Effect of Low-Amplitude Oscillation Applied to the Control Device of a Tracking Operation

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ABSTRACT

In order to find a stimulus that improves tracking operation accuracy, low-amplitude oscillation was applied to two types of control device (a grip type and a steering wheel) in a tracking simulation. The tracking operation was as follows: The target cursor moves side to side at a fixed velocity. Subjects control the device with the aim of making the control cursor follow the target cursor. The velocity of the target cursor was set at either a low or a high velocity. The separation between the target cursor and the control cursor (the tracking error) was used to evaluate the task performance. Three oscillation stimuli were used: sin waves of 10, 20, and 40 Hz, each at three different amplitude levels. A no-stimulus experiment was used as a control. In the slow cursor, the tracking error was significantly reduced with the 20 Hz oscillation compared to the control ($p<0.05$). In the fast cursor, no stimulus improved the accuracy of the tracking operation. On the other hand, the tracking error was significantly increased with the 10 Hz oscillation in comparison to the control ($p<0.01$). These results suggest that an oscillation of 20 Hz could improve the accuracy of tracking in the slow target. The oscillation of 20 Hz could affect the protagonistic muscles of the operation, and could improve sensitivity of the muscle spindles by stochastic resonance phenomenon. As a result, the devices were operated more accurately and the tracking errors were decreased.

Keywords: muscle spindle, oscillation/vibration, stochastic resonance, steering wheel, frequency

INTRODUCTION

For elderly people whose motor skills/functions have decreased, it is important to find suitable methods of improving both the accuracy and comfort of vehicle/machine operation. To maintain their quality of life, it is thought that support system for their physiological functions must be necessary. The aim of such support systems had better to recover/keep their motor skills/functions to their prior level.

In the motor control systems of humans, both visual feedback and somatosensory feedback from muscle spindles and tendons are important. In elderly people, their reduced motion ability is apparent in performing operation/ movements not smoothly. It is assumed that not only the muscle function also the somatosensory functions of them are decreased. For improvement of operational functions, we have been focusing on the somatosensory characteristics in the motor control system. The afferent signals from muscle spindles are enhanced by introducing subthreshold noise (physical vibrations) through tendons (Cordo P. et. al, 1996). This suggests that muscle spindle sensitivity could be enhanced by a suitable level of noise, and the accuracy of movement should improve as a result.

In this paper, we propose a unique method for improving operation accuracy, which is based on the stochastic resonance phenomenon (Collins and Imhoff, 1996). Furthermore, it is showed that the operation accuracy is improved by applying low-amplitude oscillation to the control device (Mukae and Yasukouchi, 2013). To verify these results, we report the effects on the accuracy of operation that result from applying low-amplitude (not subthreshold) oscillation to different type control device in the experimental setup.

EXPERIMENT 1 USING A GRIP CONTROL DEVICE

In order to find a stimulus that improves operation accuracy, low-amplitude oscillation was applied to the one-handed control device of a tracking operation. In the motor control system, there is a time delay between the afferent feedback from muscle spindles and the human's reaction (feedback delay). Therefore it is theoretically impossible to operate smoothly by feedback control in the quick movement (Kawato, 1995). If operation accuracy is dependent on the muscle spindle's sensitivity/resolution, noise during slow operations would have good effect for improving its accuracy. On the other hand, same noise during rapid operations will have no effect. Therefore, two velocity conditions (slow/fast) and three frequency conditions (similar to the resonance frequency of the arm (10 Hz), the forearm – elbow (20 Hz), the hand (40 Hz)) were used in this experiment.

Method

The experimental apparatus (the grip operation device by right hand) is shown in Figure 1. There was a computer display in front of the subject and the grip device (φ35 mm) was located in front of the subject's right arm. The operation device was operated by pronation and supination of the right hand. The strength to hold the grip was not instructed. The experimental task (the tracking operation) is shown in Figure 2. The target cursor moves side to side (between -30 and +30 degrees as rotation angle) on the display at a fixed velocity. The target cursor was set to move at either a slow velocity (5 deg/s) or a fast velocity (10 deg/s). Each subject moved the control cursor by rotating the grip with the aim of tracking the target cursor between -25 and +25 degrees. The task period was 120 seconds. During the task, the separation between the target cursor and the control cursor (the tracking error) was measured with 60 Hz sampling. The oscillations employed were three sine waves 10, 20, and 40 Hz in frequency, and each wave was used at three different amplitude levels: 0.004 Nm (hardly noticeable), 0.008 Nm, and 0.016 Nm (clearly noticeable). An experiment with no oscillation was used as a control.

