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Design of a Brain Motor Control Ability Assessment System Using a Portable Tablet PC

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Abstract

We developed and validated a portable tablet-based system to assess brain motor control abilities by engaging participants in a manual tracking task with both visible and invisible targets, thereby eliciting feedback and feedforward control mechanisms. We measured the accuracy of these mechanisms using error terms, comparing 1) the performance of the dominant and non-dominant hands and 2) the intervals of feedback and feedforward control. We showed that the dominant hand demonstrated greater accuracy than the non-dominant hand, particularly when tracking a faster-moving visible target. Furthermore, the non-dominant hand transitioned from feedback to feedforward control at a slower target speed compared to the dominant hand. This suggests differential motor control processing between hands. We present this tablet-based system as an accessible and versatile tool for assessing feedback and feedforward control during target tracking tasks, based on feedback-error learning theory. It enables efficient analysis of motor development in children, motor decline in older adults, and stroke rehabilitation outcomes from a brain motor control perspective.

Keywords: *Portable Tablet PC, Target Tracking Movement, Motor Functions, Feedback Control, Feedforward Control*

1. Introduction

The ability to control and coordinate movements improves during childhood and declines with age, especially in individuals affected by neurodegenerative conditions like Parkinson's disease (PD) or those recovering from a stroke. Quantifying motor function is crucial for understanding motor development in children, monitoring motor decline in older adults, detecting early signs of neurological disorders, and

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assessing the effectiveness of treatments designed to mitigate motor impairments. Over the past few decades, quantitative assessment systems for the upper limb have primarily adopted manual tracking tasks, including numerous systems have been developed to quantitatively assess upper limb motor function. Some systems analyzed motor control abilities, feedback (FB) and feedforward (FF) mechanisms individually, which are key to understanding brain-motor interactions.

Traditionally, these assessment systems have relied on complex setups that capture upper limb movements in one dimension (1D) or two dimension (2D), such as sinusoidal or ramp trajectories, using apparatuses like manipulanda or computer mice. For example, Miall reported a manual tracking task that involved a sinusoidal target trajectory [1, 2]. Additionally, there are several kinds of environments for assessment, such as a target with a 1D ramp trajectory for an elbow joint assessment, and using a computer mouse or two-degree-of-freedom manipulandum to pursue a target moving on a 2D plane [3-5]. Recently, an assessment system has been suggested that exploits a virtual reality apparatus to measure natural movement in a three-dimensional space [6-8]. However, despite their significant advantages in capturing realistic movement patterns, these systems often require expensive equipment and the assistance of trained professionals, making them less accessible for widespread use in clinical or everyday settings.

Given these limitations, there is a growing need for more portable, cost-effective alternatives that can still provide robust assessments of motor control abilities. In response to this need, we need to develop a novel system that leverages a tablet personal computer (tablet PC) equipped with a touch panel to perform motor function assessments. This portable, user-friendly system enables the execution of manual tracking tasks without the need for specialized equipment or professional supervision, making it accessible for use in a variety of settings. By manipulating the visibility of a target on the tablet, our system is capable of assessing both FB control (when the target is visible) and FF control (when the target is hidden), thus allowing for a comprehensive evaluation of motor control mechanisms.

Therefore, in this study, we suggest a motor function assessment system that adopts a tablet PC with a touch panel, allowing us to perform the chosen task with ease, at any convenient location. Our developed system enables us to perform a manual task on a tablet PC to assess motor function in terms of FB and FF controls, by manipulating the visibility of a target. We evaluated our system through comparisons 1) between the dominant and non-dominant hand and 2) between a FB interval and FF interval.

2. Methods

2.1 Apparatus and Environment for Quantitative Motor Function Assessment

We designed a motor function assessment paradigm based on a tablet PC. As shown in Figure 1(a), the hardware system included a tablet PC and a Mixoo stylus pen that allowed users to perform a task requiring them to track a target on screen.

