INTRODUCTION

Strokes are a major cause of disability worldwide. The resulting hemiparesis commonly limits the activities that can be performed during daily living. Although motor impairments in stroke patients vary, commonality exists in the aberrant patterns of movement. For example, abnormal synergy patterns are frequently observed in post-stroke patients, regardless of the size or location of the brain lesion. The flexor synergy of the upper limb is generally associated with forearm supination, elbow flexion, and shoulder flexion, whereas the extensor synergy is responsible for forearm pronation, elbow extension, and shoulder extension. Patients’ recovery patterns for regaining voluntary control of movement can be characterized using the Brunnstrom Recovery Stage (BRS). This framework suggests that there are common movement patterns in paretic extremities. A better understanding of common movement patterns can assist in the development of an effective rehabilitation program for hemiparesis.

Deficits in arm movements persist in a large population of stroke patients. In particular, abnormal synergies in the upper limb and the subsequent reduction of available workspace lead to a reduction in kinetic output. Although much attention has been given to the limited range of motion and limited reachable workspace of the paretic arm, little is known about the characteristics of paretic arm movement within this workspace. However, considering the stereo-
typic abnormal synergy patterns seen in the paretic arm, it is reasonable to assume that the decreased smoothness and coordination commonly seen in goal-directed movements performed by stroke patients exist even within the reachable workspace. In a previous study conducted by Levin that examined paretic arm movement within the reachable workspace, interjoint (shoulder–elbow) coordination was demonstrably impaired in post-stroke patients. However, whether the degree of impairment is influenced by the direction of movement has not yet been fully elucidated. In this study, by thoroughly investigating paretic and non-paretic arm movements, we demonstrated that paretic arm movement on a planar surface is impaired in a direction-specific manner. Specifically, we found that the trajectory of the paretic arm undergoes greater deflection during target-directed back-and-forth movements in the contralateral workspace than in the ipsilateral workspace. Consequently, this study advances our understanding of paretic arm movement within the reachable workspace.

**METHODS**

**Participants**

A total of 12 chronic hemiparetic patients who had experienced a stroke incident more than 6 months earlier participated in this study. Patients were excluded from the study if they had unilateral spatial neglect, apraxia, shoulder subluxation, or pain. The characteristics of the participants are further outlined in Table 1.

**Experimental Setup and Movement Tasks**

The arm movement tasks were designed based on the study conducted by Levin, with slight modifications. Subjects were seated in front of a desk on which three target stickers were attached (Fig. 1). One target sticker was located near the middle of the subject's body, 5 cm away from the proximal edge of the desk. The other two target stickers were placed 25 cm away from the first target: one at 45° and the other at −45°. The subjects positioned the forearm in the neutral position (pronation at 0°), held a ball (φ = 6.5 cm, 7 g, made of polyvinyl chloride) with a tracking marker, and performed the following back-and-forth arm movements on the planar surface: (1) diagonal arm movement, beginning from the proximal target to the target placed on the ipsilateral or contralateral side of the arm (ipsilateral and contralateral movement tasks), and (2) horizontal arm movement, beginning from the target on the ipsilateral side to that on the contralateral side (horizontal movement task). The subjects were asked to perform each back-and-forth arm movement as fast as possible five times. Patients who could not perform a seated reaching task without compensatory trunk movement were excluded. In this study, a compensatory trunk movement was defined as the trunk having crossed over the proximal edge of the desk during arm movement tasks.

**Data Acquisition**

The movement of the tracking marker was recorded at 60 frames/s with a camera (C920r, Logicool) that was set above the desk. Using motion analysis software (Kinovea 0.8.27, Kinovea), the trajectories of the tracking marker were depicted and the maximum speeds in each direction (extension and flexion) were calculated. The area covered by the trajectory and its minimum Feret diameter (hereafter referred to simply as the Feret diameter) were calculated using ImageJ (NIH) image analysis software for the ipsilateral and contralateral movement tasks (Fig. 1B and C). The area covered by the trajectory and the Feret diameter were analyzed also for the horizontal movement task. In addition, each trajectory obtained during the horizontal movement task was divided into two areas by a line extending from the middle target. We

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**Table 1. Clinical and demographic data of the subjects**

| Characteristics                                      | n  | Sex (male/female) | Age (years) | Dominant hand (left/right) | Months since stroke onset | Type of stroke (infarction/hemorrhage) | Paretic side (left/right) | Brunnstrom Recovery Stage of the arm (I/II/III/IV/V/VI) |
|------------------------------------------------------|----|-------------------|-------------|----------------------------|--------------------------|----------------------------------------|--------------------------|---------------------------------|
| n                                                    | 12 | 9/3               | 65.3±7.4    | 0/12                       | 52.1±50.7                | 6/6                                    | 8/4                      | 0/0/2/6/2/2                   |
| Data are shown as mean ± standard deviation or n.    |    |                   |             |                            |                          |                                        |                          |                                 |
analyzed the trajectory area (surrounded by the trajectory and the line) and the Feret diameter on each side (ipsilateral and contralateral areas of the horizontal movement task, Fig. 1D).

