Dynamic Shared Limbs: An Adaptive Shared Body Control Method Using EMG Sensors

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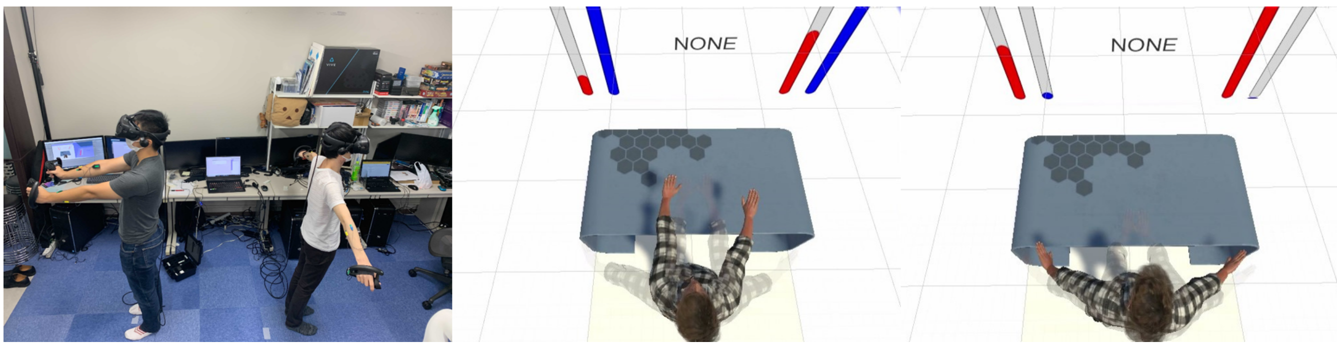

Figure 1: Shared Body controlled with EMG sensors: The averaging weights of sharing were determined by the EMG values of the two operators. The left figure shows the real world, and the middle and right figures show a shared body controlled with EMG sensors. In the middle figure, the left operator was contracting the muscle, and in the right figure, the right operator was contracting the muscle.

ABSTRACT

An inter-personal shared body is an extended body that allows an avatar or robot to be controlled by multiple people. It is possible for operators to share control over the actions of the shared body. A shared body can be operated well when the same actions are performed by its operators. However, when their actions are not the same, we need to have an adaptive control method for the operators to maintain a sense of agency and ownership. In this study, we propose dynamic adjustment methods to control a shared body using EMG sensors and movements of the operators.

CCS CONCEPTS

• **Human-centered computing → Collaborative interaction**.

KEYWORDS

virtual reality, human augmentation, shared body, EMG sensors

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1 INTRODUCTION

Human augmentation, which extends various human abilities, has received a great deal of attention and exploration. There are several remarkable designs for extending human abilities, such as attaching extra limbs [5, 10, 22, 25], switching bodies [11], or sharing another person's viewpoint [12, 13, 15, 19].

The shared body is one of the possible approaches to human augmentation. When one body is shared by two people, one person can recognize things and work in the same coordinate system as the other operator. In addition, people sometimes feel the movement of the other operator as their own movement [6, 7]. Shared bodies are considered useful for working together at remote places and for skill transfer. Furthermore, if we combine the cognitive abilities of two

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expert people in one body, they might become one better person. To share a body, previous studies have developed a control method to reflect the weighted motion of operators at a constant ratio [6, 7], to attach extra body parts operated by one person [24, 27]. However, in previous studies on shared bodies, the ratios of reflection were fixed in each condition. Under these conditions, it is possible to do simple tasks by sharing a single purpose and keeping up with the movements of another operator. On the other hand, it is difficult to directly reflect the individual's intention in the body. For example, in the case of operators who do not share task information or devote the same levels of attention, the motion of the shared body can vary. Therefore, it is not suitable for performing complicated work well without close communication.

In this paper, we explore new methods that allow multiple operators controlling a shared body simultaneously to dynamically adjust the parameters of their shared conditions. We focused on a shared body whose motion is controlled by averaging each operator's motions with an integration ratio, as in the studies mentioned above [6, 7]. To obtain the variables for dynamic adjustment, we used surface electromyography (EMG) sensors. EMG sensors are used in rehabilitation systems [18, 23], gesture recognition [17], and various other fields [1, 20, 22]. By using EMG sensors, intuitive movements, such as muscle contraction and relaxation, can be used to adjust the ratio through which the motions of operators are mixed. Furthermore, since some muscle activity does not require bodily movement, the operators are able to control mixing parameters even without making physical movements. We developed a shared body system using EMG sensors in a virtual environment (VE). We focused on the impact of this dynamic adjustment method on the task performance of the shared body, the sense of body ownership (SoBO), and the sense of agency (SoA). To evaluate the proposed adjustment method, we prepared two dynamic adjustment methods: "*EMG*" and "*SPEED*." We evaluated previous fixed ratio conditions and the conditions of these two methods.