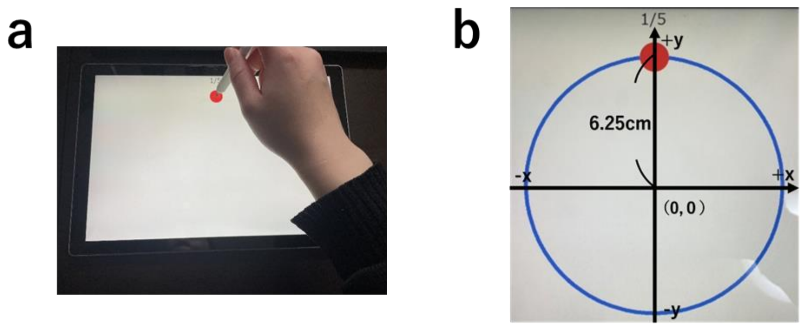

Figure 1. Brain motor control ability assessment system using a portable tablet PC. (a) Apparatus used. (b) Target and its trajectory in the task.

As shown in Figure 1(b), we set the midpoint on screen as the origin in a coordinate system with the x-axis indicating the lateral direction and the y-axis the vertical direction. In our paradigm, a participant moved the pen, whose tip had a diameter of 0.7 cm, to track a red target with a diameter of 1.5 cm that drew a blue circle with a diameter of 12.5 cm. In this study, we used a Surface pro 7 (QWF-0006) to perform the task, which featured a 12.3-inch screen with a resolution of 2736 x 1824.

2.2 Participants

Fourteen individuals (9 females and 5 males; mean age 21.9 years) performed the task, after providing written informed consent. Table 1 shows the demographic information of participants.

Table 1. Demographic information of participants

Participant index	Age	Sex	Handedness
1	21	F	Right
2	21	F	Right
3	21	F	Right
4	21	F	Right
5	21	M	Right
6	21	M	Right
7	23	F	Right
8	22	F	Right
9	21	F	Right
10	21	F	Right
11	21	M	Right
12	21	M	Right
13	22	F	Right
14	30	M	Right

Handedness was judged by the Edinburgh Handedness Inventory [9]. All participants were right-handed. The experimental protocol was approved by the IRB of Komatsu University and the experiment was conducted in accordance with the Declaration of Helsinki.

2.3 Task Description

We conducted a manual tracking experiment to validate our suggested system that quantitatively assesses motor function from a motor control perspective. Before the experiment, the participant sat on a chair at a desk to perform the tracking task with a stylus pen. The participant saw the red target, whose trajectory was invisible, unlike in Figure 1B. In the beginning of the experiment, the participant placed the pen (tracer) on the target, which was motionless in the upper part of the screen, as shown in Figure 1. After a cue, the target began to move at a constant speed, following the invisible trajectory in a clockwise direction for right-handed people (see Figure 2a) or in a counterclockwise direction for left-handed people (see Figure 2b). The participant was instructed to track the target by moving the tracer of the stylus pen.

The task was comprised of two phases: a training (TR) phase for the first two rotations, during which the target was always visible, as shown in Figure 2, and a test (TE) phase for the subsequent two rotations, during which the target was invisible in the first and third quadrant and visible in the second and fourth quadrant for right-handed people, as shown in Figure 2a, or the target was invisible in the second and fourth quadrant and visible in the first and third quadrant for left-handed people, as shown in Figure 2b.