**Statistical Analysis**

The trajectory areas, Feret diameters, and movement speeds for the ipsilateral and contralateral movement tasks were subjected to two-way repeated measure analysis of variance (ANOVA) with the arm (non-paretic and paretic) and task (ipsilateral and contralateral) as within-subject factors. When interaction was detected, Sidak's multiple comparison test was performed as post hoc analysis. For the horizontal movement task, Wilcoxon's signed-rank test was used to compare the trajectory areas and Feret diameters of the paretic and non-paretic arms. Furthermore, for the ipsilateral and contralateral areas of the horizontal movement task (Fig. 1D), two-way repeated measures ANOVA was used to examine the effect of the arm (non-paretic and paretic) and side (ipsilateral and contralateral) on the trajectory area and the Feret diameter. Statistical analysis was performed using GraphPad Prism (version 8). For all statistical tests, P < 0.05 was regarded as statistically significant.

**Ethical Considerations**

This study was approved by the Research Ethics Committee of SENSTYLE group (#19–001) and performed according to the principles of the Declaration of Helsinki and its later amendments. Written informed consent was obtained from the participants before participation.

**RESULTS**

The results for the trajectory area and Feret diameter of the ipsilateral and contralateral movement tasks are presented in Fig. 2, along with representative images of the trajectories. Two-way ANOVA revealed significant interaction between arm and task for both the trajectory area (P=0.018) and Feret diameter (P=0.0007). Post hoc analysis revealed that in the non-paretic arm, no significant difference in the trajectory area or Feret diameter was observed between the ipsilateral and contralateral movements (P > 0.99; Feret diameter, P=0.85). In the paretic arm, however, the trajectory area and Feret diameter were significantly greater in the contralateral arm compared to the ipsilateral arm.
than in the ipsilateral movements (area, P=0.0045; Feret diameter, P <0.0001; Fig. 2B and C).

**Figure 3A** shows representative examples of time courses of the tracking marker speed for non-paretic and paretic arms during the ipsilateral and contralateral diagonal movements. The maximum speed of the tracking marker in both directions (extension and flexion) was identified. For the maximum speed of extension, arm and task were both revealed to have major effects (arm, P=0.011; task, P <0.0001). For the maximum speed of flexion, task had a significant effect but not arm (arm, P=0.090; task, P <0.0001). In both directions, extension and flexion, the interaction between arm and task was not significant (extension, P=0.62; flexion, P=0.43).

In the horizontal task, the trajectory area and Feret diameter were significantly greater in the paretic arm than in the non-paretic arm (area, P=0.0010; Feret diameter, P=0.0021; Fig. 4A and B). Regarding the ipsilateral and contralateral areas of the horizontal movement task (**Fig. 1D**), two-way ANOVA revealed that arm had a significant effect of arm (area, P=0.0011; Feret diameter, P=0.0005) but not side (area, P=0.057; Feret diameter, P=0.67). No significant interaction between arm and side was found (area, P=0.084; Feret diameter, P=0.36).
Fig. 3. Analysis and comparison of the maximum speeds during ipsilateral and contralateral diagonal movements. (A) Examples of time courses of ipsilateral and contralateral diagonal movement speeds for the paretic and non-paretic arms. Black arrows show the maximum speed during each extension, and open white arrows show the maximum speed during each flexion. The maximum speed in each direction during the whole task is shown with green rectangles. (B) The maximum speed during extension and (C) the maximum speed during flexion were compared for tasks (ipsilateral and contralateral) and arms (non-paretic and paretic). Data plots obtained from the same arm are connected by a line. The asterisks indicate statistical significance: n.s. indicates P >0.05; * P <0.05; **** P <0.0001.
DISCUSSION

In this study, we aimed to identify common movement patterns in post-stroke patients and showed direction-specific movement disruption in the paretic arm within the reachable workspace of stroke patients. Specifically, reaching movement toward the contralateral side of the arm was significantly disrupted compared with movement toward the ipsilateral side in the paretic (but not in the non-paretic) arm. This investigation not only generated data on how far the paretic arm is able to reach, but our findings also indicated that the quality of movement in different directions must be considered when evaluating the paretic arm during rehabilitation.

