Original Article

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Relationship between prediction-based motor control during loading task and motor learning during lever-pressing task

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Abstract

Motor performance depends on feedback and feedforward motor control systems, and can be improved through learning processes. According to the "feedback error learning" model, the feedback of error signals improves "internal models" and refines the feedforward motor control. Thus, feedforward motor control plays a key role in improving motor performance.

Feedforward motor control has been evaluated by measuring predictive components of movement in several tasks, including ball-catching, grasping, and weight-loading tasks. In the loading task, hand movement just before the start of loading (anticipatory response) is observed only when the timing of loading is predictable. Thus, this anticipatory response is assumed to reflect prediction-based feedforward motor control. On the other hand, a multi-lever-pressing task has been used to evaluate motor performance and its improvement by analyzing accelerometer signals. Correlation coefficients of accelerometer signals have been reported to increase with the number of trials, indicating that this measure can be used as an index of motor learning.

In the present study, we examined the relationship between feedforward motor control and motor learning in 18 healthy volunteers using anticipatory responses in a loading task and correlation coefficients of accelerometer signals in a three-lever-pressing task. For the loading task, we used the Space Interface Device for Artificial Reality (SPIDAR). The subject was asked to hold the ball-shaped grip of SPIDAR. When the subject pressed the start button, a force of 4.9 N was applied to the grip. The subject was instructed to maintain the initial position during loading. The loading task was repeated 10 times, and the amplitude of upward deflection (anticipatory response) just before the start of loading was measured. In the three-lever-pressing task, the subject was instructed to press three levers as rapidly as possible using the left hand (hand), the left hand loaded with a weight (weight), and a stick attached to the left hand (stick). The three-lever-pressing task was repeated 11 times in sequence under each condition (hand, weight, stick). The hand movement was monitored using an accelerometer attached to the dorsal surface of the left hand. We found that correlation coefficients of accelerometer signals were lower in the stick condition than in the other two conditions, indicating that the stick variation of the task requires more learning. We also found that the amplitude of anticipatory response was correlated with the correlation coefficients of accelerometer signals only in case of the stick variation. These results provide evidence for a relationship between prediction-based feedforward motor control and motor learning.

KEY WORDS

feedforward motor control , motor learning , anticipatory response , loading task , lever pressing task

Introduction

Motor performance depends on feedback and feedforward motor control systems, and can be improved through the learning process [1]. A better understanding of

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neural mechanisms underlying motor control and motor learning can have important clinical implications. One of the basal models for motor learning is the "feedback error learning" scheme. In this scheme, the feedback of error signal improves "internal models," thereby refining the feedforward motor control. Thus, the feedforward motor control plays a key role in improving motor performance [2].

Feedforward motor control has been evaluated by measuring predictive components of movement. When catching a falling ball, for example, we predict the weight of the ball and the timing of contact, and generate motor command before the ball strikes the hand [3]. In a grasping task, we predict the timing of perturbation, and increase the finger force before self-generated perturbation [4, 5]. These predictive components of movements have been reported to be sensitive to cerebellar dysfunction [4, 6], which is consistent with the hypothesis that the cerebellum plays a key role in feedforward motor control [7].

In a previous study in our laboratory, the predictive component of hand movements (anticipatory responses) during a weight-loading task was compared between healthy volunteers and patients with schizophrenia [8]. It was found that the amplitude of anticipatory responses was significantly smaller in the patients than in the healthy controls, indicating that the feedforward motor control is impaired in schizophrenia. In that study, it was also found that there was great individual variability in the amplitude of anticipatory responses even in healthy controls. What is the functional significance of this individual variability? If the anticipatory response reflects the feedforward motor control and it is important in motor learning, it is possible that the person with larger anticipatory responses shows better performance on motor learning tasks.

To test this possibility, we examined the relationship between anticipatory responses in the loading task and motor performance on a lever pressing task for 18 healthy volunteers. In the lever pressing task, the subject was instructed to press three levers as rapidly as possible, by using the left hand (hand), the left hand loaded with weight (weight), and a stick attached to the left hand (stick). The three-lever pressing was repeated, and the hand movement was monitored by the accelerometer attached to the dorsal surface of the left hand. Correlation coefficients of accelerometer signals, which have been reported to increase with increased number of trials [9], were used as an index of motor learning. We found that the correlation coefficients of accelerometer signals were lower in the stick condition than in the other two conditions, and were correlated with the amplitude of anticipatory responses in the loading task. These results suggest that the individual difference of prediction-based feedforward motor control can explain partially the individual difference of motor learning.

Methods

1. Subjects

This study was approved by the Medical Ethics Committee of Kanazawa University (No. 740) and was performed according to the Declaration of Helsinki. Informed consent was obtained from 18 healthy young volunteers (20-22 years). The subjects were all right-handed female students in the Occupational Therapy Course of Kanazawa University.

2. Predictable loading task

Figure 1 shows experimental set-up and procedures used for loading task. To apply a downward force to the left hand (loading) and monitor the vertical deflection of the hand, we used the Space Interface Device for Artificial Reality (SPIDAR)[10], which consists of eight motors and strings attached to the grip (Fig. 1A). The subject was comfortably seated with the left elbow on an arm rest, and asked to hold a ball-shaped grip of SPIDAR near the center of the apparatus. When the subject pressed a start button, a force of 4.9 N was applied to the grip (equivalent to loading of 500 g weight) (Fig. 1B). When the subject pressed the button again, the force was released. The subject was instructed to keep the initial position during loading. The vertical movement of the grip was displayed on a computer screen (Fig. 1B, ball), and the vertical deflection from the initial position was recorded by SPIDAR. The loading task was repeated 10 times, and the data acquired between the sixth and the tenth loading trials were used for analysis [8].

