Manuscript for publication in Journal of Motor Behavior

Accuracy of force generation and preparatory prefrontal oxygenation in ballistic hand power and precision grips

Akari Ogawa, Mizuki Sakamoto, Amiri Matsumoto, Tetsuei Okusaki, Ren Sasaya, Keisuke Irie, Nan Liang

Cognitive Motor Neuroscience, Human Health Sciences, Graduate School of Medicine, Kyoto University, Kyoto, Japan

Running title: Prefrontal oxygenation prior to power and precision grips Manuscript word count: 8,390 words Number of tables: 2 Number of figures: 6

Correspondence: Nan Liang, PhD, OTR Cognitive Motor Neuroscience, Human Health Sciences Graduate School of Medicine, Kyoto University 53 Shogoin-Kawahara-cho, Sakyo-ku, Kyoto 606-8507, Japan TEL & FAX: +81-75-751-3973 E-mail: <u>liang.nan.3z@kyoto-u.ac.jp</u>

ABSTRACT

It remains unclear whether accurate motor performance and cortical activation differ among grasping forms across several force levels. In the present study, a ballistic target force matching task (20, 40, 60, and 80 percent of maximum voluntary force) with power grip, side pinch, and pulp pinch was utilized to explore the accuracy of the forces generated as well as the muscular activity of intrinsic and extrinsic hand muscles. By using near-infrared spectroscopy, we also examined bilateral dorsolateral prefrontal cortex (DLPFC) activation during the preparatory phase (initial 10 s) of the task. The accuracy of the power grip and pulp pinch was relatively higher than that of the side pinch, and the electromyographic activity of intrinsic hand muscles exhibited a similar trend for power grip and side pinch, while the opposite muscle recruitment pattern was observed for pulp pinch. The increment of DLPFC oxygenation across force levels differed among grasping forms, with greater activity at relatively higher levels in the power grip and side pinch, and at relatively lower levels in the pulp pinch. Taken together, the differential contribution of the DLPFC may be responsible for force generation depending on different grasping forms and force levels.

(195 words)

Key words:

Force control, grasping, strength, dorsolateral prefrontal cortex (4-5 words)

INTRODUCTION

Force generation is one of the most important factors in voluntary human movement. We produce our force in response to external trigger or internal awareness in our daily life (Ni et al., 2006). The force generated with external feedback relatively matches the target level, whereas the actual force, which is intentionally generated based on the internal perception without external feedback, does not necessarily match the intended force level. In this case, the actual force tends to overshoot at relatively lower levels, while it tends to undershoot at relatively higher levels (Jackson & Dishman, 2000; Kumar & Simmonds, 1994; West et al., 2005). These findings suggest that different muscle activations and central mechanisms are reserved for externally triggered and internally guided movements (Ariani et al., 2015; Kuhtz-Buschbeck et al., 2008; Ni et al., 2006).

The perception of the intended force is thought to be affected by central control (Lafargue & Franck, 2009; Marcora, 2009). The central motor command, a feedforward signal associated with motor effort rather than the actual exercise intensity, is transmitted from the higher brain centers during voluntary movement (Gandevia et al., 1993). A stronger voluntary drive of intended movements as well as muscle contractions may be accompanied by internally guided movements (Ni et al., 2006). In human upper limb muscles, it is known that the strength of corticomotoneuronal connections is greater in distal muscles than in proximal muscles (Palmer & Ashby, 1992). This revealed that precise movement accompanies greater and stronger voluntary drives derived from the cerebral cortex, whereas powerful movement accompanies smaller and weaker voluntary drives, which may be performed unconsciously

and is likely mediated by neural circuits at the subcortical level (Liang et al., 2011). In particular, hand dexterity and coordination are among the key elements of personhood, and the grasping forms that we utilize in our daily life can be divided into powerful and precise movements. For example, a power grip that uses the gross hand is competent to generate strong force, whereas pinches that use fine hand and finger movements are suitable for performing complex and precise movement. To achieve a precision pinch grip, different grasping forms are used for different situation in daily life. For instance, a side pinch using the belly of the thumb and the lateral of the index finger is used to manipulate a key, whereas a pulp pinch using the bellies of the thumb and index finger is used to pick up objects such as coins. It has been reported that cortical activity differs between the power grip and pinches (Ehrsson et al., 2000; Tazoe & Perez, 2017). Furthermore, the perception of force is more accurate with pulp pinch than with side pinch (Williams et al., 1991), so it is reasonable to hypothesize that there is a difference in the related cortical excitability as well as motor performance among grasping forms. However, it is unclear how cortical activity, in particular the dorsolateral prefrontal cortex (DLPFC), differs depending on its accuracy in these grasping forms.

