device. Arm lengths and attachment positions were compared in the conducted experiment as a design factor of a wearable robot arm. The experimental results indicated a correlation between evaluation indexes and design factors. As a result, we suggest that the concept design of a wearable robot arm is recommended to consist of an extended arm length without constraints of the attachment positions.**

I. Introduction

Human-robot collaboration contributes to complement our capabilities and achieve arduous tasks. Collaborative human-robot work has been introduced to achieve higher productivity and greater efficiency in industrial robotic environments [1]. In consequence, humans and robots now work together and share their workspace without separating or safety fencing.

These changes led to develop wide field of research which focuses on the optimization of human-robot cooperativeness and the minimization of related risks or their consequences. The discussion of collaborative tasks involving humans and robots is classified as the quantifying or minimizing injuries in a collision and the collision avoidance [1]. For instance, the estimation of the pain tolerance and quantification of the level of injuries was presented to analyze the consequences of a human-robot collision [2], [3], [4]. In addition, mechanical compliance systems and safety strategies involving contact detection was developed to reduce the effects of collisions [5], [6], [7]. Furthermore, the collision avoidance system was implemented to enhance safety in human robot collaboration [8], [9], [10]. In summary, human-robot collaborations have been discussed across disciplines and various safety systems have been proposed and applied in industrial environments. The human-robot cooperativeness and collision safety are therefore important evaluation elements in the collaboration between humans and robot arms.

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Fig. 1. The first prototype of the wearable robot arm; the human is carrying a box in both hands with the prototype of a wearable robot arm.

Wearable robotic devices have been recently proposed as a new concept of the human-robot collaboration. In particular, wearable robot arms have been applied to perform wide range of collaborative tasks. Parietti et al. developed a wearable device with two additional robot arms, which is called as Supernumerary Robotic Limbs (SRL) [11]. SRL has wide variety of applications such as in aircraft manufacturing and gait rehabilitations [12], [13]. Weinberg et al. developed a wearable robot arm that allows drummers to play with three arms [14]. The robot arm can be attached to the shoulder of a musician and responds to the human gestures or the music it hears. Kojima et al. developed a wearable robot arm named Assist Oriented Arm (AOA) [15]. AOA consists of passive joints with brake mechanisms which reduce the weight load of actuators and prevent accidents by erroneous operations.

However, a design principle of a wearable robot arm based on cooperativeness and collision safety has not been discussed sufficiently in the previous research. The relative position of wearable robot arms is closer to the human than the traditional robotic devices in industrial environments. As a consequence, wearable robot arms are expected to promote higher efficiency in collaborative tasks. In contrast, the risk of collision with robot arms is predicted to increase during collaborative tasks. An experimental evaluation of cooperativeness and collision safety in closer relative positions is therefore necessary for the discussion of a design concept of a wearable robot arm.

The experimental evaluation of the cooperativeness and collision safety of collaborative tasks with a wearable robot arm is presented in this paper. The collaborative task in this evaluation is based on the premise that the human perform multiple tasks simultaneously which requires an additional robot arm. The time required and number of collisions with a robot arm device during the collaborative task are evaluated as indexes of the cooperativeness and collision safety. As a result, a relation between experimental evaluation indexes and design factors of a wearable robot arm is suggested in this paper.

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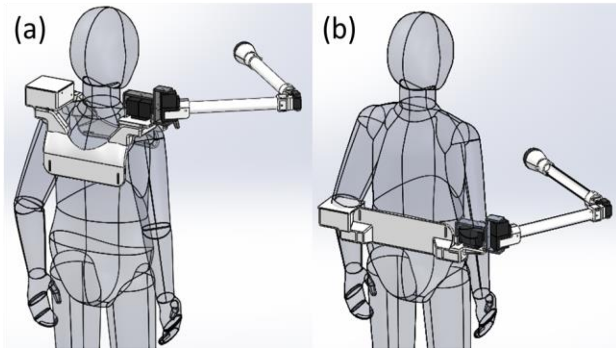