Thus, these are the contributions of this paper:

- We developed a virtual shared body system that dynamically adjusts the rate of sharing using EMG and body movements.
- We evaluated the performance of the dynamic adjustment methods by conducting reaching tasks for shard targets and non-shared targets. The experimental results demonstrated the advantage of the dynamic adjustment methods in reaching tasks with non-shared targets.

2 RELATED WORK

2.1 Human augmentation and shared bodies

Human augmentation has been widely explored in recent years. By expanding various abilities, people can experience new things. Sasaki et al. [25] developed an augmented body with a pair of robotic arms. The arms were controlled with legs and feet. They stated that by using this system, the operator could perform difficult tasks that are too difficult to achieve with a normal body alone. Parietti et al. [22] also developed extra robotic limbs. The robotic limbs were controlled with torso muscle contractions measured with EMG sensors. The authors stated that the reason for using torso muscle contraction is that it does not depend on the movements of the operators' limbs and does not induce any special movement. Iwasaki et al. [10] introduced a new concept, the "Detachable Body," in which the wearable robotic arm could be detached from the user's body and attached to something else. They used this system to evaluate a haptic feedback system and the impact of a binocular disparity in the vision presentation system. Komiyama et al. [15] developed a system that allowed users to move freely between first- and third-person perspectives in a remote work environment. It enabled both the sharing of precise work from a first-person perspective and an understanding of the situation from a third-person perspective.

In addition, there is research on sharing perceptual information with others to expand their abilities. Takagi et al. [26] conducted an experiment in a situation where two or more people engaged in physical joint action. As the size of the group increased, the movement performance of each member improved. This was because the members could detect the movements of others through tactile information in their hands. Therefore, it was noted that each member of the group could instantly estimate the group's movement goals through tactile information. Similarly, Kasahara et al. [12] developed a system that allowed four people to share their vision. In the results of their user experiments, they stated that by sharing vision, people could complement their memories and decisions and could improve viewing behaviors to understand their physical embodiment and spatial relationships with others in complex situations. In another related study, Nishida et al. [20] developed a device that could simultaneously measure EMG and electric muscle stimulation. By using this device, the user could control or receive control of another person's muscular activity, which enabled people to share a sense of motion.

A shared body is the concept of a single body shared by multiple people. By sharing a body, operators can extend and complement each other's abilities. Saraiji et al. [24] devised a shared body with robotic arms that could be operated from a remote location. They mentioned that by combining the perspectives of two people, they could extend the actions of one body. Hagiwara et al. [7] developed a shared body controlled by two operators' actions in VE. Two operators' movements were integrated into the shared body with constant ratios. As a result of their experiments, they stated that they had SoBO and SoA in the shared body, and the task performance was improved by sharing the body. Fribourg et al. [6] also developed a shared body controlled by two operators with a constant ratio. They stated that the apparent motion of the shared body provided a greater SoA than the rate of actual behavior reflected in the shared body.

2.2 Sense of embodiment in virtual reality

When operating a virtual body, it is necessary to have a high sense of embodiment (SoE) in the virtual body in order to improve the immersive feeling [14]. Kilteni et al. [14] stated that SoE consists of SoA, SoBO, and a sense of self-location. They also stated that SoA results from a comparison between the predicted actions of the avatar and its actual actions. Moreover, SoBO emerges from sensory information and cognitive processes [2, 14]. According to Debarba et al. [4], when controlling a virtual full body, the first-person perspective induces stronger SoE than the third-person perspective.