The cortical mechanisms underlying these power grips and pinches are of interest. Multiple cortical areas involving the primary motor cortex (M1), supplementary motor area, sensory area, premotor, parietal and prefrontal areas are considered candidate brain regions engaged in the planning and exertion of voluntary movements (Ehrsson et al., 2000; Ehrsson et al., 2001; König & Engel, 1995).

The DLPFC, a region that is related to both cognitive and motor functions (Faw, 2003), is also considered one of the cortical areas involved in intended force production and control. The activation of the frontal areas and left DLPFC, in addition to the motor-related areas, increased depending on the amplitude of force generation or prediction during static and dynamic exercise (Asahara et al., 2018; Dai et al., 2001; Ishii et al., 2018; Wasson et al., 2010). Using near-infrared spectroscopy (NIRS), we have also found that the oxygenated-hemoglobin concentration in the DLPFC increased 5-10 seconds prior to the intended voluntary movements (Asahara et al., 2016). Interestingly, in that study, the preceding increments of oxygenated-hemoglobin concentration in the DLPFC were prominent before intended and self-paced voluntary movements, but not with those initiated by a Go Cue. Taken together, these findings provide evidence that the DLPFC may play a crucial role in volitional force generation in an amplitude-dependent manner and suggest that it activates not only during the movement but also prior to the action execution, which may reflect the preparation of the movement in advance. However, to date there has been no clear evidence that the pre-activation of the DLPFC varies with the force amplitudes. Furthermore, whether the pre-activation of the DLPFC differs across grasping forms is unknown, although differential activation of the frontal areas has been reported between repetitive power grip and pulp pinch (Ehrsson et al., 2000). Therefore, we investigated the DLPFC activation prior to force production using an intended ballistic grip task without visual or auditory feedback in the present study.

The first aim of this study was to investigate the accuracy of force generation and the involvement of finger and forearm muscle activities during ballistic hand power grip, side pinch, and pulp pinch. Using two-channel NIRS, the second aim of this study was to define the bilateral DLPFC activity preceding the intended force production. We hypothesized that the accuracy of force generation would be higher for pinches that require more precise hand manipulation, compared to the power grip, and that the pulp pinch would be the most accurate. In addition, in the dynamic unilateral task, DLPFC activity increased in a force-dependent manner (Ishii et al., 2018), while prefrontal activity increased more when a lower force was exerted in the pulp pinch (Ehrsson et al., 2000; Tazoe & Perez, 2017). Therefore, we hypothesized that pre-activation in the DLPFC would increase depending on the force levels in power grip, and the opposite pattern might be observed in the side and pulp pinch.

METHODS

Participants

A total of 21 healthy volunteers participated in this study (10 men and 11 women; mean age 24.1 \pm 5.4 years). All volunteers were right-handed according to the Flinders Handedness Survey (FLANDERS) questionnaire (9.3 \pm 1.6 points) (Nicholls et al., 2013; Okubo et al., 2014). Twelve of the participants (five men and seven women; mean age 24.8 \pm 6.9 years) were recruited in Protocol 1 (see below), and 14 participants (six men and eight women; mean age 25.0 \pm 6.5 years) were recruited

in Protocol 2. Five participants who engaged in Protocol 1 were also engaged in Protocol 2. None of the volunteers had any known neurological or orthopedic disorders and were not prescribed any medications. The participants provided written informed consent prior to the experiments. The experimental procedures and protocols were performed in accordance with the Declaration of Helsinki and were approved by the Ethics Committee of Kyoto University Graduate School and Faculty of Medicine (Approval no. C1492).

Experimental procedures

The participants were comfortably seated in an armchair with both elbow joints flexed at approximately 90° and relaxed on a horizontal plate attached to the armrests. The right upper limb was placed with the forearm and wrist joint in a neutral position, and was immobilized with Velcro tape at the wrist. The left upper limb was relaxed and placed on the horizontal plate throughout the experiment. A light-emitting diode (LED), which was attached to a whiteboard placed 1.0 m in front of the participants, was set at their eye-level for the Go cue.