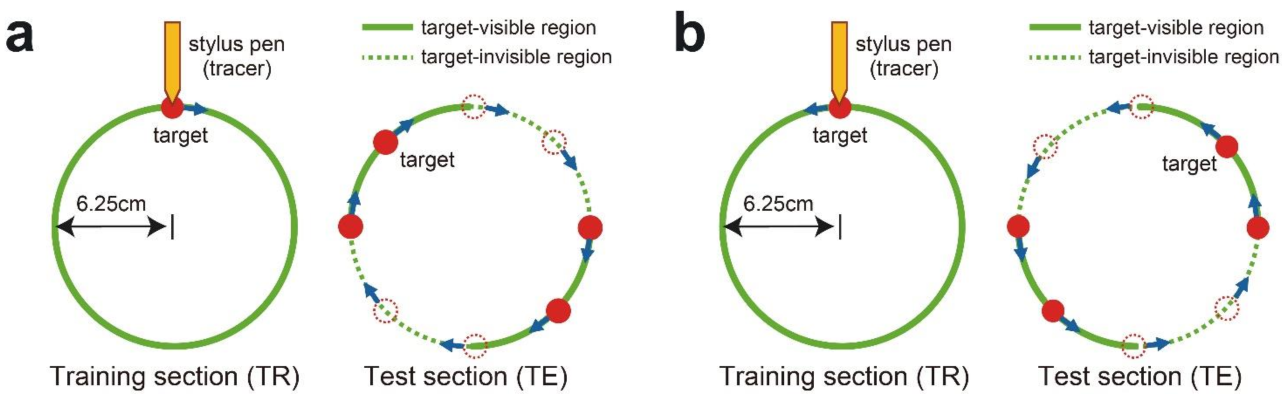

Figure 2. Trajectory of the target and tracer in the task. (a) The left panel represents the trajectory in the FB control interval for right-handed people, whereas the right panel represents the trajectory in the FF control interval for right-handed people. (b) The left panel represents the trajectory in the FB control interval for left-handed people, whereas the right panel represents the trajectory in the FF control interval for left-handed people.

Henceforth, we denote the training section as the FB control interval as it was intended to induce FB control, which acts to reduce the difference in position between the target and tracer. We denote the test section as the FF control interval as it was intended to induce FF control, which is used to predict the position of the invisible target. A trial involved the two rotations of the FB control interval and the other two rotations of the FF control interval. There were three speeds used in the experiment: 0.125 Hz (called speed 1, tangential speed: 0.049 m/s), 0.25 Hz (called speed 2, tangential speed: 0.098 m/s), and 0.5 Hz (called speed 3, tangential speed: 0.195 m/s). For each speed, five trials were performed; the first two trials were used for rehearsal and were omitted from analysis. The participants were asked to perform the task with both hands, in randomized order. In total, each participant conducted the task 30 times.

2.4 Performance Evaluation

During the task, the coordinates of the stylus pen (tracer) on the horizontal and vertical axes of the screen were recorded at a sampling rate of 60 Hz. We defined positional error as follows:

$$Error\ [mm] = \sqrt{(T_x - P_x)^2 + (T_y - P_y)^2} \quad (1)$$

where Tx [mm] and Ty [mm] represent the target's horizontal and vertical coordinates in the screen, respectively. Also, Px [mm] and Py [mm] represent the tracer's horizontal and vertical coordinates in the screen, respectively. We evaluated performance in the aforementioned conditions using this error parameter. To assess the statistical significance of differences in the data, we used the Wilcoxon signed rank test for paired observations and the Mann-Whitney U-test for independent observations.

3. Results

Figure 3 shows typical examples of the trajectory traced by the dominant hand (a1, b1, and c1) and non-dominant hand (a2, b2, and c2). Each row represents the three speeds (a: Speed 1, b: Speed 2, and c: Speed 3).