Fig. 2. Design overview of the prototype of a wearable robot arm: (a) shoulder attached model, (b) waist attached model

II. Preliminaries

A. Design Concepts of the Wearable Robot Arm

The goal of this research is to develop a concept design of a wearable robot arm which comprehensively contributes to perform some multiple tasks simultaneously. For example, we might wish to have an additional arm that can open a door when carrying something in both hands. We often encounter to these situations in our life in which we need an extra hand. We therefore propose collaboration with a wearable robot arm which allows humans to extend their physical abilities and handle more than one task at the same time in these situations.

Prototype designs of a wearable robot arm have been developed to examine the usability of those concept designs. The initial prototype of the wearable robot arm is shown in Fig.1. A novel interface system for a voluntary and intuitive control of wearable robot arms is applied to this prototype [16]. The accuracy of object instructions and adjustability of the proposed system was reported. We therefore aim to introduce a voluntary operative wearable robot arm device which allows the human to comprehensively perform multiple tasks.

The human-robot cooperativeness and collision safety are particularly important in the comprehensive application of a wearable robot arm. If the goal of a task is single, the concept design of a wearable robot can be easily discussed because the workspace is confined to particular operation area. In contrast, the robot arm will be required to be operable in a wide and unpredictable workspace if it performs multiple tasks. In consequences, users are compelled to share broad range of workspace and carry a high risk of collisions with the robot arm. However, the human-robot collaboration with a wearable robot arm which is comprehensively applied to multiple tasks simultaneously has been previously remained undiscussed.

B. Design Factors of the Wearable Robot Arm

Optimization of design factors is preferred to improve the cooperativeness and collision safety of a wearable robot arm. Design factors of a wearable robot arm are classified as joint configurations, securing positions and arm lengths. Novel evaluation indexes for the evaluation of these design factors of a wearable robot arm were previously proposed [17]. As a result, design tradeoff between cooperativeness and safety was suggested. However, a confirmation of actual collaborations with real machine devices has not been previously verified.

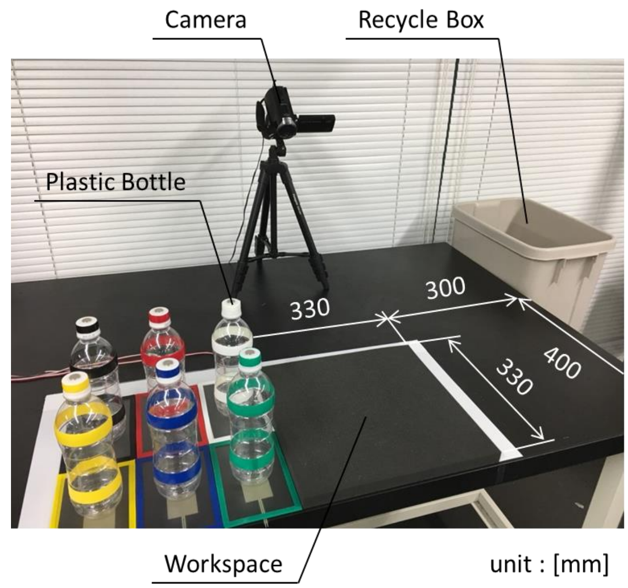

Fig. 3. Overview of the experimental environment; the human uncap plastic bottles in the workspace and throw away caps into the recycle box.

The attachment positions and arm lengths of the previous developed wearable robot arms were defined according to task goals. The prototype designs of a wearable robot arm in two different attachment positions are shown in Fig.2. The torso is considered as an attachment position in order to prevent the physical load due to the weight of a wearable robotic device. Shoulder attached robot arms alleviated overhead workloads such as raising, holding, and securing objects [12]. In contrast, waist attached robot arms are provided to augment stability and reduce the loads on human leg [13]. In addition, the arm length of a wearable robot arm is considered as a length which allows extending physical capabilities of a human body. For this reason, the arm length of a robot arm was previously designed longer than an approximated arm length of a human.