Grip force and electromyography recordings

The force involved during power grip, side pinch, and pulp pinch during the motor tasks were recorded using grip and pinch dynamometers (MT-130 and MT-140, respectively, SAKAI Medical Corporation Ltd., Tokyo, Japan), which were fixed and placed at the end of in the right hand. The grip dynamometer was adjusted for each participant's hand so that the proximal interphalangeal joint was flexed at approximately 90° during power grip. The pinch force during the side and pulp pinches was measured with the thumb and index finger, and the other fingers were mildly flexed. The participants were instructed to pinch the plate with the lateral side of the index finger and belly of the thumb in a side pinch, and with the bellies of the thumb and index finger in a pulp pinch (Figure 1).

Surface electromyography (EMG) was recorded from two intrinsic (first dorsal interosseous [FDI] and thenar [THENAR]) and two extrinsic (extensor carpi radialis [ECR] and flexor carpi radialis [FCR]) hand muscles in the right hand using a pair of silver-bar electrodes (10 mm in length, 1 mm in diameter, and 10 mm in distance, Bagnoli-4 EMG System, Delsys, Boston, Massachusetts, USA). The reference electrode was attached to the right styloid process of the ulna. The EMG signals were amplified (x1,000) and passed through a bandpass filter between 20 and 2,000 Hz. The EMG activity with the maximum voluntary contraction (MVC) of each muscle was recorded at the beginning of the experiment.

NIRS recording of the DLPFC

The changes in the concentration of total-hemoglobin (total-Hb) were recorded using a two-channel NIRS (HOT-2000, NeU Corporation, Tokyo, Japan) attached to the bilateral DLPFC. A pair of photoemission and photodetection probes (inter-probe distance, 30 mm) was placed on the forehead

between Fp1 and F3 (left side) and between Fp2 and F4 (right side) according to the 10-20 international electrode system. The NIRS probe placement corresponds to underlying cortical areas, including the DLPFC (Rossi et al., 2001; Herwig et al., 2003; Endo et al., 2013). Near-infrared light (wavelength 800 nm) reflected through the cerebral tissue was sampled and recorded at a rate of 10 Hz.

Experimental protocols

In Protocol 1, we conducted a power grip force-matching task to compare the accuracy of grip force by movement type with visual feedback. At the beginning of the motor task, the maximum voluntary force (MVF) of the power grip was measured for 2-3 s, and 20, 40, 60, and 80 percent of the MVF were defined as the target force levels. The display was placed 1.5 m in front of the participants, on which the target force levels (a horizontal line) and the actual force levels recorded from a grip dynamometer were displayed in real time. Force-matching tasks consisted of ballistic (reaching the target levels within 1 s) and static (maintaining the force levels for 2-3 s) movements with visual feedback.

In Protocol 2, participants performed a force-matching task without visual or auditory feedback using power grip, side pinch, and pulp pinch to compare the differences in muscle and DLPFC activity as well as force accuracy with grasping form and force levels. The MVF for each grip was measured at the beginning of the motor task. Similar to Protocol 1, 20, 40, 60, and 80 percent of the MVF for each

grip were defined as the target levels. After confirming the resting state of the participants from the surface EMG and NIRS signals, the Go cue was provided using an LED light (Figure 2A). The participants were asked to take sufficient time (more than 10 s) before the volitional and self-paced force generation of the power grip or pinches. A metronome set at 60 beats-per-minute was used throughout the experiment (at rest or performing a motor task) to confirm the duration. They were also instructed to perform the motor task with ballistic movement (within 1 s). Neither visual nor auditory feedback regarding the generated force was provided to the participants. The order of the target force levels and grasping forms was randomized in individual participants. We also confirmed in the control session without the motor task that the metronome and LED light had no significant influence on the NIRS signals of the DLPFC.

In both protocols, sufficient trials were performed before recording to familiarize the participants with the motor task. An illustration of a selected force level was provided to the participants during the experiment to ensure the target force level of the upcoming task (Figure 2B).

Data analysis

Force signals and EMG activities were recorded using the data acquisition software (LabChart. AD Instruments, Sydney, Australia) for the PowerLab analog-to-digital converter (PowerLab 7/30, AD Instruments, Sydney, Australia) at a sampling rate of 2000 Hz. For the force signals, the mean value

of the force during the steady phase (1 s) under the static condition (Protocol 1) and the peak value of the force under the ballistic condition (Protocols 1 and 2), as well as the integrated EMG activity, were calculated and presented as a percentage of MVF (%MVF). We calculated the error in the actual force level from the target force level for each condition. The EMG signals were rectified, and the integral value was calculated as the duration from the onset of the EMG activity to the peak of the force signal. The onset of the EMG signal was defined as the time at which the amplitude increased by more than 100 % from the baseline level (time = 0).