3. Lever pressing

Figure 2 shows experimental set-up and procedures used for lever pressing. The subject was seated in front of three levers (A-C). The left (A), center (B) and right (C) levers were positioned as shown in Figure 2A, and the B-lever was set 17.5 cm higher than the other two levers. The subject was instructed to press three levers in the order of A-B-C as rapidly as possible, by using the left hand (hand), the left hand loaded with weight (weight), and a stick attached to the left hand (stick)

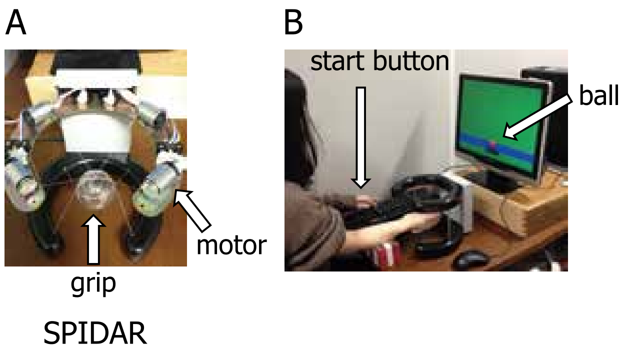

Figure 1. Experimental set-up for loading task. A: A photograph of SPIDAR, which consists of eight motors and strings attached to a ball-shaped grip. B: Loading starts when a start button is pressed by the subject. The vertical movement of the grip is displayed on a computer screen.

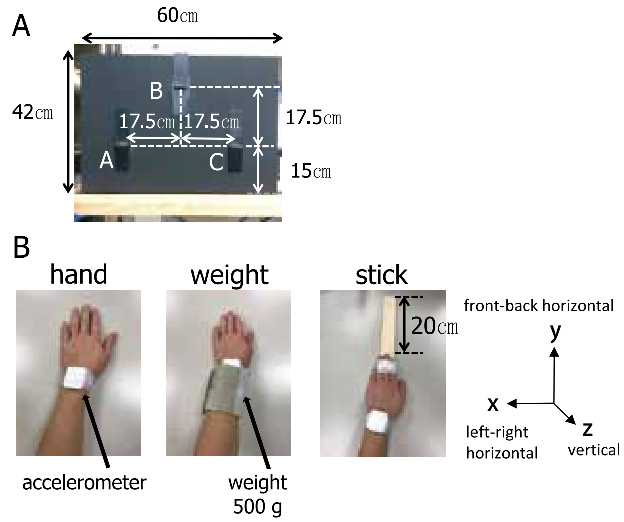

Figure 2. Experimental set-up for lever pressing task. A: A photograph of three levers (A, B, C). The B-lever is set 17.5 cm higher than the other two levers. B: The subject was asked to press three levers in the order of A-B-C using the left hand (hand), the left hand loaded with weight (weight), and a stick attached to the left hand (stick).

(Fig. 2B). The three-lever pressing was repeated 11 times in sequence under each condition (hand, weight, or stick), and the data acquired between the first and the tenth trials were used for analysis. We expected that the weight would affect vertical movements of the hand, whereas using the stick would disturb movements in all directions. The weight 500 g in the weight condition, the extension length 20 cm in the stick condition (Fig. 2B), and the trial number 11 were decided based on the results of preliminary experiments. All subjects performed the task under these three conditions in the order of hand, weight, and stick. The lever signal was recorded by Vital Recorder II (Kissei Comtec Co., Ltd., Matsumoto, Japan) installed in a personal computer. Hand movement of the subject was monitored by an accelerometer (WAA-006, ATR-Promotions. Inc., Kyoto, Japan) attached to the dorsal surface of the left hand. Accelerometer signal was recorded at a sampling frequency of 200 Hz by Accel Real Time 2 (ATR-Promotions. Inc., Kyoto, Japan).

4. Data analysis

Results are presented as means ± SD or SEM in figures as noted in figure legends. Statistical significance was assessed by one-way analysis of variance (ANOVA), two-way ANOVA, and Student's t-test with the Bonferroni correction. Similarity of two accelerometer signals was evaluated by using Pearson's correlation coefficient (Table 1). The relationship between two different variables was assessed by using Pearson's correlation coefficient (Fig. 9) or Spearman's correlation coefficient (Fig. 10, Table 2, Table 3). P values less than 0.05 were considered statistically significant. Single and double asterisks in figures indicate $P < 0.05$ and $P < 0.01$, respectively. The P value, effect size (d), and power ($1-\beta$) were obtained with Statcel 4 software.

Results

1. Predictable loading task

Figure 3 shows representative data obtained from one person in loading task. Five traces (Fig. 3A), each showing vertical hand movement during a loading trial, were averaged (Fig. 3B), and the amplitudes of downward deflection during loading (Fig. 3B, P-down) and upward deflection just before the start of loading (Fig. 3C, P-up) were measured. P-down and P-up reflect feedback and feedforward motor control, respectively. We also measured a rise time from 1/2 peak to peak (Fig. 3D, $t_{1/2}$). Figure 4 shows individual and averaged data for P-down, P-up, and t1/2 obtained from 18 participants. The P-down ranged from 4.6 to 15.9 mm. The P-up was highly variable, ranging from 0.27 to 2.19 mm. The $t_{1/2}$ was less variable, and ranged from 21 to 62 ms except for one person.