Direction-specific movement disruption in stroke patients was previously speculated upon in a study by Levin in which extension reaching movements (not back and forth) were performed by ten hemiparetic subjects. In that study, Levin found a significant difference in the movement of the paretic and non-paretic arms. However, no significant differences were reported between ipsilateral and contralateral arm movements, although the average values did appear to be different (Fig. 4 in Levin’s study). Consequently, Levin attributed the apparent difference to the large variability between subjects. In the current study, we changed the movement task to a series of fast back-and-forth movements and detected deflection that may have been caused by instability in arm movement. The difference in our findings compared with those of Levin may be the result of the decreased variety of movement strategies used in our movement trials.

One possible cause of direction-specific disruption in the paretic arm is the demand of a particular combination of joint movement patterns. Briefly, in contralateral movement, a combination of shoulder horizontal flexion and elbow extension is required, whereas in ipsilateral movement, a combination of shoulder lateral rotation and elbow extension is required. Difficulty in movement, therefore, might be affected by these combinations. In concordance with our results, Levin demonstrated that the elbow joint angle in the paretic arm is disrupted in contralateral movement but not in ipsilateral movement. Further work is required to elucidate the conditions under which paretic arm movements are disrupted. Nonetheless, our research will serve as a basis for future studies on the common characteristics of paretic arm movement.

Whereas trajectory disruption in the paretic arm was greater for contralateral movements, the maximum arm speed was greater in the ipsilateral than in the contralateral movement tasks for both arms. This finding indicates that motor functions (trajectory and speed in the current study) are not always equally impaired in the paretic arm. Speed differences between the directions were also observed in our pilot study with young healthy subjects (data not shown). Another study with healthy subjects has also demonstrated a lower peak velocity in pointing movement toward contralateral targets. Consequently, it can be speculated that contralateral movement is kinematically more difficult than ipsilateral movement. Because the speed and accuracy of movement have a trade-off relationship, slower movement speeds could increase the stability of the trajectory. In the paretic arm, however, the movement trajectory was disrupted at a slower speed in the contralateral than in the ipsilateral movement task, further supporting the hypothesis that there is direction-specific movement disruption in the paretic arm.

Because the contralateral target is far from the shoulder joint of the task-performing arm, the accuracy of arm movement may depend on the distance from the shoulder joint. To clarify this issue, we divided the trajectory area obtained during the horizontal movement task into two areas by a line extending from the middle target, and compared the horizontal arm movements between these two areas. As a result, we found no difference in the trajectory area or Feret diameter between the workspaces on the ipsilateral side (closer to the shoulder joint) and on the contralateral side (further from the shoulder joint). Therefore, it appears that paretic arm movement is disrupted in a movement direction-specific manner and not in a workspace-specific manner. However, in this study, the horizontal trajectories were analyzed only by splitting the series of movements. More sophisticated investigations may be necessary.

Overall, our data imply that there is direction-specific disruption in the paretic arm within the reachable workspace. However, some limitations of the current study should be noted. First, our sample size was limited to 12 participants, and a larger sample may have strengthened our results. Second, the precise lesion sites were unknown because of the time that had elapsed from stroke onset and the limitation and regulation of our facility providing only self-pay rehabilitation services (i.e., not covered by health insurance). Consequently, there was no direct access to patient medical information. Although our results identified characteristics of paretic arms with statistical significance, we cannot completely deny the possibility that differences in the lesion site could have influenced our results. Finally, this was not a longitudinal study, and therefore, it is unknown whether...
the disruption we revealed can be ameliorated during the recovery process. In contrast to Levin’s study, we were able to detect direction-specific movement disruption in the paretic arm. Even subjects who were ranked as BRS VI demonstrated significant disruption in movement toward the contralateral side when using the paretic arm. It is not surprising, however, that direction-specific movement disruption in the paretic arm persists over a long period. Because the contralateral workspace for the paretic arm is ipsilateral workspace for the non-paretic arm, the paretic arm is used less for reaching toward the contralateral side. This could be the cause of learned non-use of the paretic arm that often develops in chronic stroke patients. A rehabilitation program that involves handling objects in, or reaching toward, the contralateral workspace might alleviate the progress of direction-specific impairment.
CONCLUSION

The present study indicates that the paretic arm in post-stroke patients has direction-specific instability during movement to the contralateral side of the arm. The quality of movement within the reachable workspace may be improved not only by extending the reaching distance but also by improving the movement trajectory.

ACKNOWLEDGMENTS

This work was supported in part by the Higo Foundation for Promotion of Medical Education and Research. The authors thank Sae Nishimura, Kana Nitta, and Takato Hidaka (Kumamoto Center, Rehabilitation Center for all Customers with Stroke and Cerebrovascular Diseases) for their help in conducting this study.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

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