Each baseline value of the resting state NIRS signal (concentration of total-Hb) was determined as the mean amplitude over 10 s prior to the Go cue of the motor task, and the changes from the baseline amplitudes were then expressed as the relative changes from the baseline (Δ mMmm). In the time course, the preparatory phase was defined as the time from the Go cue until EMG onset, and the average value of the relative changes during the preparatory phase was calculated for the 10 s immediately before the EMG onset (from -10 to 0 s) for each task. Apart from the data for each force level, the data of 20 and 40 % MVF (low force level), or those of 60 and 80 % MVF (high force level) were pooled and averaged for further investigating the difference in the concentration of total-Hb between relatively low and high force levels.

Statistical analysis

Data were analyzed using JMP Pro 16.1 software (SAS Institute Incorporation, Cary, North Carolina, USA). Two-way analysis of variance (ANOVA) with repeated measures was used to compare the error between ballistic and static movements with visual feedback in Protocol 1 (factors: target force level, movement type). Then, to compare the effect of visual feedback on the accuracy of force generation, a two-way factorial ANOVA was used between the error of ballistic power grip force with (n=12) and without visual feedback (n=14) (factors: target force level, feedback). For the EMG data of each muscle, two-way ANOVA with repeated measures (factors: target force level, grasping form) was performed to examine the influence of the grasping form at different force levels. The relationship between EMG data (% MVC) and the actual force levels (% MVF) was also analyzed using the Pearson coefficient of correlation. Regarding the NIRS data, the average values of the concentration of total-Hb were analyzed using two-way ANOVA with repeated measures (factors: target force level, laterality). To compare the NIRS data among grasping forms, two-way ANOVA with repeated measures (factor: grasping form, laterality) was performed for each target force level. Significant results were followed by a post-hoc multiple comparison with Bonferroni correction. The correlation between the actual generated force and activation of the bilateral DLPFC was analyzed using Pearson's correlation coefficient. The level of the statistical significance was defined as P < 0.05. Results are presented as the mean \pm SE.

RESULTS

The accuracy of force generated

The averaged data of the actual power grip force and errors in the Protocol 1 (n = 12) and Protocol 2 (n = 14) are shown in Table 1. There was a significant difference in the error to the target force level between the static and ballistic conditions ($F_{(1,11)} = 20.2$, P < 0.0001), and the error under the ballistic condition was larger than that under the static condition. We did not find any significant differences between the target force levels and interaction. There was no significant difference between the error under the ballistic condition with and without visual feedback across the target force levels and the interaction effect.

Figure 3A and B show the absolute value of the actual force generated (kgf) and relative value to 100 % MVF, respectively. The numerical values of 100 % MVF were 33.2 ± 8.1 kgf with power grip, 7.4 ± 2.4 kgf with side pinch, and 5.9 ± 2.1 kgf with pulp pinch. The absolute values were obviously larger for the power grip than pinches, but the relative value to 100 % MVF was similar among grasping forms. The error rate was significantly differed among the target force levels ($F_{(3, 39)} = 10.2$, P < 0.0001) and was also significantly different among the grasping forms ($F_{(2, 26)} = 4.6$, P = 0.0115) (Figure 3C). No significant interaction was detected between the target force level and grasping form. Post-hoc analysis of the grasping forms revealed that the error in the side pinch was significantly larger than that in the power grip (P < 0.001). Among the target levels, a post-hoc analysis revealed that the

error in the 20 % MVF was larger than that in 60 and 80 % MVF, and the error in the 40 % MVF was larger than that in 80 % MVF (P < 0.005, respectively).