However, a quantitative evaluation of design factors using a real robot arm has not been discussed sufficiently in previous developments. The design factors such as arm lengths and attachment positions are considered to be dominant factors of the cooperativeness and collision safety. In addition, design evaluations of these factors are essential to develop a concept design for a comprehensive application of a wearable robot arm. We therefore present an experimental design evaluation of the cooperativeness and collision safety in a representative collaborative task with a real robotic device.

III. Materials and Methods

A. Experimental Overview

We conducted a plastic bottle recycling task to evaluate the cooperativeness and collision safety in collaborations with a robot arm device. Overview of the experimental environment is shown in Fig.3. The human uncap a plastic bottle and throw away the cap into the recycle box. However, the recycle box is outside the workspace and the human is not able to reach to throw away the cap from the workspace. Instead, the human hand over the cap to a wearable robot arm which assists the carrying task. The time required and number of collisions in plastic bottle recycling tasks was evaluated as an experiment.

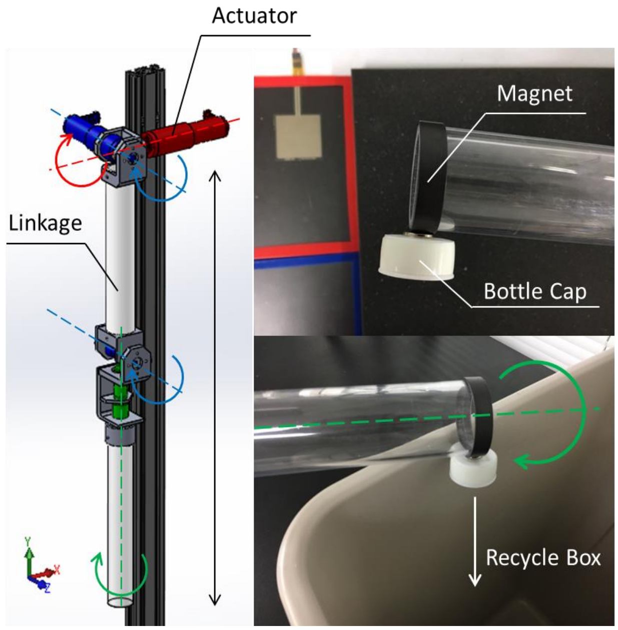

Fig. 4. Device overview of the experimental robot arm; the robot arm consists of four actuators with an adjustable base and linkages; the robot arm assists the carrying tasks using a magnet on the end of the linkage.

The plastic bottle recycling is a representative task which describes general movements of both hands in comprehensive workspace. The plastic bottle recycling task is also applied to a rehabilitative evaluation of total upper limb functions of both hands [18]. In addition, a wearable robot arm is required to enable reaching for, storing, and handing over an object out of the reach for a worker according to the previous survey [19]. Handing over bottle caps and carrying caps into the recycle box satisfies these required functions. The experimental task therefore involves essential factors to evaluate a human-robot collaborative work in a comprehensive workspace.

B. *Design Overview of the Experimental Robot Arm*

An experimental robot arm was developed for evaluations of the cooperativeness and collision safety. Device overview of the experimental robot arm is shown in Fig.4. The robot arm device was designed based on the evaluation indexes for assistive robot devices [20]. The previous evaluation analyzed that the lifting task is the most frequent function of assistive robot devices. Total number of degrees of freedom and joint configurations of the experimental robot arm was designed to satisfy this required function. The robot arm therefore consists of four actuators (maxon DCX35L GB KL 12V) that recreate the movement of the upper limbs of a human [21].