There are various studies exploring the remapping of the virtual body. Regarding the effect of the latency of a virtual body, Ismail et al. [9] investigated the SoBO and the SoA caused by visual and motor integration on a virtual hand by reflecting the actual movement of the real hand. They stated that the image of the virtual hand can be reconstructed if the latency is 200 ms or less. Similarly, Waltemate et al. [28] investigated the effect of delayed feedback on virtual full-body avatars on SoE and motor performance. The results showed that a latency above 75 ms affected motor performance and simultaneity perception, while a latency above 125 ms reduced SoBO and SoA. They stated that people perceive the latency of the VE through performing movements rather than through cognition of the body. On the other hand, Won et al. [29] conducted experiments using virtual avatars of various configurations. They stated that the operator could adapt in a short amount of time even if the operation assignment was different from the actual body. Kondo et al. [16] explored the difference between body part ownership and the full body illusion. They developed a scrambled body that scrambled the positions of hands and feet compared to a body with a normal layout. As a result of their experiments, they suggested that the spatial arrangement was important for the full body illusion. The SoE about extra body parts has also been explored. Hoyet et al. [8] implemented a virtual hand by placing a sixth finger between the ring finger and the little finger in a VE. In the study, the SoBO of the sixth finger was high when the sixth finger simply existed and became higher when it was moving. Drogemuller et al. [5] conducted experiments where a virtual avatar attached a third arm that could dynamically switch the remapping target to the head, arms, or legs. As a result, the SoBO was lower under the condition that the remapping target could be switched than it was under the condition that it could not be switched; however, the mental workload was also lower.

On the other hand, SoE is also a focus in the field of joint action. Obhi et al. [21] explored SoA and intentional binding in joint action. They stated that in the joint action situation, "a 'we' identity" [21] was automatically generated. Moreover, both operators had an unconscious SoA even if they were actually doing nothing.

3 SHARED BODY DESIGN

In order to conduct experiments with a shared body, we developed a system to synchronize virtual environments via a network connection. In this section, we introduce our system configuration for this study.

3.1 Setup

A virtual environment was developed in Unity 3D (2019.2.4f1) and run on two computers. We used Photon Unity Networking to synchronize the data between computers. Each participant's body was tracked by the Valve index and the two controllers. Each full-body skeleton was reconstructed with inverse kinematics (IK) by the FinalIK Unity package using a three-point tracking method. We used Delsys Trigno quattro sensors to measure EMG signals.

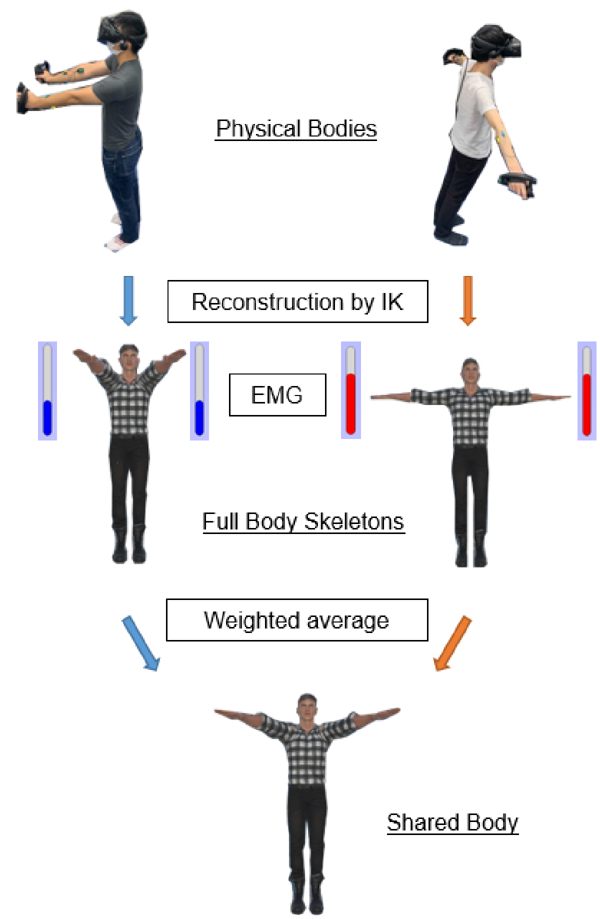

Figure 2: Configuration of a shared body. The red and blue bars represent the EMG values of operators.

3.2 The shared body

In this study, a weighted average of the relative rotation, position, and scale of the two full-body skeletons reconstructed by IK was applied to the shared body.