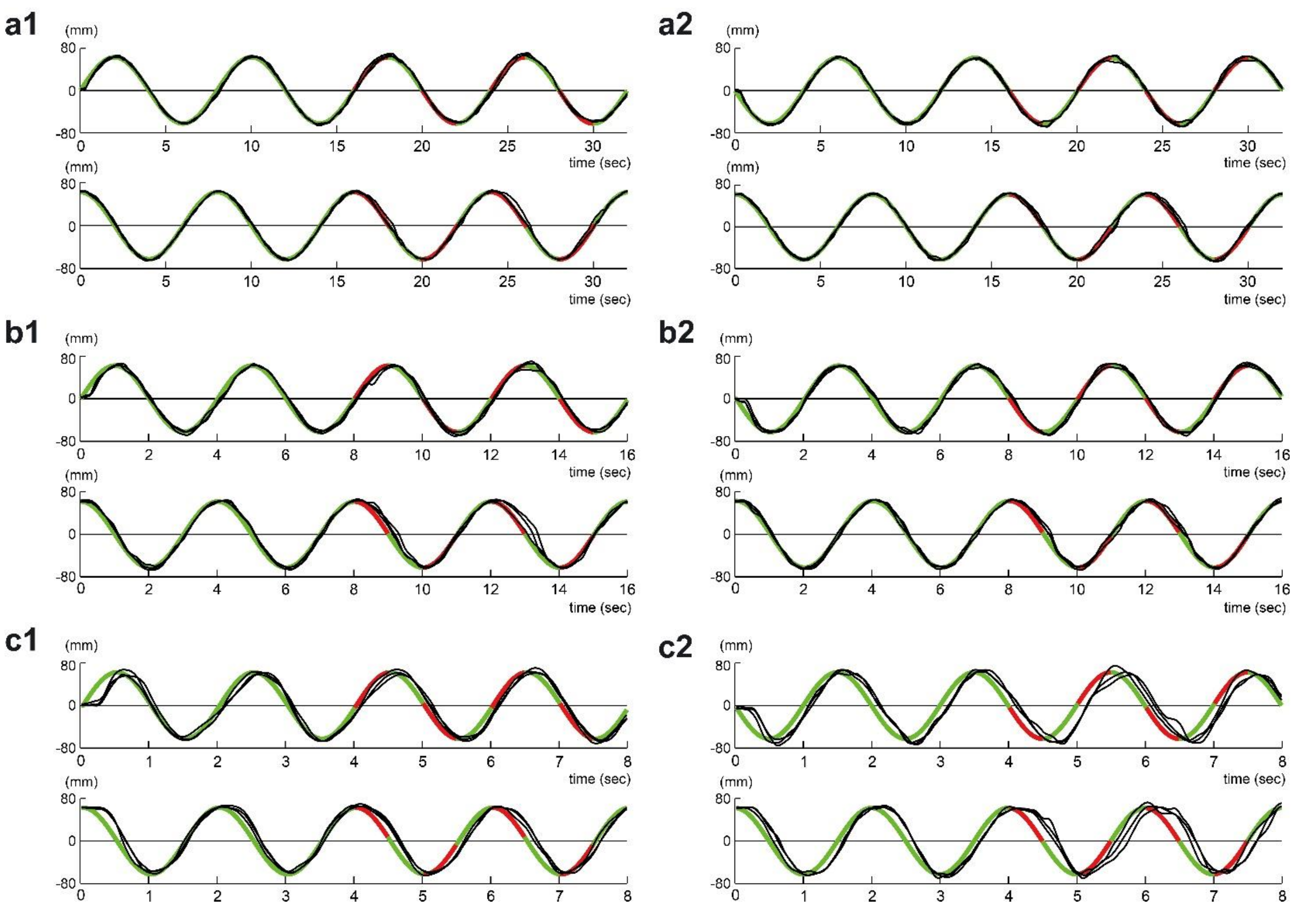

Figure 3. Examples of tracking movement in the experimental paradigm. The left column (a1, b1, and c1) represents trajectories traced by the dominant hand, and the right column (a2, b2, and c3) represents those traced by the non-dominant hand at the three speeds: (a) Speed 1, (b) Speed 2, and (c) Speed 3. The black line represents the tracer's movement, and the green line represents the target's movement when visible while the red line represents the trajectory of the target when invisible.

In both dominant and non-dominant hand conditions, the faster the target speed, the greater the extent to which the movement varied during both FF and FB intervals. In addition, the dominant hand outperformed the non-dominant hand especially at the Speed 3, regardless of the visibility of the target.

3.1 Comparison between the Dominant and Non-dominant Hand

Figure 4 shows the comparison between the dominant and non-dominant hand at the three speeds in the FB control interval (Figure 4a) and the FF control interval (Figure 4b).