The hypothetical attachment position and link length of the developed robot arm are designed to be arbitrarily selected. The experimental robot arm was firmly fastened to the floor and the human performs the task right next to the device. The actuator is clamped to a pole which can adjust the height of the base of a robot arm. Hypothetical situations in which a human collaborates with a wearable robot arm was examined using this developed device. In addition, the length of the robot arm is adjustable to various experimental conditions by replacing linkages. The experimental robot arm was therefore applied to evaluate the cooperativeness and collision safety in different hypothetical attachment positions and arm lengths.

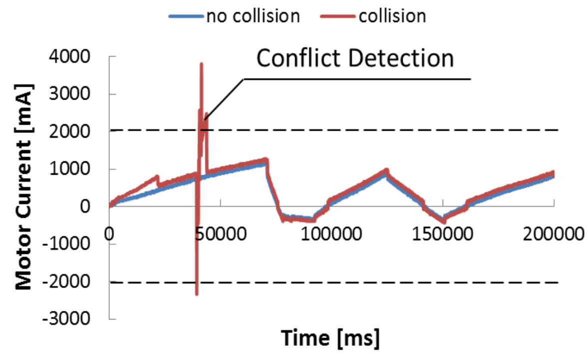

Fig. 5. The motor current value of a preliminary experiment; the number of collision is counted if the motor current is above the threshold value.

Fig. 6. The camera footage of a preliminary experiment; the collision is additionally confirmed according to the visual verification of the video.

Magnets were bonded to the end of the linkage and bottle caps in order to simplify the handing over task. The human performed the handing over task by attracting magnets of the linkage and caps to each other. The robot arm axially rotated the linkage to throw away attracted bottle caps into the recycle box. The human was required to perform experimental tasks on the most basic level and the cooperativeness and collision safety were evaluated without the influence of end effectors.

C. *Evaluation of the time required and number of collisions*

The time required and number of collisions was evaluated in the experimental task. The total time to throw away caps of six plastic bottles was measured as an evaluation index of the cooperativeness. Time required for the experimental task was compared before and after the assistant of the robot device. The availability of a wearable robot arm was evaluated along with a human-robot cooperativeness based on the comparison.

The number of collisions was counted according to the motor current value and camera footage showing movements of the human and robot arm. The motor current value and camera footage of preliminary experiment is shown in Fig.5 and Fig.6. The proportional relation between input torque and output current value of a robot arm was shown in the previous development [2]. A collision with a robot arm was counted if the motor current exceeds the threshold value. In addition, camera footage was confirmed for the visual verification of collisions. The number of collisions was therefore counted based on both quantitative and qualitative evaluation factors.

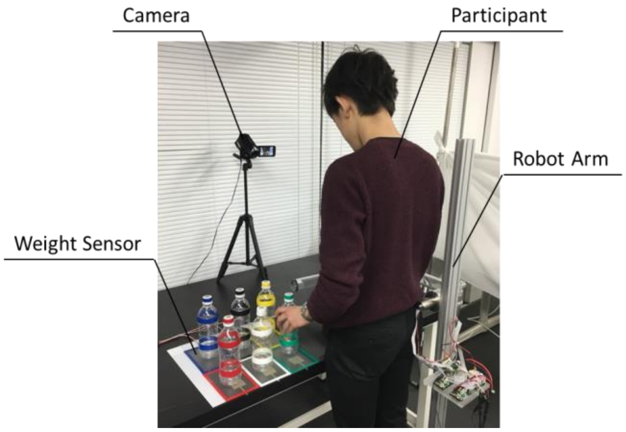

Fig. 7. Overview of the conducted experiment; the robot arm move to specified positions if the participant take off plastic bottles from the weight sensor; the design factor of the robot arm is compared as shown in Table 1.

