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Control of reaching finger movement accompanied with inhibitory intention

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Abstract— **In the present study, we investigated the motor control of reaching finger movement interfered by the inhibitory intention triggered by the stop-signal. In the experiment, the subject started the reaching movement of the index finger with the go-signal of a green LED and stopped the ongoing movement with the stop-signal of a red LED. The stop-signal delay (SSD) was set at 0, 100, 200, 300 and 400 ms. The movement trajectory was measured during the task. The index finger was able to stop prior to the target point when SSD was less than 400 ms, whereas not when SSD was 400 ms. We also measured electroencephalogram (EEG) during the task. A negative peak around the stop-signal response time (SSRT) and a positive peak around 400-600 ms of the event-related potentials (ERPs) were observed at Fz and Cz. These results indicate that these components of the ERPs were associated with the stop-signal task in the human reaching movement.**

I. Introduction

In human voluntary reaching arm movements, the hand path is roughly straight and the tangential velocity is bell-shaped. The central nervous system (CNS) plans such smooth movement trajectory in the feed-forward manner according to the hypotheses of the smoothness performance indices [1, 2]. On the other hand, inhibitory control of the voluntary movement plays an important role of behavioral flexibility. The stop-signal task (SST) has been used to investigate the behavioral and neural processes of the inhibition of action [3]. In the SST, the subject responds a go-signal which instructs the subject to start a response action such as a button press and then inhibits the response action with a stop-signal immediately. It has been found that the inhibition of the movement becomes more difficult as the delay of the stop-signal from the go-signal is extended.

Event-related potentials (ERPs) of the cerebral cortex have been used to investigate the neural mechanisms underlying response inhibition. In Go/No-Go tasks, N2 peak around 300-400 ms related to the No-Go tasks, called “No-Go N2” has been observed. This ERP has a fronto-central scalp distribution and may derive from the prefrontal structures [4-6]. The No-Go N2 peak is followed by a positive component which peaks around 400-600 ms, called “No-Go P3.” This component has a central maximum midline distribution [7]. In the button press task with a stop-signal paradigm, the N2/P3components were related to stop-signal trials and the P3 component reflects not only stop-signal processing but also efficiency of inhibitory control [6].

In a reaching arm movement, it has been found by a behavioral study that the efficiency of the stop task decreased as the stop-signal delay (SSD) increased and the stop-signal response time (SSRT) was estimated at 206 ms [8]. However, the related dynamics to the cortical mechanism of intervention, which requires the CNS to stop the ongoing reaching movement, is still poorly understood.

In the present study, we investigated behavioral and cortical mechanisms underlying the motor control of reaching finger movement interfered by the inhibitory intention triggered by the stop-signal.

II. Methods

A. Subjects

A right-handed subject (males, aged 23 years) with no known neurological abnormalities participated in the present study. The protocol was approved by the local ethics committee in Hiroshima City University and the subject gave informed consent. The subject participated in the same experiment twice at a three-week interval.

B. Apparatus

A parallel-link manipulator (PHANTOM Premium 1.0, SensAble Tech Inc., U.S.) was used to measure the position and velocity of index finger tip with sampling rate of 1 kHz. The subject’s index finger tip was fixed on the end of the manipulator with a plastic thimble. The proximal and distal interphalangeal joints of the index finger were fixed in the extension using a splint in order to avoid the flexion movement. The horizontal movement of the index finger was achieved by flexion and extension of the metacarpophalangeal joint (MCP joint) and the vertical movement was achieved by abduction and adduction of the MCP joint. The initial posture of the index finger was extension in which the flexion and abduction angles of the MCP joint were assumed to be zero degree and the terminal posture of the index finger was flexion of 45 degrees from the initial posture. The positions of the finger tip at the initial and terminal postures were measured using the parallel-link manipulator and used as a starting point and target point of the reaching movement. The current position of the finger tip, starting point, target point and desired path (straight line between starting point and target point) in the frontal plane

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were displayed on the screen of a 23 inch LCD monitor (SyncMaster 2233RZ, SAMSUNG, South Korea) with the refresh rate of 120 Hz.

Yellow, green and red LEDs were attached on the screen of the monitor. The yellow LED was located at 5 mm below the target point displayed on the monitor. The green and red LEDs were located at 5mm left and 5 mm right from the yellow LED, respectively. Go- and stop-signals were presented using the green and red LEDs, respectively. The yellow LED was used as an attention-signal to engage attention and eye fixation before the go-signal was presented.