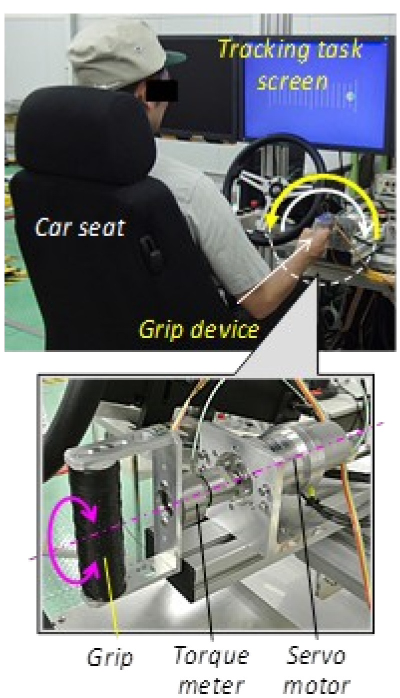

Fig.1 Experimental apparatus in the experiment 1

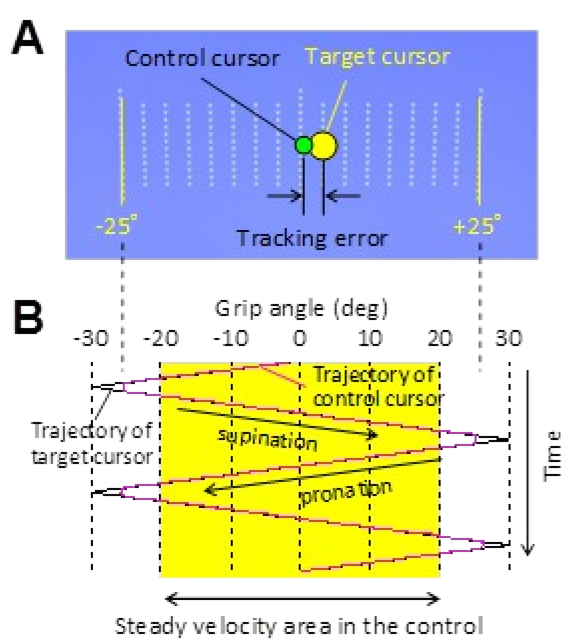

Fig.2 A: Tracking operation on the display
B: An example of the tracking operation result

Table 1: Experimental conditions using the grip control device

Oscillation (sin wave)	
Frequency (Hz)	None (control), 10, 20, 40
Amplitude (Nm)	0.004 (hardly noticeable), 0.008, 0.016 (clearly noticeable)
Tracking Task	
Rotation angle (deg)	-25 (pronation) to +25 (supination)
Velocity of target cursor (deg/s)	5 (slow), 10 (fast)

The experimental conditions are shown in Table 1. The oscillation was applied in the rotating direction (pronation and supination) of the grip device. The sequences of the oscillation conditions were randomized. Eight healthy males and females participated in the experiment (ranging from 23 to 60 years old, mean age is 38.3 (SD=12.7)). Informed consent was given by each subject before experiment.

The average tracking error between -20 and +20 degrees (steady velocity area in the control, see Fig. 2B) for each oscillation condition were analyzed with a three-way ANOVA (main effect: cursor velocity, frequency, amplitude). The statistical significance level was set to less than 5%.

Results

The average tracking errors of the experimental conditions are shown in Figure 3. The average tracking error was reduced in the 5 deg/s (Fig. 3A) experiment compared to that in the 10 deg/s (Fig. 3B) significantly ($F(1, 165)=354.0$, $p<0.01$). Therefore, the tracking error data for the different velocities were analyzed separately. Statistical analysis showed that the frequency of oscillations was a significant factor in both tracking velocities (5 deg/s: $F(2, 79)=36.3$, $p<0.01$, 10 deg/s: $F(2, 79)=25.4$, $p<0.01$). On the other hand, the amplitude of the oscillations had no significant effect.