In case of n operators condition, by using the weights w_i of each operator $i(1, 2, \ldots n)$, the relative rotation r_{shared}, position p_{shared} and scale s_{shared} of each body joint of shared body were defined as follows (in this study $n = 2$). Here, r_i, p_i and s_i are the parameters of each operator.

$$r_{shared} = \sum_{i=1}^{n} w_i r_i \tag{1}$$

$$p_{shared} = \sum_{i=1}^{n} w_i p_i \tag{2}$$

$$s_{shared} = \sum_{i=1}^{n} w_i s_i \tag{3}$$

In our full-body skeletons, 23 joints were used to control the posture: 4 each on the left and right arms, 15 on the body. The 23 joints' pose parameters of each operator were shared. To determine the pose of the shared body, a weighted average of each parameter was calculated for all the joints. The weights w_i were adjusted for each body part. The weights w_i for position and rotation of left and right arms were adjusted for each joint as a part of experimental conditions. Weights w_i for position and rotation of other body parts, and scale of all the parts were always set at 50:50. The scale parameters s_i were obtained at the initialization process of the VR system via a standard T-pose calibration. The weights of left and right arm rotations and positions were (1) 50:50 (*STATIC*), (2) dynamically adjusted using EMG (*EMG*), and (3) dynamically adjusted using hand speed (*SPEED*) for each experimental condition. The details of the conditions are stated below.

(1) **STATIC condition**
In the *STATIC* condition, the pose of the two participants were always averaged with a 50:50 weight for both arms.

(2) **EMG condition**
EMG sensors were attached to the left and right forearms, as shown in Fig. 3. We attached the sensors on forearms because it was easier to contract the muscles and there was less interference from the arms movement of upper arms. Based on the data obtained by the EMG sensor (222 Hz), the root mean square (RMS) was calculated for every 20 samples. Participants were asked to contract their muscles during a pre-task calibration session to measure the maximum voluntary contraction (MVC) and normalize the RMS value from 0.0 to 1.0. In the *EMG* condition, the ratio of the normalized EMG values of the left and right arms of two participants was used as the weight for averaging the joint parameter of the arms of the shared body. By using the normalized EMG values (v_i), the weights of each operator's arm (w_i) were defined as follows.

$$w_i = \frac{v_i}{\sum_{i=1}^{n} v_i} \tag{4}$$

$$\sum_{i=1}^{n} w_i = 1.0 \tag{5}$$

In other words, the average weights changed dynamically in response to EMG fluctuations caused by voluntary muscle manipulation.

(3) **SPEED condition**
In the *SPEED* condition, the ratio of the left and right hand velocities of the two participants was calculated and used as the average weight of each arm of the shared body. By using the hand velocities (v_i), the weights of each operator's arm (w_i) were defined as same as *EMG* condition (formula 4, 5). The greater the hand speed, the more the operation was reflected. In other words, a shared body is expected to follow an arbitrary intentional movement.

As for the viewpoint, the horizontal position was adjusted to the position of the head of the shared body to make it the first person viewpoint of the shared body, but the vertical position and the rotation were not synchronized with each other to avoid motion sickness. Although it is possible to display the operator's original avatar, we did not display it in our experiments because it might have adversely affected the results. The model of the shared body was realistic to enhance SoE. The EMG values of both arms were always displayed in front of the participants, as shown in Fig. 1.

Figure 3: EMG sensors were attached to the left and right forearms.

4 EXPERIMENT

In this study, we conducted user experiments to evaluate dynamic adjustment methods for average weights in shared body operations.

4.1 Hypothesis

We formulated several hypotheses about adjustment techniques in shared body control.

(H1) A shared body with dynamic weight adjustment improves SoBO and SoA compared to a shared body with static weight.

(H2) There is no performance difference between static and dynamic weights in reaching tasks with a single target where the target is shared among the operators.

(H3) The performance of dynamic weights is better for reaching tasks with multiple targets where the targets are not shared among the operators.

4.2 Participants

Twelve students from our university campus participated in the experiment. Two people controlled one shared body and performed the experiment. The pairs were selected at random, and communication during the task was prohibited to account for the effect of the relationship.

4.3 Experimental task

In our study, we conducted two types of tasks in following conditions. (1) reaching for a single target: the target object is visible for all participants, (2) reaching for multiple targets: target objects are randomly assigned to the following two conditions: (2a) shared targets: shard visibility for both participants, (2b) non-shared targets: split-ted visibility for participants

In this section, we introduce these tasks.

(1) **Task 1: Reaching for a single target**
The participants touched a block that appeared at random locations in front of the shared body (140 deg horizontally, 90 deg vertically, 35–65 cm from the chest) with the shared body's right hand (Fig. 4). When the shared body touched it, the block disappeared and reappeared at a random location five seconds later. They repeated this task for five minutes. We also instructed them to put their right hand down when the block disappeared until it reappeared.