2. Lever pressing

Figure 5 shows an example of the data for accelerometer signal of one axis (vertical) obtained from one person in three-lever pressing trials under one condition ("hand"). Using the lever signal, we picked up the accelerometer signal from the time of A-lever press to the time of C-lever

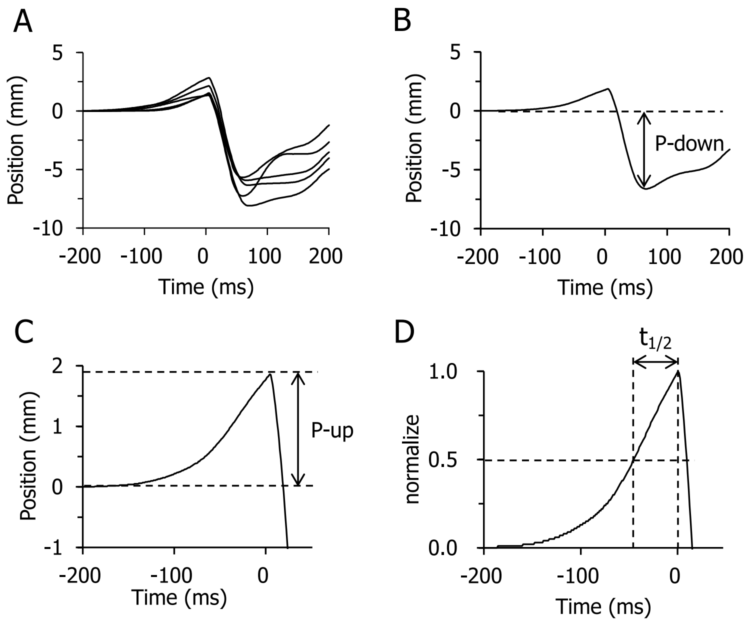

Figure 3. Representative data obtained from one person in loading task. A: Five traces of vertical hand movements obtained from repeated loading task (from the sixth to tenth trials). B: The averaged hand movement obtained from five traces shown in A. P-down is the difference between the initial position on the vertical axis 200 ms before the start of loading and the peak of downward deflection. C: A part of the trace shown in B is vertically expanded. P-up is the difference between the initial position on the vertical axis 200 ms before the start of loading and the peak of upward deflection. D: The amplitude of P-up was normalized, and a rise time from 1/2 peak to peak ($t_{1/2}$) was measured.

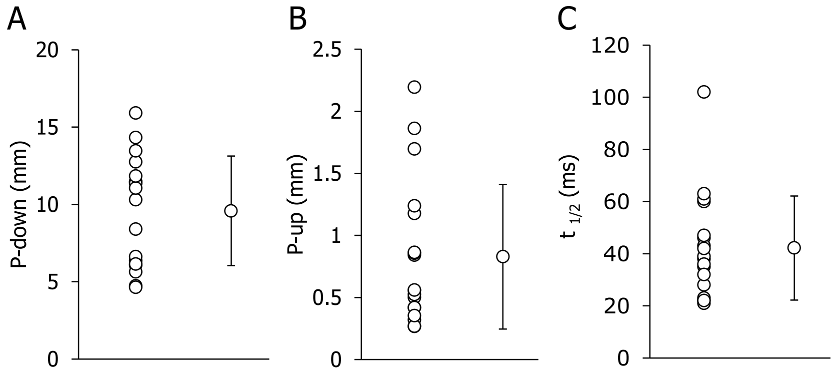

Figure 4. Individual and averaged data for P-down (A), P-up (B), and $t_{1/2}$ (C) obtained from 18 participants. Vertical bars mean SD. The data show that the amplitude of P-up was highly variable.

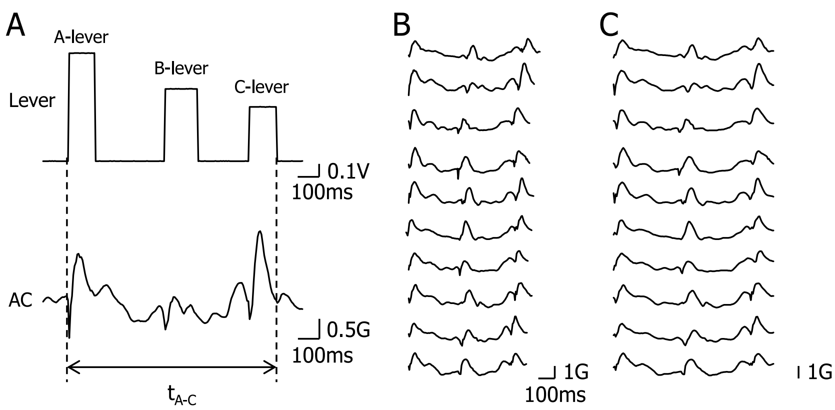

Figure 5. An example of the data for accelerometer signal of one axis (z) obtained from one person in three-lever pressing trials under one condition ("hand"). A: Lever signal (upper) and accelerometer signal (bottom) obtained during one trial of three-lever pressing. B: Ten raw traces of accelerometer signal obtained from ten trials. C: Ten resampled traces.

Table 1. An example of the data for correlation coefficients of accelerometer signals.