The average tracking errors of the oscillation frequencies are shown in Figure 4. In the slow tracking (5deg/s, see Fig. 4A), the average tracking error was reduced by the 20 Hz and 40 Hz oscillations in comparison with the control (no oscillation) significantly ($p<0.05$). On the other hand, the tracking error was increased by the 10 Hz oscillation significantly ($p<0.01$). In the fast tracking (10deg/s, see Fig. 4B), there was no oscillation that reduced the tracking error. On the other hand, the tracking error was increased by the 10 Hz oscillation significantly ($p<0.01$).

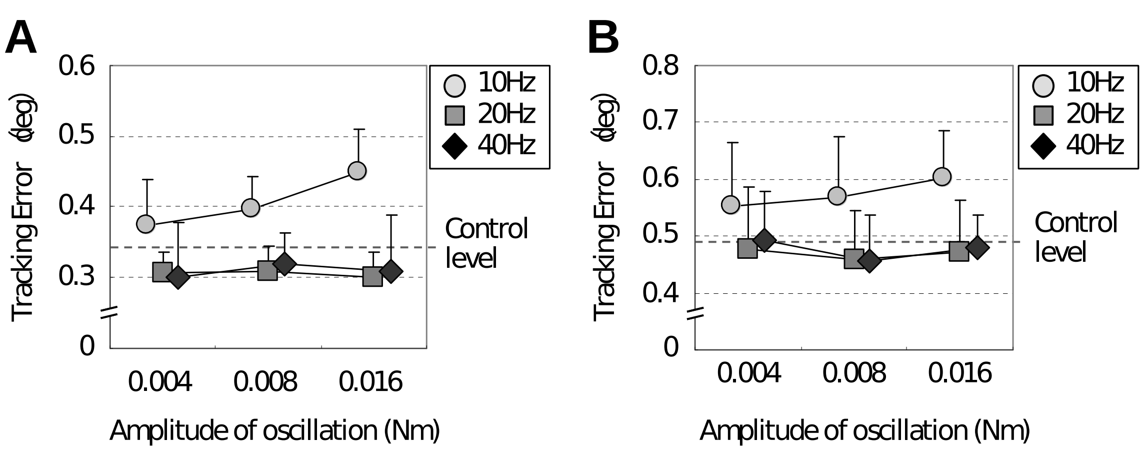

Fig.3 The average tracking error of the experimental condition
A: 5 deg/s (slow tracking), B: 10 deg/s (fast tracking) (N=8 mean + SD, *: p<0.05, **: p<0.01)

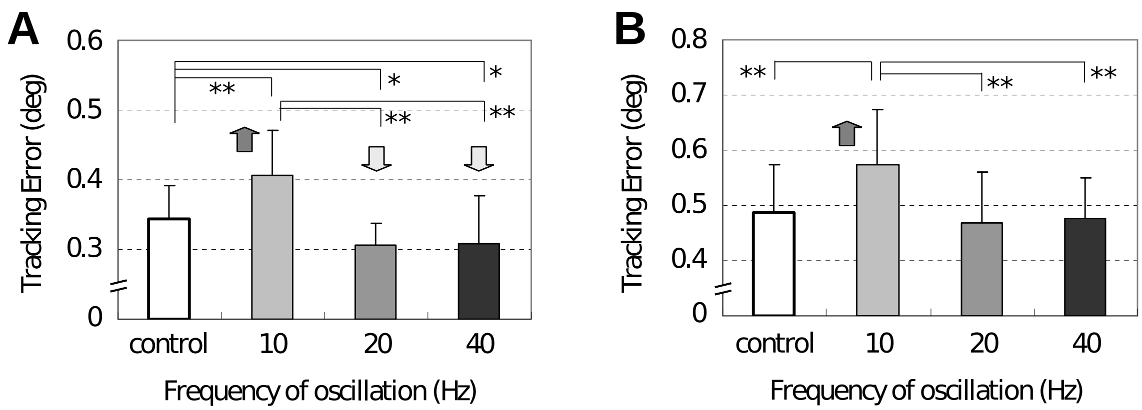

Fig.4 Effects of oscillation frequency on the average tracking error
A: 5 deg/s (slow tracking), B: 10 deg/s (fast tracking) (N=8 mean + SD, *: p<0.05, **: p<0.01)

EXPERIMENT 2 USING A STEERING WHEEL

To confirm results of Experimental 1, the same low-amplitude oscillation was applied to a steering wheel.