(2) **Task 2: Reaching for multiple targets**
Two blocks appeared in front of the shared body. Participants were asked to touch them. The blocks disappeared when the shared body touched it and reappeared when the hands was returned to the initial position. In this experiment, to see task performance change with participant behaviors for shared and non-shared targets, we randomly assigned two visibility options for the blocks. The first one was visible for all of participants (shared targets). The second one was a split-ted visibility for participants. One of two blocks was visible for one participant and the other block was visible for the other participant (non-shared targets). Participants were instructed to be able to use both hands, but, move their hand(s) only to the block(s) they can see. This was repeated 27 times in randomized order.

In the experiment, the order of the three weight conditions was counterbalanced. We did not give details to the participants about the conditions.

4.4 Evaluation

At the end of each task, participants responded to a subjective questionnaire on the System Usability Scale (SUS) [3], SoBO, and SoA (cf. Table 1). They were asked questions on a 5-point Likert scale for SUS, a 7-point Likert scale for SoBO, and a number between 0% and 100% for SoA, respectively. To measure the task performance, we used the time between the block(s) appearing and being touched by the shared body in the reaching tasks (Task 1 & 2). At the end of the experiment, we prepared time for open questionnaires.

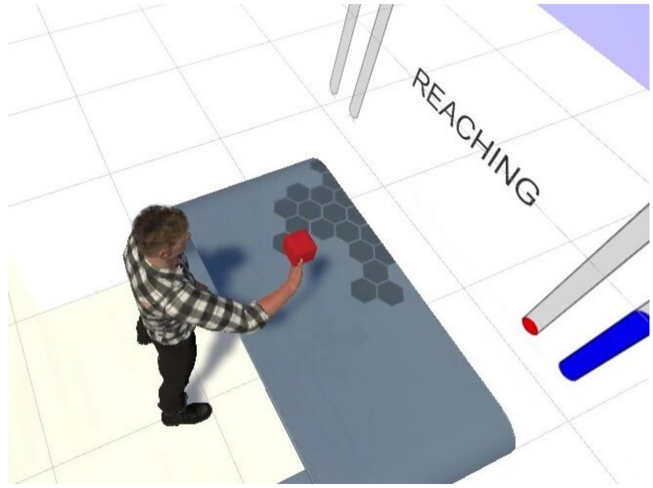

Figure 4: Task 1: Reaching task

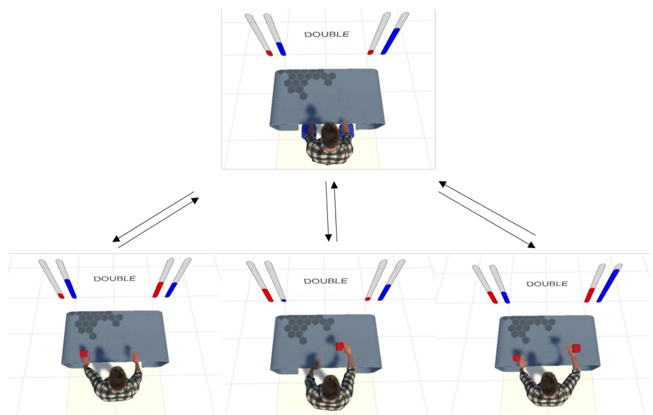

Figure 5: Task 2: Reaching task for multiple objects. The bottom left and bottom middle are snapshots of non-shared targets, and the bottom right is a snapshot of shared targets.

5 RESULTS

5.1 Task performance

Fig. 6 shows the task performance in Task 1. After a one-way repeated measures ANOVA, Shaffer's post hoc tests were conducted. There was no significant difference in the results.

Fig. 7 shows the task performance in Task 2. After a one-way repeated measures ANOVA, Shaffer's post hoc tests were conducted. As a result, we found a significant difference in the conditions of sharing targets and non-sharing targets, the time for the *STATIC* condition was significantly longer than both the *EMG* and *SPEED* conditions ($p < 0.05$).

Table 1: Sense of Body Ownership (SoBO) and Sense of Agency (SoA) questionnaire

Variable	Question
SoBO+	(1) I felt as if the shared body was my body.
SoBO-	(2) I felt as if the shared body was someone else's body.
SoA+	(1) I felt as if the shared body movements were caused by me.
SoA-	(2) I felt that the shared body movements were caused by someone else.