Trace no.	1	2	3	4	5	6	7	8	9
2	0.636								
3	0.608	0.762							
4	0.581	0.726	0.641						
5	0.571	0.763	0.785	0.739					
6	0.648	0.772	0.794	0.714	0.749				
7	0.535	0.791	0.738	0.780	0.753	0.767			
8	0.491	0.763	0.791	0.633	0.817	0.743	0.815		
9	0.672	0.818	0.732	0.775	0.710	0.765	0.840	0.744	
10	0.583	0.790	0.810	0.727	0.806	0.776	0.859	0.891	0.778

$\overline{CC}$ = 0.733 (all, n=45), $\overline{CC\ (i-1)}$ = 0.737 (dark gray, n=9), $\overline{CC\ (i-2)}$ = 0.758 (light gray, n=8)

release (Fig. 5A). Ten raw traces obtained from ten trials (Fig. 5B) were resampled to yield the same length of data points (150 points) (Fig. 5C). Correlation coefficients (CC) between two resampled traces were then calculated for all combinations, producing 45 CC values (Table 1). CC (i-1) and CC (i-2) were used to designate the CC between one trace and the next trace (Table 1, dark gray), and the CC between one trace and the trace after next (Table 1, light gray), respectively. $\overline{CC}$, $\overline{CC(i\text{-}1)}$, and $\overline{CC(i\text{-}2)}$ were used to designate the mean values of all 45 CC values, 9 CC (i-1) values, and 8 CC (i-2) values, respectively (Table 1).

Figure 6 shows averaged time courses of the change in CC (i-1) for accelerometer signals of three axes (x, y, z) obtained from 18 participants under three conditions (hand, weight, stick). Accelerometer signals of x, y, and z axes reflect the hand movements in left-right horizontal axis, front-back horizontal axis, and vertical axis, respectively. In the hand condition, CC (i-1) increased with increased number of trials in all three axes. In the weight condition, CC (i-1) was high at the beginning and remained relatively stable with slight decrease in the end. In the stick condition, CC (i-1) was low at the beginning, especially for x axis, increased during several trials, and then decreased slightly. For the x axis, a two-way ANOVA (time×condition) showed no significant interaction effect of time and condition ($P = 0.81$), and significant main effects of both time ($P < 0.01$) and condition ($P < 0.01$) (Fig. 6A). For the y axis, a two-way ANOVA showed no significant interaction effect of time and condition ($P = 0.09$), and a significant main effect of condition ($P < 0.01$), but not time ($P = 0.10$) (Fig. 6B). For the z axis, a two-way ANOVA showed a significant interaction effect of time and condition ($P < 0.05$) (Fig. 6C).

Figure 7 shows individual and averaged data for $\overline{CC}$. A one-way ANOVA showed statistically significant difference between conditions for x and z axes ($P < 0.01$ for x, $P < 0.05$ for z). The $\overline{CC}$ in x axis was higher in the weight condition ($P < 0.01$, $d = 0.76$, $1-\beta = 0.78$), and lower in the stick condition ($P < 0.01$, $d = 0.72$, $1-\beta$

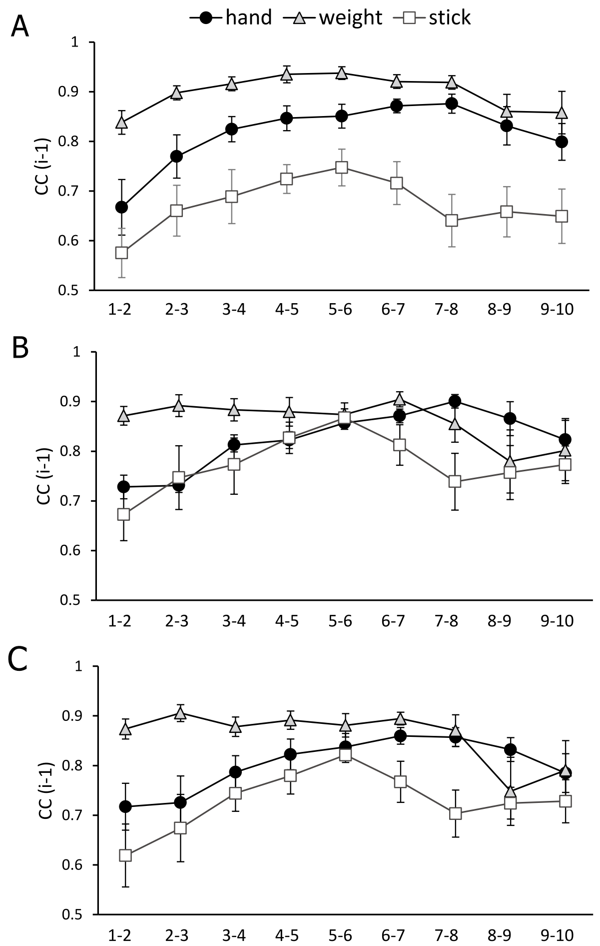

Figure 6. Averaged time courses of the change in CC (i-1) obtained from 18 participants. Mean CC (i-1) values for x (A), y (B), and z axis (C) were plotted against the paired trial numbers obtained in the hand (filled circles), weight (gray triangles), and stick (open squares) variations of the task. Vertical bars mean SEM.