Method

The experimental apparatus (a driving simulator cockpit) is shown in Figure 5. This apparatus can apply any reaction force and oscillation around its rotational axis. The subjects held the wheel in the 10:10 position using both hands. The tracking task was the same as that in Experiment 1. The target cursor moves side to side (between -60 and +60 degrees as rotation angle) at a fixed velocity on the display. In this experiment, the slow velocity was 20 deg/s and the fast velocity was 30 deg/s. The subjects controlled the cursor by rotating the steering wheel. The strength to hold the steering wheel was not instructed. The oscillation frequencies were the same as in Experiment 1, but the amplitudes were used 0.05 (hardly noticeable), 0.1, and 0.2 Nm (clearly noticeable). Again, an experiment with no oscillation was used as a control. The experimental conditions are shown in Table 2. The sequences of the oscillation conditions were randomized. The same subjects were participated and the informed consent was given by each subject before experiment.

The average tracking errors between -45 and +45 degrees (steady velocity area in the control) for each oscillation condition were analyzed with a three-way ANOVA (main effect: cursor velocity, frequency, amplitude). The statistical significance level was set to less than 5%, the same as that in Experiment 1.

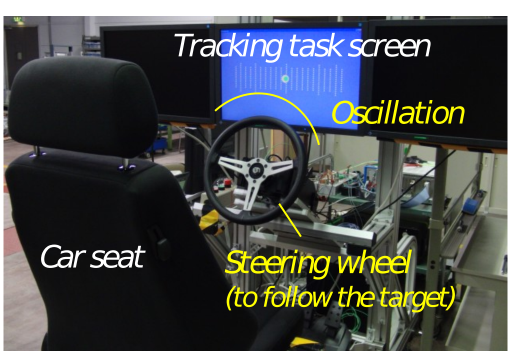

Fig.5 Experimental apparatus in the experiment 2

Table 2: Experimental conditions using the steering wheel

Oscillation (sin wave)	
Frequency (Hz)	None (control), 10, 20, 40
Amplitude (Nm)	0.05 (hardly), 0.1, 0.2 (clearly noticeable)
Tracking Task	
Rotation angle (deg)	-60 to +60
Velocity of target cursor (deg/s)	20 (slow), 30 (fast)

Results

The average tracking error was reduced for the 20 deg/s condition compared to that in the 30 deg/s significantly (F(1, 165)=66.1, p<0.01). Therefore, the tracking error data for the different velocities were analyzed separately. Statistical analysis showed that the frequency of oscillations was a significant factor in both tracking velocities (20 deg/s: F(2, 79)=5.11, p<0.01, 30 deg/s: F(2, 79)=3.80, p<0.05) . On the other hand, the amplitude of the oscillations had no significant effect. The average tracking errors for the different oscillation frequencies are shown in Figure 6. In slow tracking, the average tracking error was reduced by the 20 Hz oscillations in comparison with the control significantly (p<0.05: see Fig. 6A). In the high-velocity tracking, there was no oscillation that reduced the tracking error. On the other hand, the tracking error was significantly increased by the 10 Hz oscillation in comparison with the control (p<0.05: see Fig. 6B).