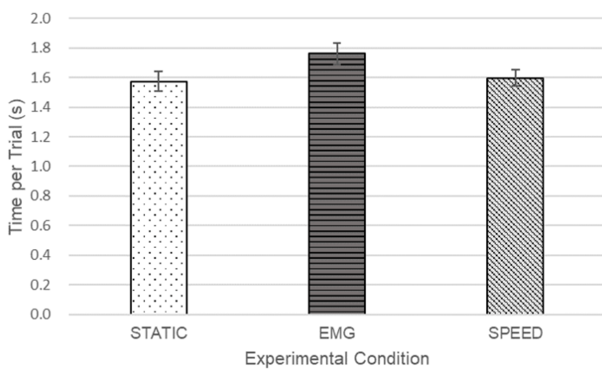

Figure 6: Task performance of Task 1 (reaching task for a single object): time taken for each reaching trial

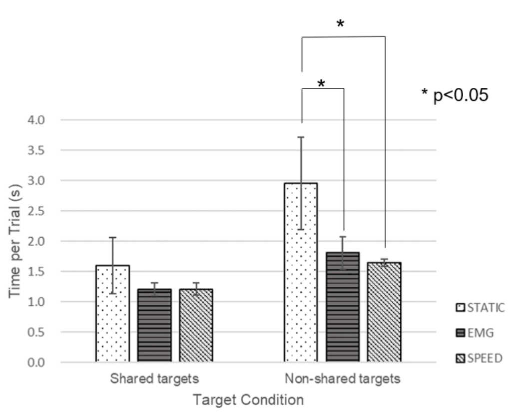

Figure 7: Task performance of Task2 (reaching task for multiple objects): time taken to reaching each object

5.2 System Usability Scale (SUS) score

We calculated and compared SUS scores for each task trial. The results for the SUS scores are shown in Fig. 8. Bonferroni's post hoc tests were conducted after Friedman's test. In Task 1, there was no significant difference. In Task 2, the SUS score for the *EMG* condition was significantly higher than the one for the *STATIC* condition ($p < 0.05$).

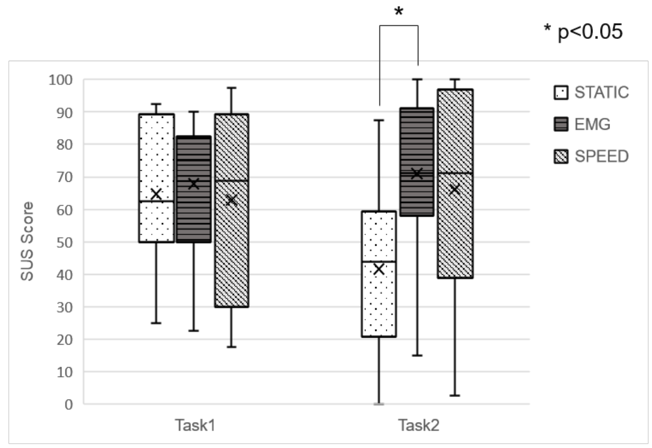

Figure 8: Results of SUS scores

5.3 Sense of Body Ownership (SoBO)

The results of the SoBO questionnaires are shown in Fig. 9. After Friedman's test, Bonferroni's post hoc tests were also conducted. The results showed no significant difference between Task 1's SoBO+ and SoBO- and Task 2's SoBO-. In Task 2's SoBO+, the rating of the *EMG* condition was significantly higher than the one for the *STATIC* condition ($p < 0.05$).

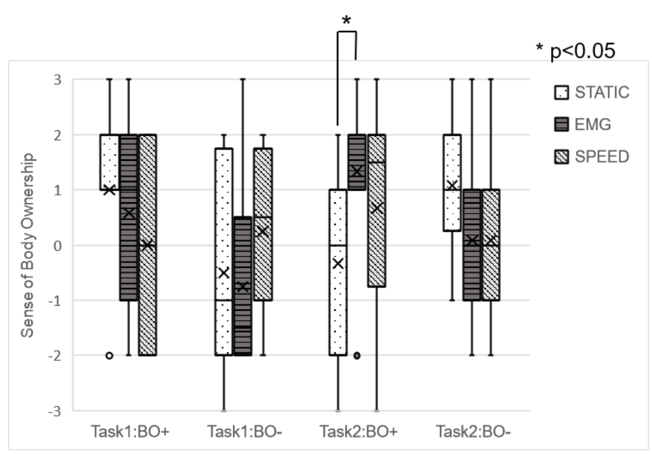

Figure 9: Results of SoBO questionnaires

5.4 Sense of Agency (SoA)

The results of the SoA questionnaires are shown in Fig. 10. After Friedman's test, Bonferroni's post hoc tests were also conducted. The results showed no significant difference between Task 1's SoA+ and SoA- and Task 2's SoA-. In Task 2's SoA+, the rating of the *EMG* condition was significantly higher than the one of the *STATIC* condition ($p < 0.05$).