The electroencephalogram (EEG) was recorded from 49 surface electrodes (47 gBUTTERFLY active electrodes and two g.GAMMAearclip Au electrodes, g.tec medical engineering, AUSTRIA) mounted in a cap (g.GAMMAcap) with the left earlobe as a reference. The EEG signals were filtered using a band-pass filter with cut-off frequency of 0.1-200 Hz and digitized at 512 Hz by an amplifier (g.USBamp 3.0).

C. Procedure

The subject positioned the index finger tip at the starting point. The subject fixated the yellow LED when it turned on. The subject started the reaching movement from the starting point to the target point when the go-signal appeared after a randomized time interval between 1 s and 1.5 s with 0.1 s steps. The subject was instructed to stop the ongoing reaching movement when the stop-signal appeared. The stop-signal delay (SSD), the delay of the stop-signal from the go-signal, was set at 0, 100, 200, 300 and 400 ms. Five kinds of SSD trials (go-stop trials) and the no-stop-signal trials where the stop-signal did not appear were randomly mixed. The subject practiced the tasks so that the reaching movement was successfully performed in the no-stop-signal trials and the index finger remained at the starting point in the 0 ms SSD trials. After sufficient training, the subject performed a series of 360 trials of the movement which was composed of 300 go-stop trials (60 trials in each SSD) and 60 no-stop-signal trials. The time intervals of the trials were around 5 s. In the intervals, the subject was permitted eye blinks and re-positioned the index finger tip at the starting point.

D. Data analysis

Measured movement trajectory including the position and velocity in the frontal-horizontal axis (x-axis) were smoothed using a digital low-pass filter with cutoff frequency of 20 Hz. The beginning and end of the movement were extracted based on the amplitude of the velocity and acceleration in the x-axis. The following properties of the movement trajectory were calculated; (1) go-signal response time (RT), (2) movement time (MT), from the time of movement onset to the time of end of the movement, (3) end position of the movement (EP), (4) overshoot from the end point in the x-axis (OS) which would not appear theoretically in the smooth reaching movement according to the minimum torque change model [2], (5) peak velocity (PV) and (6) latency of PV (LPV). Each of these properties was compared between the SSDs including the no-stop-signal trial using an analysis of variance (ANOVA) and Tukey-Kramer post-hoc test with level of significance of 1 %. In order to estimate the stop-signal response time (SSRT), latency of stop action (LSA) was determined as follows. First, for each of SSDs and no-stop-signal conditions, the velocities of the finger tip were averaged at each time sample across the trials and then the acceleration was calculated using the averaged velocity. Second, the deviation of the acceleration in each SSD from that in the no-stop-signal trial was calculated at each time sample. Third, the LSA was determined as the first time when the deviation of acceleration was larger than a criterion. The criterion of the deviation was set at 10 % of the maximum acceleration in the no-stop-single trials. Then, SSRT was calculated by subtracting the SSD from the LSA.

EEG signals were segmented into each period of 4 s from 2 s before onset of the go-signal and then smoothed using a digital band-pass filter with cut-off frequency of 1-35 Hz. A period of 1s preceding the go-signal (the minimum of time interval between the attention-signal and go-signal) was used as a baseline. The processing of the EEG signals was carried out using a gBSanalyze software (g.tec medical engineering).

III. Results and Discussion

The x-axis position and velocity of the finger tip averaged at each time sample across the trials were shown in Fig. 1. The abscissa indicates the time from the go-signal. In the 0 ms SSD, the subject's index finger remained at the starting point in most of the trials but moved in a few trials. The velocity of the movement was bell-shaped in the no-stop-signal trials, whereas the overshoots of the movement path and velocity were observed at the end of the movement in the 100 and 200 ms SSDs. The average and standard deviation (S.D.) of the RT across the trials was shown in Fig. 2 (a). Excluding the 0 ms SSD, the main effect of the RT with the SSDs and no-stop-signal was not significant. The average of the RT across 100, 200, 300, 400 ms SSDs and no-stop-signal was 197 ms (4 ms S.D.) in the first experiment and 184 ms (8 ms S.D.) in the second experiment. This result indicates that the subject could respond to the go-signal similarly in all SSDs where the reaching movement of the index finger was generated.