TABLE I. EXPERIMENTAL CONDITIONS OF THE ROBOT ARM

Height from the floor [mm] (attachment position)	1370 (shoulder attached)
	1000 (waist attached)
Arm length [mm]	700 (human sized length)
	800 (extended sized length)

IV. RESULTS AND DISCUSSIONS

A. Experimental Setup

The experimental environments and device configurations were set up according to a preliminary experiment. Overview of the conducted experimental evaluation is shown in Fig.7. The human workspace and position of the recycle box were determined by the dimension of which participants performed the task in a preliminary experiment. The rotation velocity and angular range of the actuator were also approximately defined based on the movement of participants in the preliminary experiment. Weight sensors were arranged at equal distances under plastic bottles in order to discriminate the status of a task. The robot arm was programmed to automatically move to a specified position which corresponds to the color of the plastic bottles if weight sensors detect human tasks. The positions for handing over task were specified according to preliminary detections of human workspace [17]. The experimental robot arm was therefore able to assist collaborative tasks in the shortest distance without the influence of manual operations. In addition, arrangements of colored bottles were changed for every participant to reduce bias of experimental conditions.

Experimental conditions of the conducted evaluation were defined according to the anthropometric dimensions of an average human [22]. The experimental conditions of the robot arm are shown in Table 1. Hypothetical attachment positions of the robot arm were compared between shoulder and waist as representative coordinates on the torso. In addition, the arm length was set up as an approximated size or an extended size based on the average of the human length. The experimental evaluation was therefore conducted in order to compare each two design factors of a hypothetical wearable robot arm.

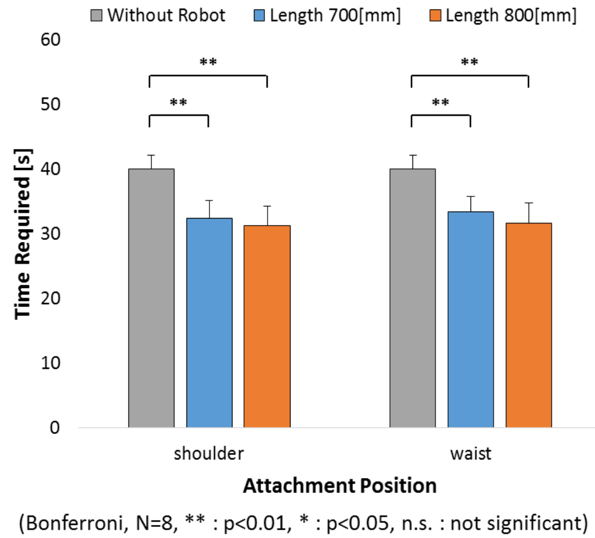

Fig. 8. Results of the availability assessment; the results show that collaboration with a robot arm device significantly decrease time required.

B. Experimental Results

The experiment was conducted with participants including adult male and female (N=8). At first, participants performed the experimental task without the assistant of a robot arm. All participants were required to temporary interrupt the task and move closer toward the recycle box from the position of the workspace to throw away caps. Next, participants performed a collaborative task with the robot arm device. The experimental robot arm enabled participants to accomplish tasks without moving from the human workspace. The time required and number of collision in each task was evaluated under different hypothetical attachment positions and arm lengths of a robot arm. A two-way analysis of variance was conducted to define the relation between evaluation indexes and design factors.

The experimental result suggests that a wearable robot arm contributes to perform efficient collaborative tasks. The result of the availability assessment is shown in Fig.8. The results show that collaboration with a robot arm device significantly decrease time required for an experimental task. In addition, the reduction of time required for an experimental task was confirmed under all of the each condition of design factors.

Furthermore, the experimental result suggests the relation between experimental evaluation indexes and design factors. The results of evaluations of the time required and number of collisions are shown in Fig.9 and Fig.10. Statistical interaction was not detected between hypothetical attachment positions and arm length. Significant differences in the time required between two arm lengths were shown in each attachment positions. On the other hand, a difference in time required was not significant between two attachment positions. Significant differences in number of collisions between two arm lengths were shown in each attachment positions. The difference in number of collisions was significant between two attachment positions in human sized lengths but not in extended lengths. As a result, an experimental evaluation of the time required and number of collisions in a human-robot collaboration using a real robot arm device was successfully conducted.