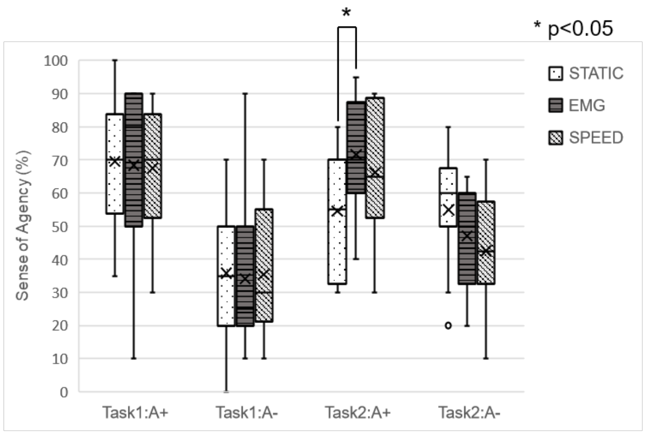

Figure 10: Results of SoA questionnaires

6 DISCUSSION

6.1 Regarding H1: SoBO and SoA

H1 was the hypothesis that a shared body with dynamic adjustment would improve SoBO and SoA. The results showed that there was no difference in the reaching task for a single object in Task 1. In contrast, for the reaching task for multiple objects with shared / non-shared targets, both SoBO and SoA were significantly higher in the *EMG* condition compared to the *STATIC* condition. The *SPEED* condition had higher values than the *STATIC* condition, although the difference was not significant. It is suggested that H1 was supported in the experimental condition in Task 2. We presume that the reaching task for non-shared targets contributed to the result, since it was not included in the Task 1, but included in Task2. In the reaching task for non-shared targets, operators had different targets. A larger movement was required to make the intended movement in the *STATIC* condition. By contrast, in the dynamic condition, the SoBO and SoA were higher because the intended movement could be directly reflected in the shared body accord with the muscle activities and movements.

6.2 Regarding H2 and H3: Task performance

In terms of task performance, in Task 1, there was no significant difference. The participants were naturally shared a target in this experiment. Even, without dynamic adjustment, the participants were able to complete tasks intuitively. H2 was the hypothesis that expect no difference in task performance between static and dynamic conditions in reaching tasks for a shared target and this was supported as an experimental result in the Task 1.

On the other hand, the *EMG* and *SPEED* conditions showed shorter time with the non-shared target condition in Task 2.Since the participants had asynchronous behaviors due to visibility of blocks in the experimental condition, *STATIC* condition showed the worst result. In contrast, the dynamic adjustments in *EMG* and *SPEED* improved task performance because one of the operators was able to reflect the intended movement to the shared body even with asynchronous behavior of the other operator. H3 was the hypothesis that expect a better performance in reaching tasks for non-shared targets under dynamic adjustments, and this was supported by the experimental result.

6.3 Dynamic Adjustment

The *EMG* condition showed shorter time than the *STATIC* condition with reaching tasks for non-shared targets in Task 2. This was because each intention could be reflected in the shared body by the intuitive action of muscle contraction. The high SUS scores suggested that the system was easy to use. We thought that dynamic adjustment by EMG would be useful in complicated collaborative work because it easily reflects individual intentions with their muscle activity.

The *SPEED* condition also had high task performance compared with the *STATIC* condition in both tasks, but there was no significant difference in subjective ratings between the other conditions. Since the operators' individual movements were directly reflected to the shared body by the speed ratio, the task performance was high. In contrast, the reason why the subjective evaluation of the *SPEED* condition did not show a significant difference compared with the *STATIC* condition might be due to the adjustment mechanism which depends on the actual movements of the participants while the *EMG* condition allows the participant to reflect their pose to the shared body just with their muscle activities even without movements.