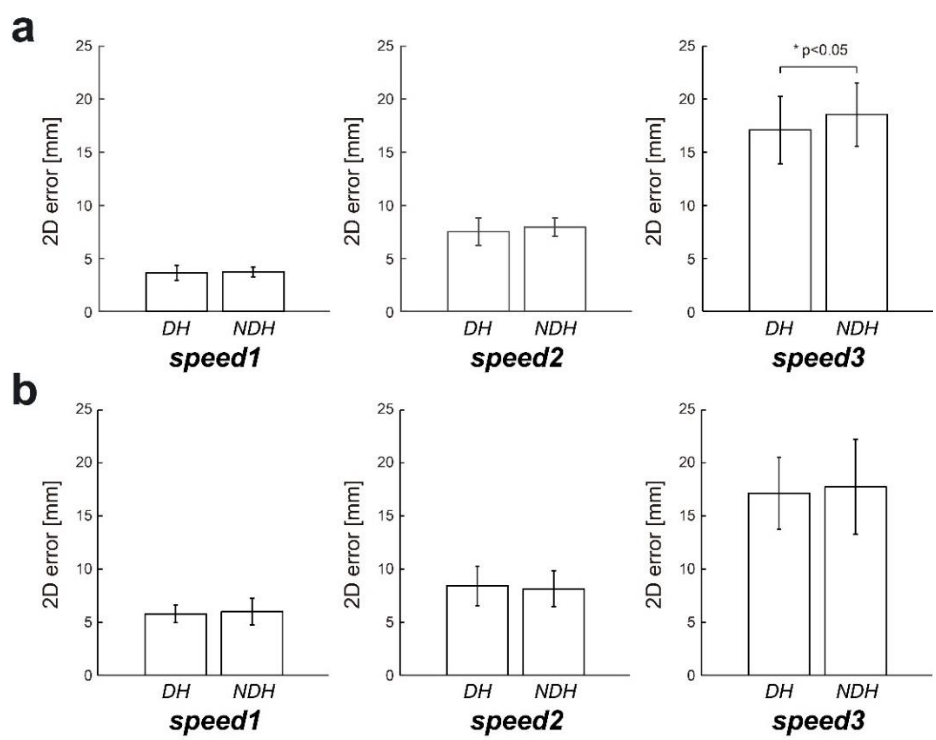

Figure 4. Comparison between the dominant hand (DH) and non-dominant hand (NDH) for the three speeds. Each column represents Speed 1, Speed 2, and Speed 3, and each row represents (a) the FB control interval and (b) the FF control interval.

Table 2 shows a summary of the comparison. As shown in Figure 4 and Table 2, we found a significant difference only in the FB interval at Speed 3 ($p < 0.05$), indicating that the dominant hand outperformed the non-dominant hand in FB control. The other comparisons did not exhibit any significant differences.

Table 2. Assessment of performance, comparing handedness for the three speeds (Mean ± SD).

	Speed 1		Speed 2		Speed 3	
	Dominant hand	Non-dominant hand	Dominant hand	Non-dominant hand	Dominant hand	Non-dominant hand
FB control interval	3.63 ± 0.7	3.73 ± 0.5	7.52 ± 1.3	7.94 ± 0.9	17.1 ± 3.2	18.6 ± 3.0

P-value	0.470		0.124		* 0.016	
FF control interval	5.78 ± 0.8	5.99 ± 1.3	8.43 ± 1.9	8.14 ± 1.7	17.2 ± 3.4	17.8 ± 4.5
P-value	0.397		0.433		0.638	

* p < 0.05 (Wilcoxon signed-rank test)

3.2 Comparison between the Dominant and Non-dominant Hand

Figure 5 shows the comparison between the FB control and FF control at the three speeds, as performed by the dominant hand (Figure 5a) and the non-dominant hand (Figure 5b).