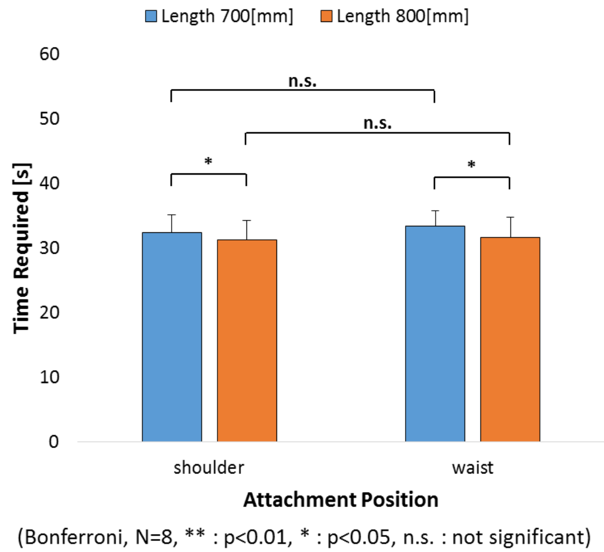

Fig. 9. Evaluation results of the time required; a significant difference between two arm lengths was shown in each attachment positions; a significant difference was not shown between two attachment positions

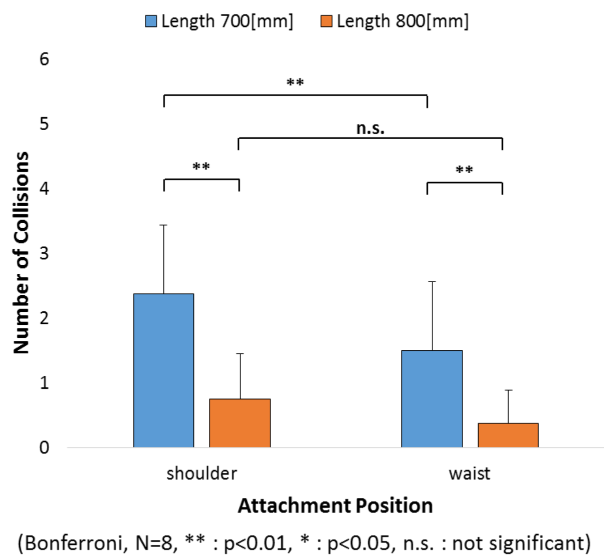

Fig. 10. Evaluation results of the number of collisions; a significant difference between two arm lengths was shown in each attachment position;

C. *Design Evaluation of the Wearable Robot Arm*

At first, experimental results suggest a relation between evaluation indexes and arm lengths of the wearable robot arm. A significant difference in the number of collisions between two arm lengths was shown in each attachment positions. The arm length is suggested to be correlated with collision risks with a wearable robot arm according to these results. In addition, a significant difference in the time required between two arm lengths was shown in each attachment positions. Deterioration of collision safety decreases the cooperativeness with a wearable robot arm according to these results. The arm length is therefore suggested to be extended than a human length in order to improve the cooperativeness and collision safety in a collaborative task with a wearable robot arm.

Next, experimental results suggest an absence of relation between evaluation indexes and attachment positions under the condition of extended arm length. The difference in time required and number of collisions was both not significant between two attachment positions in a condition of extended arm length. The attachment position is suggested to be uncorrelated with the cooperativeness and collision safety of an extended sized length. However, the difference in number of collisions was significant between two attachment positions in a condition of a human arm length. The attachment position is correlated with number of collisions of a human sized robot arm. A human sized robot arm which is attached to a shoulder generates a trajectory approximated to the movement of a human. The generated trajectory of a human sized robot arm which is attached to a shoulder is considered to interference the human workspace and to create higher collision risks. The arm length of a wearable robot arm is therefore recommended to be longer than a human length according to these results.