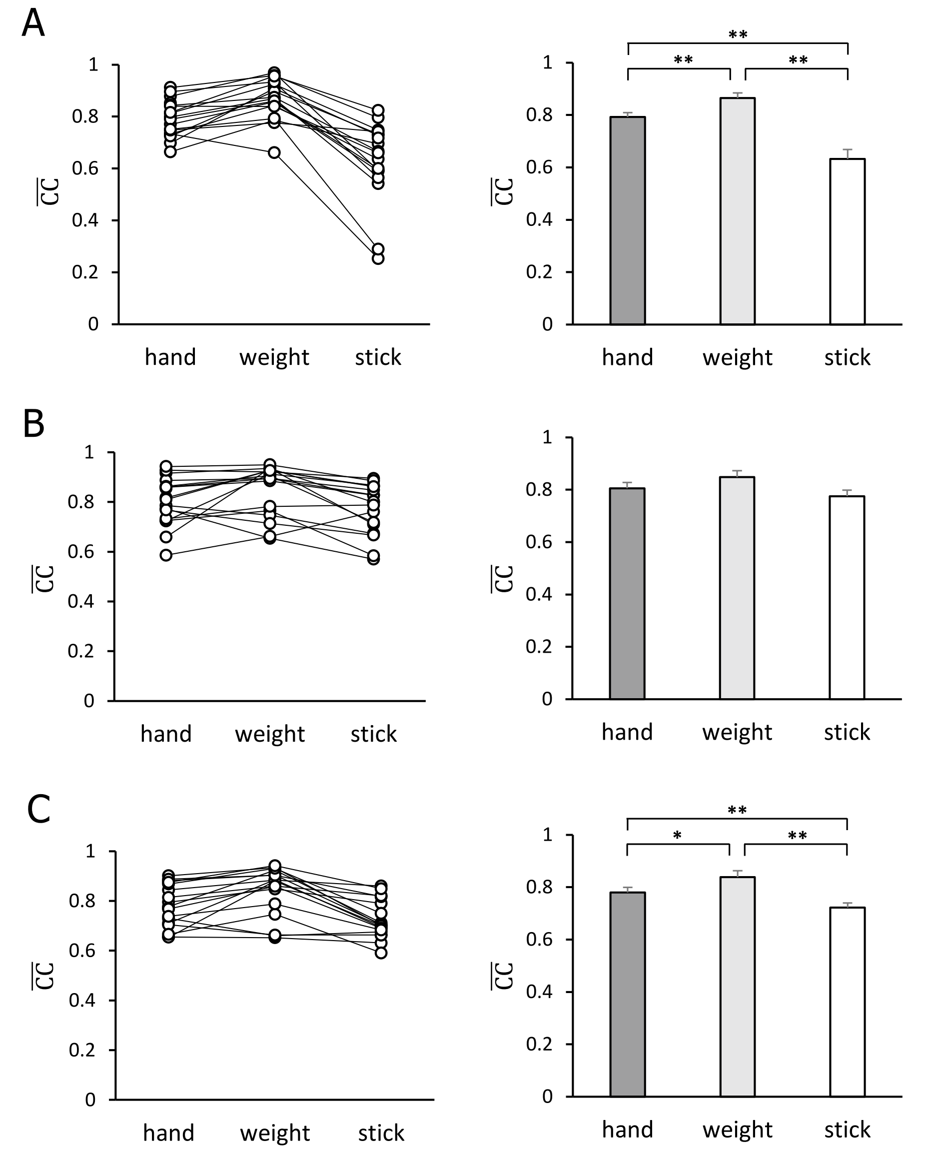

Figure 7. Individual (left) and averaged (right) data for $\overline{CC}$ obtained from 18 participants. The $\overline{CC}$ values for x (A), y (B), and z axis (C) were obtained in the hand (dark gray), weight (light gray), and stick (white) variations of lever pressing task. The results from the same person are connected by lines. Vertical bars mean SEM.

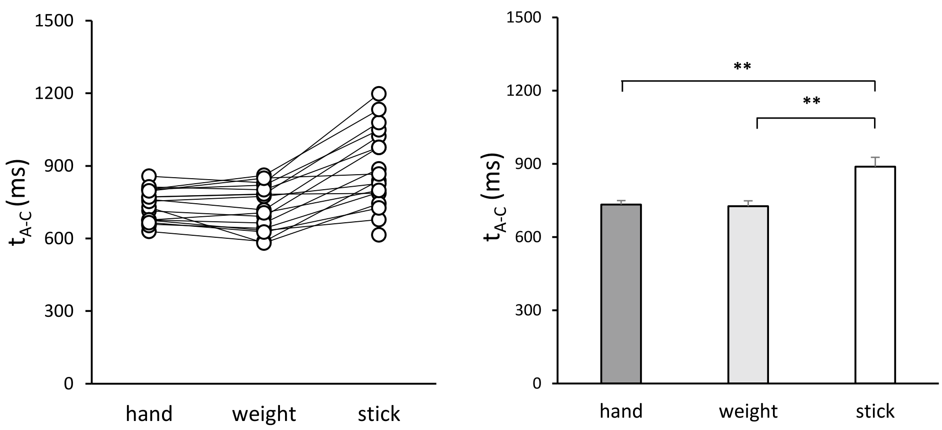

Figure 8. Individual (left) and averaged (right) data for the time $t_{A\text{-}C}$ obtained from 18 participants under the hand (dark gray), weight (light gray), and stick condition (white). The results from the same person are connected by lines. Vertical bars mean SEM.

Table 2. Spearman correlation coefficients (r_s) between tA-C and $\overline{CC}$ for three axes in three conditions.