EMG activity

Table 2 shows the mean EMG activity for each muscle. In all four muscles, the EMG activity significantly varied across the target force levels (FDI; $F_{(3, 39)} = 16.7$, THENAR; $F_{(3, 39)} = 29.9$, ECR; $F_{(3, 39)} = 29.7$, FCR; $F_{(3, 39)} = 13.9$, P < 0.001), and among the grasping forms (FDI; $F_{(2, 26)} = 9.7$, THENAR; $F_{(2, 26)} = 23.4$, ECR; $F_{(2, 26)} = 91.8$, FCR; $F_{(2, 26)} = 13.1$, P < 0.001). There was no interaction between the target force level and grasping form in any of the muscles. Regarding the intrinsic hand muscles, post hoc analysis of the grasping forms revealed that the EMG activity of FDI was significantly smaller in the side pinch than that in the pulp pinch (P = 0.0001), and the EMG activity of THENAR was significantly smaller in the pulp pinch than in the power grip and side pinch (P < 0.0001, respectively). On the other hand, the EMG activity in the extrinsic hand muscles ECR and FCR were significantly larger in the power grip task than in the side and pulp pinches (P < 0.005, respectively), especially in the case of the ECR.

As shown in Figure 4, there was a significant positive correlation between the EMG signals and the actual force in all grasping forms and muscles (P < 0.05). In the power grip, the EMG activity of the THENAR and ECR tended to be larger than that of the FDI and FCR. The EMG activity of THENAR

was larger than that of FDI in the side pinch and, conversely, the EMG activity was larger in FDI than that of THENAR in the pulp pinch.

The DLPFC activation prior to the hand grips

The time course of the changes in the total-Hb concentration in the bilateral DLPFC is shown in Figure 5A. The average duration from the auditory cue to EMG onset was 12.7 ± 2.0 s (mean \pm SD). In the control session, the average changes in the total-Hb did not significantly differ from baseline on both sides (P = 0.48). In contrast, in the preparatory phase of the motor tasks, the total-Hb concentration was significantly increased from baseline before the visual cue (P = 0.00015). However, there was no significant difference among the target force levels generated between the left and right sides of the DLPFC, and interaction effect for each grasping form (Figure 5B). The two-way ANOVA of grasping form x laterality for each force level revealed that, In 20 % MVF, the DLPFC activation was significantly different among grasping forms ($F_{(2,26)} = 6.4$, P = 0.0028). Post-hoc analysis of the grasping forms revealed that the total-Hb concentration in the power grip was significantly smaller than that in the pulp pinch (P = 0.0052). For other target force levels, there was no significant difference among the grasping forms, laterality, and interaction effect.

To explore any difference in the DLPFC activation between force levels, we then compared the data between relatively low (20 and 40 % MVF) and high (60 and 80 % MVF) force levels in each grasping

form (Figure 6A). The total-Hb concentration between low and high force levels showed no significant difference with the power grip task, while it was significantly different with side pinch ($F_{(1, 13)} = 4.8$, P < 0.05) and pulp pinch ($F_{(1, 13)} = 5.6$, P < 0.05). A significant difference was not detected between the left and right sides of the DLPFC nor in the interaction between the target force level and laterality. Interestingly, the increment in total-Hb concentration was significantly larger with a high force level in the side pinch, while it was larger with a low force level in the pulp pinch, suggesting a distinct difference between the total-Hb concentration with a low target force level among the grasping forms ($F_{(2.26)} = 5.8$, P = 0.0049), and post-hoc analysis revealed that DLPFC activation in the power grip tended to be smaller than that in the pulp pinch (P = 0.018). No significant difference was detected with a high target force level.

Correlation analysis revealed a negative correlation between the actual force level and left DLPFC activation with pulp pinch (r = -0.33, P = 0.012), while there was no significant correlation with side pinch. With the power grip, on the other hand, the actual force level positively correlated with bilateral DLPFC activation (left: r = 0.32, P = 0.016; right: r = 0.32, P = 0.018) (Figure 6B).

DISCUSSION

In the present study, we utilized ballistic power grip, side pinch, and pulp pinch tasks to investigate the accuracy of intentionally generated force, the related intrinsic and extrinsic hand muscle activations, and the changes in cortical activities in the bilateral DLPFC at different target force levels. The major findings from this investigation are as follows: 1) without visual feedback, the accuracy of power grip and pulp pinch was relatively higher than that of the side pinch. Considering the fact that the absolute value of force was comparable between side and pulp pinches but was quite different between power grip and pinches, it seemed that the pulp pinch involved the most precise force control among these grasping forms, 2) EMG activity of intrinsic hand muscles exhibited a similar trend for power grip and side pinch, while the opposite pattern in the recruitment of these muscles was observed for the pulp pinch; and 3) DLPFC activation in the preparatory phase was observed in all motor tasks, while the increment in oxygenation was different and displayed opposite results between relatively low and high force levels in side and pulp pinches. Taken together, it is suggested that the accuracy of the generated force, as well as intrinsic hand muscle activities, may vary among different grasping forms, even when using a similar thumb and index finger combination for pinching (side and pulp pinches). The characteristics of motor performance and associated EMG activity in pulp pinch showed distinct differences to those in power grip and side pinch, suggesting that differential activities of the DLPFC prior to the intended force generation contribute to the precise force control. To the best of our knowledge, this is the first study to demonstrate both DLPFC activation prior to single-shot and