The MT in the no-stop-signal trials was 720 ms and 710 ms in the first and second experiments, respectively. The MT increased as SSD increased as shown in Fig. 2 (b). A significant main effect with the SSD was revealed but the MT was not significant between the 400 ms SSD and no-stop-signal trials. The difference between the EPs in the no-stop-signal trials and that in the 400 ms SSD trials was not significant whereas differences between the EPs in the no-stop-signal trials and those in the other SSDs (0-300 ms) trials were significant as shown in Fig. 2(c). These results indicate that the subject was able to stop the ongoing reaching movement prior to the target point in the 100, 200 and 300

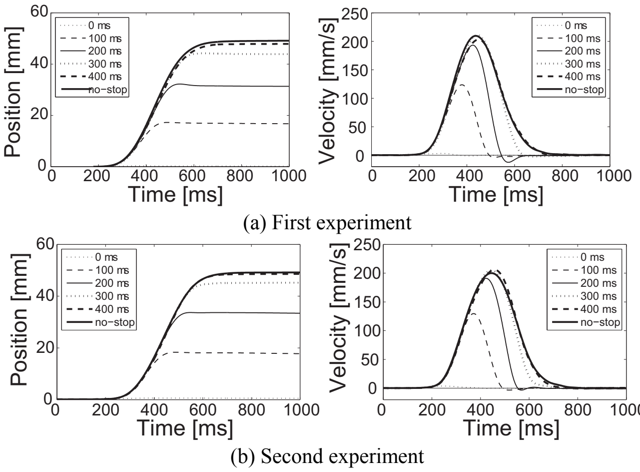

Fig. 1. Averaged movement trajectory (left: position, right: velocity) in the go-stop and no-stop-signal tasks. The time of the go-signal is 0 ms.

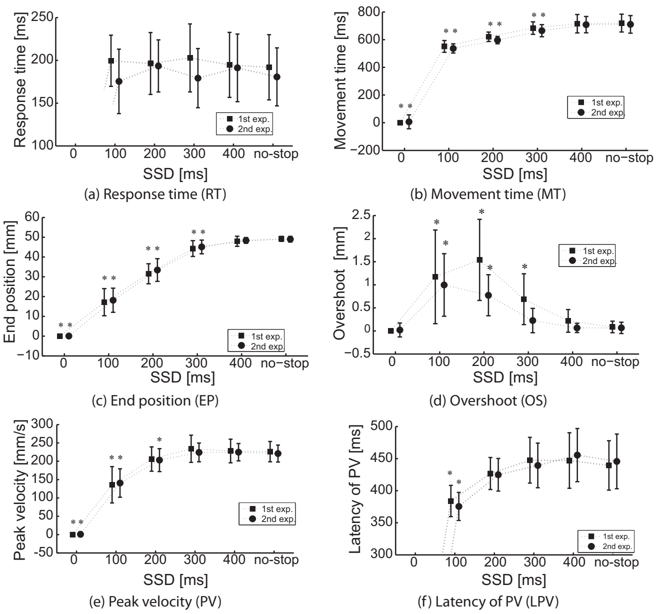

Fig. 2. Properties of movement trajectory. The asterisks indicate significant difference from no-stop-signal trials with level of significance of 1 %.

SSDs whereas not in the 400 ms SSD.

The OSs was observed in the 100, 200 and 300 ms SSDs in the first experiment and in the 100 and 200 SSDs in the second experiment whereas not in the other SSDs. The overshoot at the end of the movement does not appear in the reaching movement controlled in the feed-forward manner according to the minimum torque change model [2]. Accordingly, it is possible that the stop actions observed in the present study was controlled in the feedback manner.

The PV in the no-stop-signal trials was significantly larger than that in the 100 ms SSD of the first experiment and in the 100 and 200 ms SSDs of the second experiment. The LPV in the no-stop-signal trials was significantly different from that in the 100 ms SSD in both experiments. This means that the stop action was generated before, around and after the time of the peak velocity in the 100, 200 and 300 ms SSDs, respectively. The LSA is shown in Table I. The averages of

TABLE I
LATENCY OF STOP ACTION (LSA)

SSD	1st exp.	2nd exp.	Ave.
100 ms	287 ms	313 ms	300 ms
200 ms	419 ms	407 ms	413 ms
300 ms	514 ms	476 ms	495 ms
400 ms	*	*	*

* LSA could not be calculated from the movement trajectory.

TABLE II
STOP-SIGNAL RESPONSE TIME (SSRT)

SSD	1st exp.	2nd exp.	Ave.
100 ms	187 ms	213 ms	200 ms
200 ms	219 ms	207 ms	213 ms
300 ms	214 ms	176 ms	195 ms
400 ms	*	*	*

*SSRT could not be calculated from the movement trajectory.

the LSA across the first and second experiments were 300, 413 and 495 ms in the 100, 200 and 300 SSDs, respectively. The SSRT is shown in Table II. The average of the SSRT across combination of the 100-300 SSDs and the first and second experiments was 203 ms (17 ms S.D.). This finding is consistent with that the SSRT was estimated at 206 ms in a SST with a reaching movement [8]. In the 400 ms SSD, the LSA could not be calculated in the 400 ms SSD because the velocity and acceleration of the finger tip in the 400 ms SSD was similar to that in the no-stop-signal trials. According to the SSRT estimated in the present study, the SSRT from the go-signal in the 400 ms SSD was estimated at 603 ms which was around 100 ms earlier than end of the movement.