Variation	Hand			Weight			Stick		
Axis	x	y	z	x	y	z	x	y	z
r_s	0.14	0.26	0.23	0.05	0.16	0.27	−0.19	0.29	0.46

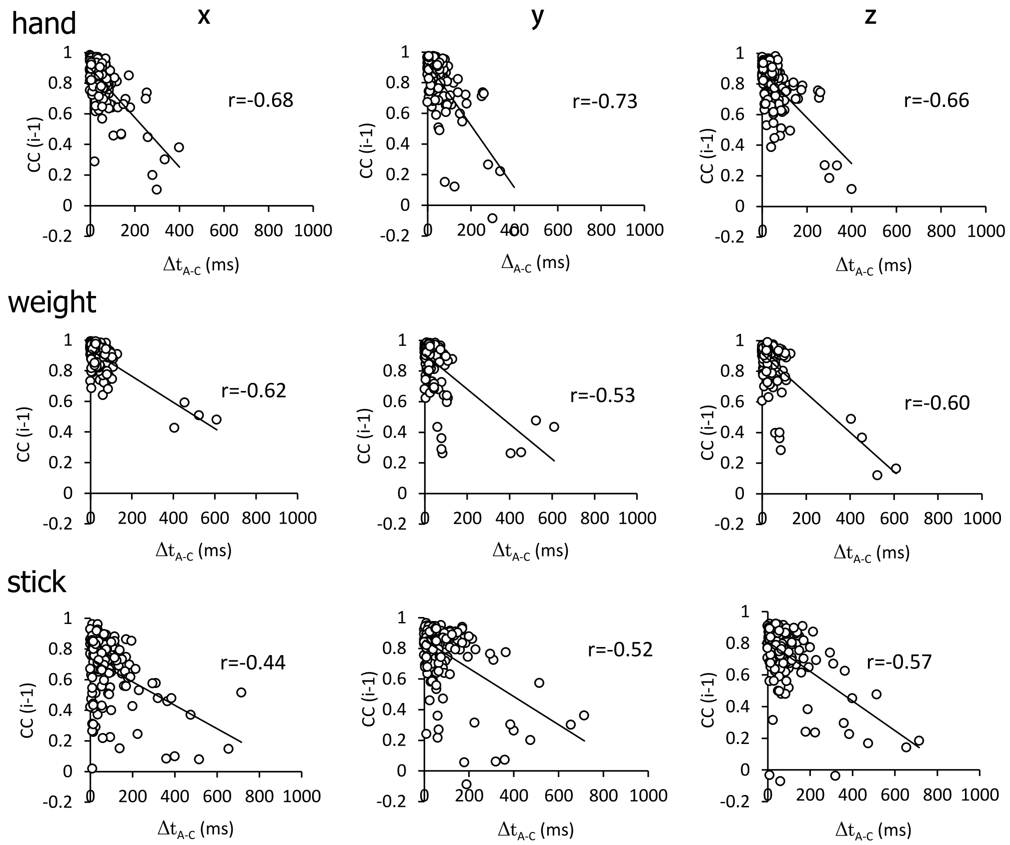

Figure 9. Relationships between CC (i-1) values and the corresponding changes of $t_{A\text{-}C}$ for three axes in three variations of lever pressing task. Each point represents the data obtained from two consecutive trials in the same person. One graph contains 162 points (9 CC (i-1) × 18 participants).

= 0.74) than in the hand condition. The difference in $\overline{CC}$ between weight and stick conditions was also significant (P < 0.01, d = 0.89, 1 − β = 0.90) (Fig. 7A). The $\overline{CC}$ in z axis was higher in the weight condition (P < 0.05, d = 0.64, 1 − β = 0.63), and lower in the stick condition (P < 0.01, d = 0.66, 1 − β = 0.66) than in the hand condition. The difference in $\overline{CC}$ between weight and stick conditions was also significant (P < 0.01, d = 0.85, 1 − β = 0.85) (Fig. 7C). These results indicate that subjects were not familiar with the stick variation of the task, and needed to adjust the hand movement, especially their left-right movement.

Figure 8 shows individual and averaged data for $t_{A\text{-}C}$, which is the time between the start of A-lever press and the time of C-lever release. Each symbol represents the value of $t_{A\text{-}C}$ averaged from 10 trials obtained with each subject in each condition (hand, weight, stick). A one-way ANOVA showed statistically significant difference between conditions (P < 0.01). The time $t_{A\text{-}C}$ was comparable in the hand and weight conditions, but significantly longer in the stick condition (P < 0.01, d = 0.80, 1 − β = 0.83 vs hand, P < 0.01, d = 0.85, 1 − β = 0.87 vs weight). These data confirmed that pressing levers with the stick was difficult for subjects, compared with the hand and weight variations of the task.

We then examined the relationship between $t_{A\text{-}C}$ and $\overline{CC}$ (Table 2). In the hand and weight conditions, there was no correlation between $t_{A\text{-}C}$ and $\overline{CC}$ (r_s < 0.4). In the stick condition, a mild correlation (r_s = 0.46), which was statistically insignificant (P = 0.059, 1 − β = 0.52), was observed between $t_{A\text{-}C}$ and $\overline{CC}$ for z axis. We also examined the relationship between CC (i-1) and the change of $t_{A\text{-}C}$ (Fig. 9). Negative correlations (r < -0.4, P <

0.01, 1 − β = 1.00) were seen for all three axes in all three variations, indicating that higher CC (i-1) values were obtained when $t_{A\text{-}C}$ did not fluctuate from trial to trial.