In addition, relations between arm lengths and evaluation indexes agree with results of previous design evaluations [17]. A negative correlation between the arm length and predicted interference with a human workspace was previously defined. The extension of the arm length is considered to expand the domain of coordinate singularity of a robot arm which does not interact with human workspace. The validation of previous evaluation of the workspace interference with a robot arm was therefore verified based on conducted experimental results.

The recommended attachment position of a wearable robot arm is not able to be sufficiently suggested according to the experimental results. In particular, the time required was most reduced under the condition of shoulder attached position and extended arm length. On the other hand, number of collisions was most decreased under the condition of waist attached position and extended arm length. The design properties of the attachment positions can be suggested according to these two results. A shoulder attached robot arm contributes to bring an efficient cooperativeness with a human compared to the waist attached position. The robot arm trajectory generated by a shoulder attached position is considered to reduce cognitive loads for the human to recognize cooperative movements with a robot arm. The reduction of cognitive loads might lead to perform high cooperativeness in collaborative tasks such as handing over objects. In addition, a waist attached robot arm contributes to reduce collision risks with a human compared to the shoulder attached position. The relative position of a robot arm is considered to reduce interference with the human arm when the coordinate origin of the robot arm is different from a shoulder. The difference of the relative position of a robot arm might lead to decrease collision risks of collaborative tasks.

In summary, results showed that the cooperativeness and collision safety are correlated with arm lengths but not with attachment positions. The arm length of a wearable robot arm is suggested to be extended than a human length in order to improve the cooperativeness and collision safety. However, attachment positions cannot be concluded in terms of these evaluation indexes. In conclusion, a wearable robot arm is therefore recommended to consist of an extended length robot arm without constraints of attachment positions. Note that a robot arm with highly extended length has less collaborative workspace, which might decrease the cooperativeness [17].

The presented evaluation is necessary to be conducted in additional experimental conditions. The Joint configurations are considered as an additional design factor of a wearable robot arm. The robot arm trajectory generated by other joint configurations such as spherical configuration, is predicted to be different from those of vertically articulated. The difference of generated trajectories might relate to the cooperativeness and collision safety. The controlled velocity is also considered as an additional experimental condition of the robot arm. The collision risks might increase when the velocity of actuators is faster than the actual speed of a human. Furthermore, the task condition of the human and robot arm is a factor which has an influence on the experimental result. The number of trials and complexity can be given as an additional condition of the task. The proficiency in the operation of a collaborative task might be able to be assessed when the number of trials is more than one. The cognitive load due to operations of a wearable robot arm is also possible to be evaluated if the task goal is more complicated. The discussion of human-robot collaborations in terms of cognitive science is expected to be suggested based on future works of the presented experimental evaluation.

V. Conclusion

In this paper, we presented an experimental evaluation of the cooperativeness and collision safety of collaborative tasks with a hypothetical wearable robot arm. The results suggested that cooperativeness and collision safety are correlated with arm lengths but not with attachment positions of the wearable robot arm. We therefore recommended designing a wearable robot arm to consist of an extended length robot arm without constraints of attachment positions to the human body.

The experimental results are expected to be applied to not only for the concept design of a wearable robot arm but also for discussions of the human-robot collaboration in a close relative position including the industrial environments. For example, cooperativeness and collision safety are necessary to be considered when the workspace of a robot arm is shared with the human in a manufacturing planted environment. The presented experimental evaluation therefore contributes to discuss the collaboration between a human and proximally positioned robot arm in general terms.

The attachment positions of a wearable robot arm was not able to be recommended based on the experimental results. The concept design of a wearable robot arm is considered to be defined from the task goals of the human and robot arm. The applicability of human-robot collaborations is therefore an important factor to define the design concept of a wearable robot arm. As a future work, research and development of a wearable robot arm should be continued to propose novel possibilities of applications for human-robot collaborations.

Acknowledgment

Research is financially supported by Waseda University Global Robot Academia Institute. The author would like to thank R. Tsumura and R. Sato for valuable discussions. The author also would like to thank to the research participants for commitments to the experiment.

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