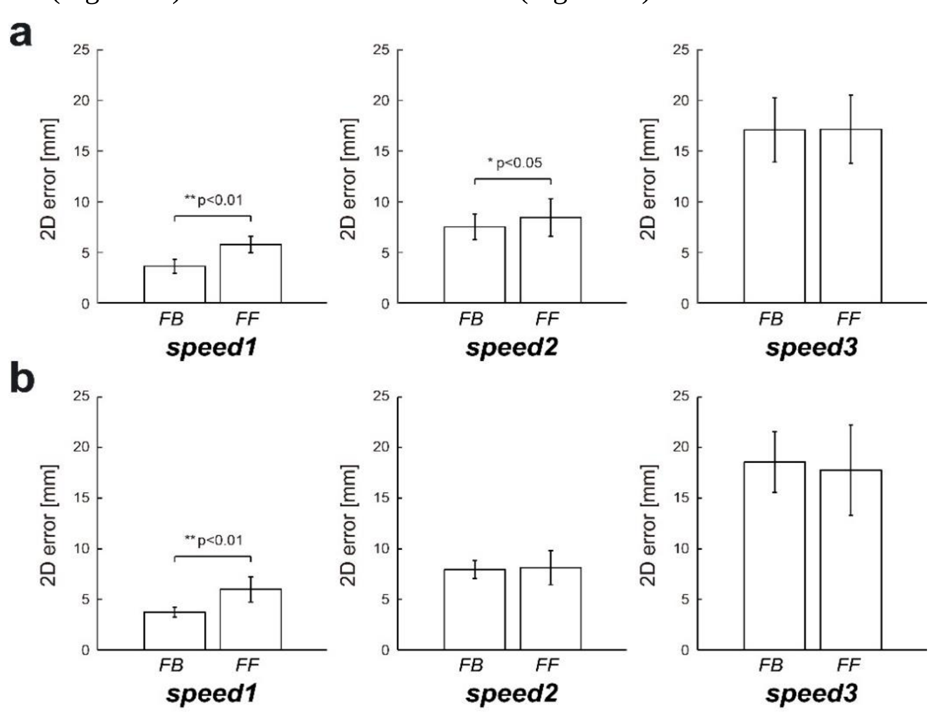

Figure 5. Comparison between FB control and FF control at three speeds. Each column represents Speed 1, Speed 2, and Speed 3, and each row represents the performance by (a) the dominant hand and (b) the non-dominant hand.

Table 3 shows a summary of the comparison. As shown in Figure 5 and Table 3, for the dominant hand, we observed significant differences for Speed 1 and 2, indicating that FB control performance was better than that of FF control. Moreover, the lower the speed, the greater the difference. For the non-dominant hand, we found a significant difference only for Speed 1, whereby FB control performance was better than FF control performance.

Table 3. Assessment of performance, comparing two types of motor control at three speeds (Mean ± SD).

	Speed 1		Speed 2		Speed 3	
	FB control interval	FF control interval	FB control interval	FF control interval	FB control interval	FF control interval
Dominant	3.63 ± 0.7	5.78 ± 0.8	7.52 ± 1.3	8.43 ± 1.9	17.1 ± 3.2	17.2 ± 3.4

hand						
P-value	** 0.001		0.124		0.778	
Non-dominant hand	3.73 ± 0.5	5.99 ± 1.3	7.94 ± 0.9	8.14 ± 1.7	18.6 ± 3.0	17.8 ± 4.5
P-value	** 0.001		0.433		0.140	

* p < 0.05, ** p<0.01 (Wilcoxon signed-rank test)

4. Discussion

In the following, we will discuss two aspects of the system: 1) the development of the quantitative system and its clinical applicability and 2) the difference in motor function performance between the dominant and non-dominant side.