Dynamic adjustment by *EMG* and *SPEED* can be considered effective to reflect individual behaviors of the operators in a complicated task. It may contribute to skill transfer or shard body with massive operators because it is good at reflecting large muscle activities and movements into account. Speed based adjustment allow us to make a simple implementation just with an ordinal body pose tracking system while EMG based adjustment requires an additional measurement device.

Fig. 11 indicate a sequential image with a complex task (building blocks) which expect asynchronous behaviors. Dynamic conditions can be more operable than the *STATIC* condition in such a case.

7 LIMITATION AND FUTURE WORK

The experiment was conducted with only 12 participants. By increasing the number of participants and trials, we might find more statistical significance between conditions.

In this study, we focused on dynamic adjustment techniques in shared body operations. Multi-modal communication such as conversations among operators affect their coordination and performance when it comes to working on realistic and complex tasks. Therefore, we would need to consider the interactions between operators in further investigation.

In this study, the shared body was controlled by two operators. For the future work we want to explore the shared body controlled by more than two operators. In such a condition, it will be more important to reflect the intentions of each operator through dynamic adjustments. The dynamic adjustment methods we developed were linearly dependent on the ratio of EMG and speed. It is desirable to develop a dynamic tuning method that is easier to manipulate through an intelligent parameter adjustment in accordance with the context of human augmentation.

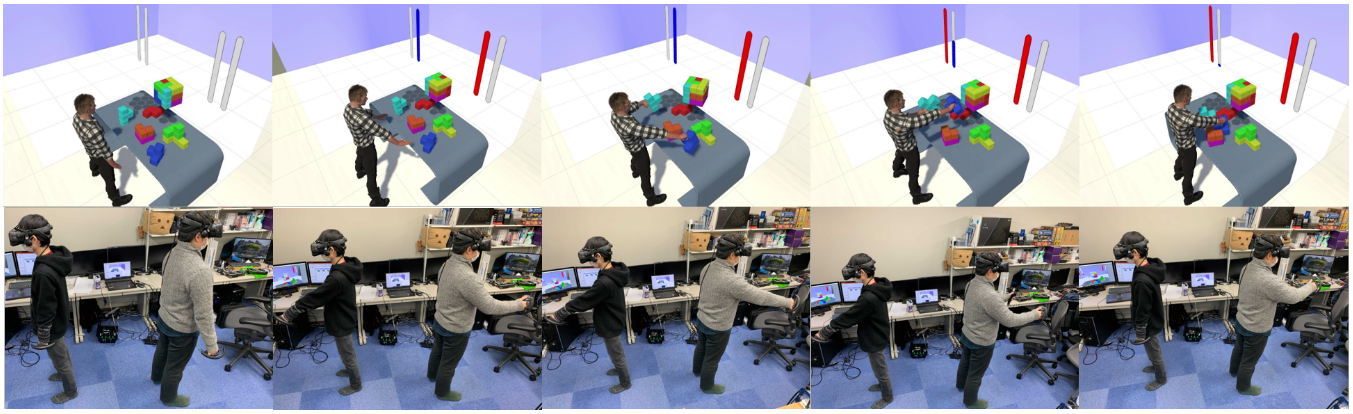

Figure 11: By using dynamic adjustment with EMG, operators can intuitively reflect motion to the shared body. It is possible to perform complex tasks even without synchronization of behaviors of the operators.

Some participants commented that the shift in perspective due to unintended movements of the shared body led to motion sickness. One solution to avoid the motion sickness is for each operator to have a perspective independent of the shared body. Although this reduces the effect of motion sickness, the SoE for the shared body will be reduced. This is an unavoidable issue in constructing a shared body system, and it is necessary to explore an ideal perspective that provides a comfortable view for all operators.

8 CONCLUSION

In this study, we investigated dynamic adjustment methods in shared body operations. We developed "*EMG*" and "*SPEED*" methods as forms of dynamic adjustment. We conducted reaching tasks with shared targets and non-shared targets and evaluated the adjustment methods in terms of task performance, SUS score, SoBO, and SoA.

For Task 1, there was no significant difference between the conditions. We found that dynamic adjustment conditions could enable non-inferior task performance relative to the static condition, even for simple tasks with shared objectives.

For Task 2, the dynamic adjustment conditions produced a better task performance than the static condition. The *EMG* condition was also better than the *STATIC* condition in terms of SUS score, SoBO, and SoA.

We expect that these results could provide useful insights to design an advanced body sharing methods with two or more operators for future investigation.

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