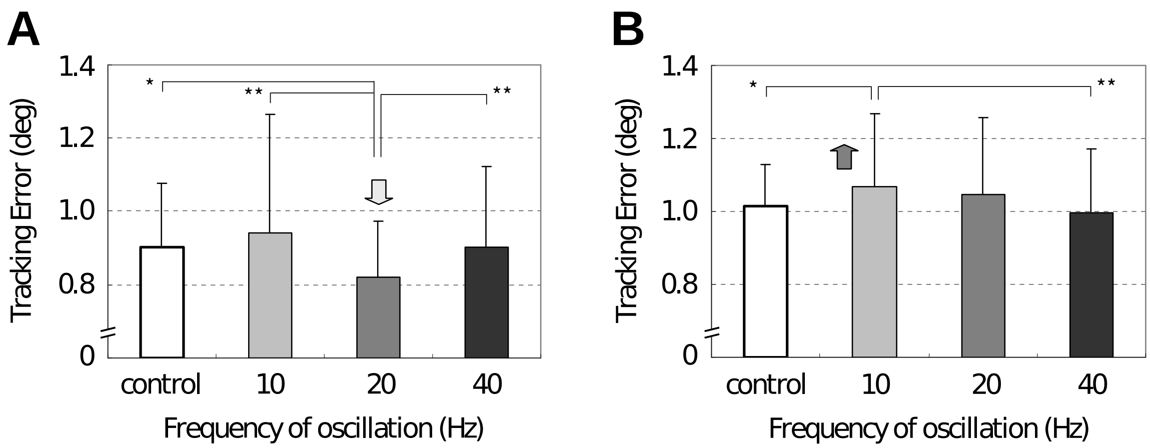

Fig.6 Effects of oscillation frequency on the average tracking error
A: 20 deg/s (slow tracking), B: 30 deg/s (fast tracking) (N=8 mean + SD, *: p<0.05, **: p<0.01)

DISCUSSION

From the results of Experiment 1, it was found that the average tracking error in both the high and low-velocity condition was increased by the 10 Hz oscillation in comparison with the control significantly (p<0.01 see Fig. 4). Results in Experiment 2 showed that with the high-velocity experiments, the average tracking error was significantly increased by the 10 Hz oscillation (p<0.01 see Fig. 6B). These results suggest that 10 Hz oscillation is an obstacle in fast tracking operations. The reason for this is that 10 Hz oscillations are transmitted to the shoulder, and are close to the resonance frequency of the whole arm. Therefore, the tracking operation would be affected with oscillation of whole arm as disturbances. Furthermore, one-handed operation is easily affected, and the correction of movements made through somatosensory feedback is insufficient for fast operations.

The low-velocity results in Experiment 1 showed that the tracking error was reduced by the 20 Hz and 40 Hz oscillations significantly (p<0.05 see Fig. 4A). In Experiment 2, the tracking error was also reduced by the 20 Hz oscillation when the low-velocity (20 deg/s) condition significantly (p<0.05 see Fig. 6A). These results suggest that there are some oscillation conditions that improve the operation accuracy in slow tracking tasks. However, the extent of the improvement for fast operations was insufficient (no significant difference). Thus, it can be concluded that the effect of oscillations on operation accuracy is dependent on the tracking velocity.

The protagonistic muscles used to manipulate the grip control are located between the wrist and elbow. 20 and 40 Hz oscillations are close to the resonant frequencies of these parts. On the other hand, the protagonistic muscles used to turn the steering wheel are located between the forearm and shoulder. 20 Hz is close to the resonant frequency of the forearm and elbow. Thus, appropriate oscillation of the control device can stimulate the corresponding protagonistic muscles through resonance. These stimuli would affect the muscle spindles and improve sensitivity through stochastic resonance. As a result, the device controls were operated more accurately (the tracking error decreased).

On the other hand, there were no significant differences among the results obtained with the different oscillation amplitudes used in Experiment 1 and 2. It is thought that the range of the amplitudes used was too narrow to identify any effects on the results.

CONCLUSIONS

The experimental results have determined the conditions under which low-amplitude oscillation applied to the control device can improve the accuracy of operation. The conditions are as follows:

- There are some oscillations that will improve the accuracy of operation. To realize this, the frequency of the oscillation must be close to the resonant frequency of the part of the arm in which the protagonistic muscles are located.
- The velocity of operation affects the extent of the improvement gained due to the oscillation. Low-amplitude oscillation would improve operation accuracy in slow task.
- The effect of the oscillation is independent of the device being used.
- There were no significant differences between the results for oscillations of different amplitudes in this experiment. Therefore the effects of amplitude were unable to be confirmed.

This work has revealed that operation accuracy can be improved by applying low-amplitude oscillation to the control device. This is due to the occurrence of the stochastic resonance phenomenon in the muscle spindles and improves sensitivity. However, the above results were obtained using limited conditions and subjects. Therefore it is necessary additional experiments to clarify the mechanism of the phenomenon.

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