4.1 The Development of the Quantitative System and Its Clinical Applicability

In this study, we developed a motor function assessment system with the mobility advantages of a cell phone or tablet computer, which can be used in daily life at any time, without the need for support by a developer or expert. Previously, a small number of motor function assessment systems have adopted touch screen panels. Yamaguchi et al. developed an upper limb motor function assessment system for patients with PD that utilized a tablet and stylus pen that can sense pen pressure [10]. In addition, Tokunaga et al. used an iPad in their system, which evaluates motor coordination in ataxia and correlates their indicator with a clinical index [11]. However, these systems focused only on evaluating the movement performance itself, regardless of the relationships between motor function and brain mechanisms, especially in terms of FB and FF controls, which are essential factors in motor control. However, our system adopted a visual-guided tracking task, which enabled us to independently evaluate FB the FF control by manipulating the visibility of the target during the task. That is, our system can quantitatively evaluate motor control capability in terms of the brain's control strategies. In particular, this manual tracking task was inspired by motor learning in the cerebellum and internal models based on FB error learning theory [12, 13]. In addition, by virtue of its uniform circular motion, which was utilized in our previous study, the present paradigm can also analyze the cerebellum's internal model and motor learning [5]. Furthermore, as our system adopted a tablet PC with high accessibility and focused on assessment in terms of motor functions that the brain actually processes, we expect the system to be utilized for efficient rehabilitation of patients following stroke.

4.2 Differences in Motor Function Performance between the Dominant and Non-dominant Side

Many previous studies that compared the dominant and non-dominant upper limb used a task that required multi-joint movement, such as a reaching task, a tapping task, or tracking task [14-16]. These studies reported that the dominant hand side exhibited greater manual dexterity than that of the non-dominant side. However, this difference by handedness was vulnerable to the required motion and task difficulty; these factors could attenuate or even negate the difference between sides. For instance, it was reported that the difference between the dominant and non-dominant hand was not significant in a grasping task, a simple drawing task, and a postural task when given a perturbation whose magnitude was similar to a background muscle activity [17-19]. The task in the present study successfully showed that performance was much better for the dominant arm in the FB interval than the non-dominant arm as the speed increased (see Figure 4a). However, when the target was not visible, requiring predictive control, the difference between sides was not significant as the speed increased (see Figure 4b). This is interpreted as performance with each arm during the FF interval using the same internal model that was learned during the FB intervals. In contrast, in circular tracking tasks, both FB and predictive control work efficiently to predict target trajectory [5, 20]. However, the faster the target moves, the more FF works because sensory information cannot be processed as fast as required, with the result that FB control cannot be utilized for tracking movement [21, 22]. That is, FB control based on position information that exhibits high accuracy is primarily used for slow targets, whereas FF control with poor accuracy based on speed information is primarily used for pursuing fast targets [1, 2]. The present study also revealed the same result. As shown in the left column of Figure 5a and 5b, the difference between the FF and FB control was significant as feedback control suitable for a slow target was primarily used with better accuracy. However, as the speed of the target increased, movement by FF control was observed with worse accuracy because of limited sensory information processing within the brain. Consequently, as shown in the right column of Figure 5a and 5b, when the target moved at the fastest speed we assessed, FB and FF controls did not differ in accuracy, suggesting that the proportion of FB control needed to perform the task at this speed is similar to that of FF control. This also implies that our paradigm can reveal a transition in the control method adopted in the brain from FB control to FF control. Considering the difference between the dominant and non-dominant hand based on this interpretation, Figure 5 reveals a transition in the control method varied depending on handedness. As the non-dominant arm was less accurate than the dominant arm when using FB, FF control was used for the faster targets.

In further studies, our system could be used to observe a shift in children's development of motor processing to understand how the mechanisms of motor control depend on handedness [23]. Likewise, motion tracking by older persons could be investigated to elucidate the mechanisms by which motor function degrades depending on handedness.

5. Conclusion

In this study, we proposed a motor function assessment system using a tablet PC. We employed a manual tracking task to independently assess FF and FB control, confirming the feasibility of our system by evaluating the effects of three different tracking speeds and the differences between the dominant and non-dominant hand from a motor control perspective (i.e., FF and FB control). We found that the dominant hand was more accurate than the non-dominant hand when the visible target moved at a higher speed. Additionally, we observed that, as the speed of the target increased, the non-dominant hand transitioned from FB control to FF control at a slower speed compared to the dominant hand.

Finally, we demonstrated that our tablet-based system provides an accessible and versatile tool for assessing FB and FF controls during a target tracking task, grounded in the FB-error learning theory [12]. In further studies, we believe our system enables easy analysis of motor development in children, motor decline in older adults, and stroke rehabilitation outcomes, particularly in terms of motor control and motor learning [24].

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