3. Relationship between P-up and CC

Next we examined the relationships between the data obtained from loading task and the data obtained from lever pressing task. We used P-down, P-up, and $t_{1/2}$ from loading task, and $\overline{CC}$, $\overline{CC(i\text{-}1)}$, $\overline{CC(i\text{-}2)}$, and $t_{A\text{-}C}$ from lever pressing task. The correlation coefficients (r_s) of all combinations are shown in Table 3 and the values larger than 0.4 are highlighted. Correlations (r_s > 0.4) between P-up and CC values were observed only in the stick condition, and the correlated CC values were mostly seen in x axis.

Table 3. Spearman correlation coefficients (r_s) between the data from loading task (P-down, P-up, $t_{1/2}$) and the data from lever pressing task ($\overline{CC}$, $\overline{CC(i\text{-}1)}$, $\overline{CC(i\text{-}2)}$, $t_{A\text{-}C}$).

			P−down	P−up	$t_{1/2}$
Hand	x	CC	0.00	0.22	−0.09
		CC(i−1)	0.15	0.27	−0.14
		CC(i−2)	0.00	0.26	0.10
	y	CC	−0.11	−0.06	−0.28
		CC(i−1)	−0.21	0.00	−0.28
		CC(i−2)	−0.27	0.05	−0.25
	z	CC	−0.07	0.09	−0.31
		CC(i−1)	−0.12	0.15	−0.36
		CC(i−2)	−0.22	0.03	−0.26
Weight	x	CC	0.08	0.18	0.33
		CC(i−1)	0.12	0.29	0.25
		CC(i−2)	0.01	0.21	0.29
	y	CC	0.09	0.25	0.08
		CC(i−1)	0.08	0.10	−0.05
		CC(i−2)	0.10	0.03	−0.03
	z	CC	−0.10	0.18	0.04
		CC(i−1)	−0.07	0.17	−0.06
		CC(i−2)	−0.07	0.19	0.14
Stick	x	CC	0.10	0.35	0.10
		CC(i−1)	0.15	0.41	0.19
		CC(i−2)	0.09	0.49	0.12
	y	CC	0.16	0.40	−0.16
		CC(i−1)	0.18	0.36	−0.09
		CC(i−2)	−0.11	0.33	−0.11
	z	CC	0.21	0.17	−0.43
		CC(i−1)	0.17	0.17	−0.42
		CC(i−2)	0.09	0.15	−0.37
Hand		t_{A-C}	0.32	0.19	−0.27
Weight			0.09	0.05	−0.40
Stick			0.02	0.03	−0.32

Figure 10 shows the relationship between P-up in the loading task and $\overline{CC(i\text{-}2)}$ for x axis in the stick version of lever pressing task. The values of r_s and P were 0.488 and 0.044 (1 − β = 0.61), respectively, indicating that this correlation was statistically significant. The other correlations were not statistically significant.

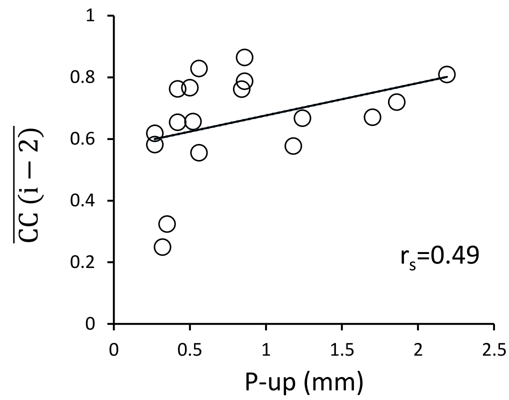

Figure 10. The relationship between P-up in loading task and $\overline{CC(i\text{-}2)}$ for x axis in the stick variation of lever pressing task.

Discussion

In the present study on healthy volunteers, we examined the relationship between prediction-based feedforward motor control and motor learning. We used anticipatory responses (P-up) in predictable loading task as an index of prediction-based feedforward motor control [8], and correlation coefficients between two accelerometer signals (CC) in lever pressing task as an index of motor learning [9]. The lever pressing task was conducted in three conditions (hand, weight, and stick). We found that $\overline{CC}$ was lower in the stick condition than in the other two, indicating that the hand movement in the stick condition was more fluctuated, namely, less controlled. We found also that the amplitude of anticipatory responses was correlated with $\overline{CC}$ only in the stick condition. These results provide evidence that prediction-based feedforward motor control is crucial for better performance in difficult motor task.

We prepared the weight variation in order to make the task harder. Thus, we expected that CC values in the weight condition should be lower than those in the hand condition. However, opposite results were obtained. The $\overline{CC}$ in the weight condition was even higher than that in the hand condition. The better performance in the weight condition might be caused by the order of variations during experiments. All participants conducted the three variations in the fixed hand-weight-stick order. Thus, the participants might be already accustomed to the lever pressing task in the weight condition. The time courses of the change in CC (i-1) support this possibility. In the hand condition, CC (i-1) was low at the beginning and increased gradually. In the weight condition, CC (i-1) was high at the beginning and remained almost stable. When compared at the end of each variation of the task, CC (i-1) values were comparable between the hand and weight variations, indicating that in terms of difficulty these variations are similar.