However, the behavioral data mentioned above do not give us the suggestion about that which is a cause of the failure in the stop action that the motor command for controlling the stop action could not compensate the inertia force of the ongoing movement or that the motor command was not outputted simply. The waveforms of the ERPs at Fz, Cz, Pz and Oz averaged across the first and second experiments were shown in Fig. 3. At Pz and Oz, P100 component evoked by the go-signal (Pgo) and the negative peaks which may be associated with the stop-signal processing (Nstop) were observed in all SSDs and no-stop-signal trials. At Cz, large negative peaks (Nstop) appeared around the SSRT (estimated at 203 ms) in the 100, 200 and 300 ms SSDs. It is possible that these negative peaks were associated with the generating motor command for controlling the stop action and corresponding to the N2 peak observed in the button press task [6]. Moreover, at Fz and Cz, positive peaks (Pstop) appeared around the 400-600 ms in the 100 and 200 ms SSDs. It is considered that these positive peaks were corresponding to the P3 peak observed in the button press task [6]. In the 400 ms SSD, large negative peak was not observed at the time of the SSRT (= 603 ms). Therefore, it is suggested that the motor command for controlling the stop action was not outputted. These results indicate that the ERPs associated with the SST

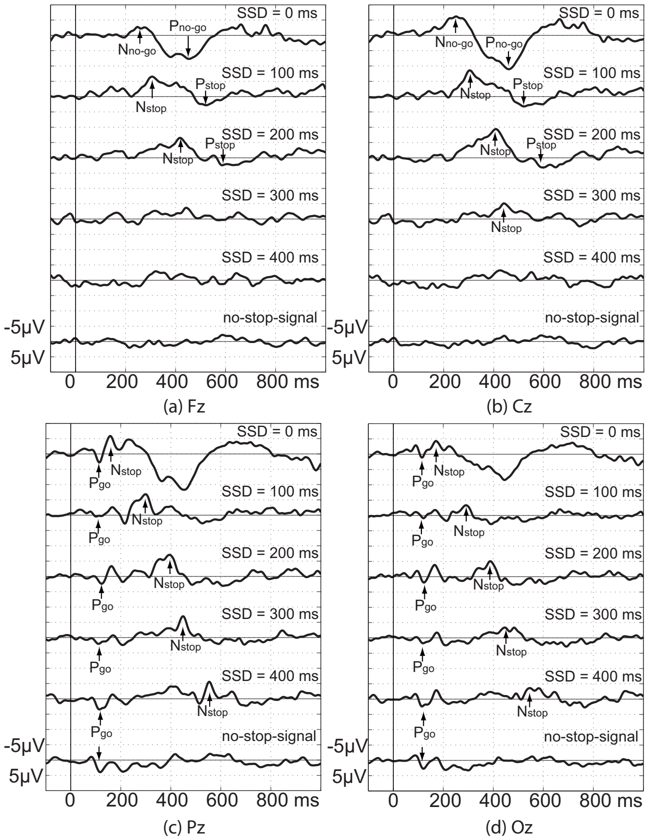

Fig. 3. Event-related potential waveforms synchronized with onset of the go-signal.

were observed not only in the button press task but also in the human reaching finger movement when the stop-signal task was successfully performed. The 0 ms SSD trials were considered to be similar to the No-Go trials since the subject's index finger remained at the starring point. Therefore, the negative peak around 300 ms (Nno-go) and the positive peak around 450 ms (Pno-go) are possible to be corresponding to the No-Go N2 and No-Go P3 observed in the Go/No-Go task [6].

IV. Conclusions

In the present study, we investigated behavioral and cortical mechanisms underlying the motor control of reaching finger movement interfered by the inhibitory intention triggered by the stop-signal. The behavioral data indicated that the subject was able to stop the ongoing reaching movement prior to the target point in the 100, 200 and 300 SSDs whereas not in the 400 ms SSD when the movement time in the no-stop-signal trial was around 700 ms. As a result of the ERP analysis, the negative peak around the SSRT and positive peak around 400-600 ms observed at Fz and Cz that were associated with the No-Go (SSD = 0 ms) and go-stop (SSD = 100, 200 and 300 ms) task in the reaching index finger movement.

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