Our CC data indicated that the stick variation is more difficult than the weight variation. In the stick condition, failure of lever pressing was seen occasionally, and decreased the CC values. Considering our activities of daily living, this is not surprising. We have had many opportunities to carry heavy objects, and probably have already created the internal model for it. On the other hand, using a stick as a tool was relatively rare. When we use a tool to reach for a distant object, specific neural networks holding "body schema" change as if our own hand is elongated to the tip of the tool [11]. The training in the stick condition (11 trials) is not enough to change the networks. The number of trials required for motor learning depends on the difficulty or the type of tasks. In the case of cerebellum-dependent motor learning such as prism adaptation, the performance was rapidly improved and became constant after about 20 trials [12, 13]. Thus, the performance on the stick variation of lever-pressing task might be improved more if we set the number of trials to 20 instead of 11. However, we preferred to use 11 trials, because our preliminary experiments showed that more trials induced fatigue, especially in the weight condition. In addition to the CC values, our $t_{A\text{-}C}$ data also showed the difficulty of the stick condition. The time $t_{A\text{-}C}$ was significantly longer in the stick condition than in the hand and weight conditions. The longer $t_{A\text{-}C}$ can be explained if visual feedback is used more frequently in the stick condition. Proprioceptive information is important for fine movement, and expected to be used for monitoring the hand position in the lever-pressing task. In the stick condition, however, proprioceptive information is not enough, or even impossible, for monitoring the position of the stick tip. Visual feedback would be used to adjust the position of the stick tip during the stick variation of lever-pressing task.

Correlations with r_s values larger than 0.4 between P-up and CC values were observed only in the stick condition. Since P-up and CC values reflect prediction-based motor control and motor learning, respectively, our data suggest that prediction-based motor control is more important for better performance in difficult motor task. Interestingly, CC values were not correlated with P-down in any conditions (Table 3). If P-down depends solely on feedback motor control, our data might indicate that the feedback control is not as critical as the feedforward control in motor learning. However, the amplitude of P-down is influenced also by other factors such as stiffness. Thus, interpretation of the results is difficult.

A gradual decrease in motor learning occurs with aging, and is related to brain structural, functional, and biochemical changes [14]. The age-related changes in motor learning have been linked to decreased volume in the dorsolateral prefrontal cortex (DLPFC), striatum (caudate and putamen), cerebellum, and hippocampus [15], decreased integrity in the caudate-DLPFC tract [16], and disruptions in the dopaminergic system [17, 18]. Although these changes are associated with learning deficits in older adults, the specific influence of each of the changes on motor learning is not fully understood [19, 20].

Age-related changes in feedforward motor control have also been reported, including decreased anticipation in rapid self-paced movement [21], decreased feedforward adjustments of multi-finger synergies [22], decreased ability to use feedforward adjustments to self-triggered perturbations [23], decreased reliance on the feedforward control [24], and decreased amplitude of anticipatory responses during predictable loading task [8]. The above-mentioned studies suggest that elderly people use different strategies for motor control. Although aging is associated with changes in motor learning and feedforward motor control, the relationship between them has not been fully elucidated.

Similarly, changes in motor learning and feedforward motor control have been reported in the patients with various diseases. A previous study in our laboratory using the lever pressing task (hand condition) reported that CC values were lower in the patients with schizophrenia than in healthy controls [25]. Another study in our laboratory using the loading task showed that the amplitude of P-up was smaller in the patients with schizophrenia than in age-matched healthy controls [8].

Limitations of this study and future challenges

In the present study, we examined the relationship between prediction-based feedforward motor control and motor learning using only healthy young volunteers. Further studies are needed to determine if our findings obtained from healthy young volunteers can apply to other populations, including healthy elderly people and patients with various neurological and psychiatric disorders.

Conclusion

In the present study on healthy young volunteers, we examined the relationship between prediction-based feedforward motor control and motor learning. We used the amplitude of anticipatory responses (P-up) during loading task as an index of prediction-based motor control, and CC values of accelerometer signals during lever pressing task as an index of motor learning. Our data show that P-up is correlated with the CC values only in a difficult variation (stick) of the lever pressing task, providing evidence that prediction-based motor control is crucial for better performance in difficult motor task.

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重り負荷課題の予測に基づく運動制御とレバー押し課題の運動学習の関係

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要　　旨

運動をなめらかに行うためには、フィードバックおよびフィードフォワードの運動制御が必要である。運動学習と運動制御の仕組みを説明する現在の仮説は、誤差情報をフィードバックすることにより内部モデルを修正し、フィードフォワード制御の精度を上げる、というものであり、運動の上達においてフィードフォワード制御は重要な要素と考えられている。

フィードフォワード制御を評価する課題の１つとして、重りの負荷課題がある。予測が可能な条件で見られる、負荷の直前の手の動き（先行反応）は、予測に基づくフィードフォワード制御を反映するものと考えられている。一方、マルチレバー押し課題は、レバーを押す上肢の動きを加速度計で計測することで、上肢の運動制御を客観的に評価できる課題である。また、レバー押しを繰り返した時の加速度波形の類似性（波形間の相関係数）は、動作の習熟に伴い高くなることが報告されており、動作の習熟度を評価する指標として用いることができる。本研究では、健常者 18 名を対象とし、重りの負荷課題と３レバー押し課題の手の動きを解析し、フィードフォワード制御と運動の習熟との関係を調べた。左手で直接レバーを押す場合は、先行反応の大きさと加速度波形の類似性との間には相関はみられなかったが、左手に取り付けた棒でレバーを押す課題では、左右軸の動きに関して中程度の正の相関がみられた。以上の結果は、フィードフォワード制御と不慣れな運動の習熟との間に関係がある可能性を示唆している。