ballistic force generation, and the resulting accuracy of the generated force and associated EMG activities with power grip and pinches.

The accuracy of the intentionally generated force

Regarding the motor performance of force generation, some reports have investigated the accuracy of the actual force produced at different force levels (Cooper et al., 1979; Jackson & Dishman, 2000; Kumar & Simmonds, 1994; Li et al., 2020; Miyamoto et al., 2020a, 2020b; West et al., 2005). In conditions where visual or auditory feedback is not available, the generated force tends to overshoot at relatively lower levels, while it tends to undershoot at relatively higher levels (Jackson & Dishman, 2000; Kumar & Simmonds, 1994; Li et al., 2020). Kumar and Simmonds (1994) have reported that there was no significant difference between perceived and objective strength effort with 40 % MVF, suggesting that it would be the most accurate force when individuals perform approximately half of their maximum effort. In the present study, we confirmed that the force generated with visual feedback with both static and ballistic movements were quite accurate (Table 1). However, without visual feedback, the results were not necessarily consistent with those of these previous studies, and the force generated tended to be larger than those in previous studies for all grasping forms and force levels. The slight difference between the previous and present studies might be due to the difference in the muscle contraction mode used in the motor tasks. It has been shown that the force generated with ballistic movements and associated muscular activities are larger than those generated with static

movements, even though the same target force levels are intended (Miyamoto et al., 2020b). The magnitude of force production is affected by the recruitment and firing rates of the motor units. It has been reported that the increased firing rate and the decreased recruitment threshold under ballistic conditions (Masakado et al., 1995), resulted in an increase in surface EMG amplitudes (Yoneda et al., 1983). In addition, the rapid muscle contraction associated with ballistic movement requires an enhanced rate of force development (Semmler, 2002). This rapid force development is related to the synchronization of motor units, and the synchronization is thought to be important under ballistic conditions (Farina & Negro, 2015; Semmler, 2002). However, the high synchronization of motor units eauses an increase in the amplitude of EMG and a decrease in the stability of the produced force (Yao et al., 2000). Therefore, it is suggested, especially at lower target force levels, that the lower accuracy with ballistic contraction might be related to the synchronization of the motor units.

Although the overshoot of generated forces decreased depending on the increment of force levels in all three grasping forms in the present study, the accuracy with the side pinch was significantly lower than that in the power grip task, and tended to be lower than that with the pulp pinch (Figure 3B and C). The pinches required more precise and detailed adjustment during force generation because the absolute value of the MVF in pinches was considerably smaller than that in the power grip (Figure 3A). Because the two pinches were almost equal in maximum muscle strength, the pulp pinch could generate intentional force more accurately than the side pinch, even with the same precision grip using the thumb and index finger (Kozin et al., 1999). On the other hand, participants made a comparable number of errors (% MVF) with the power grip and pulp pinch, suggesting that the pulp pinch is more precise in generating the intended force than the power grip in terms of absolute magnitude of force. It also suggested that the perception of the intended force was similar and independent of the absolute value, although the contribution of related muscles and central mechanisms might be different among these grasping forms.

EMG activity during ballistic force generation tasks with three grasping forms

Both intrinsic and extrinsic hand muscles are thought to be engaged in the hand motor tasks such as power grip and pinches. Intrinsic hand muscles are involved in precise hand manipulation, including movement direction and speed, while extrinsic hand muscles are primarily related to joint stability (Adewuyi et al., 2016). When performing a sustained grasping task, the synchronization of the extrinsic hand muscles increased during the power grip task compared to during the pinch task, and this increased with the magnitude of the generated force (Zhang et al., 2021). The results of the present study showed that the EMG activities of extrinsic hand muscles (ECR and FCR) were significantly larger during the power grip task than those during side and pulp pinches over a wide range of generated force levels. Therefore, in line with previous studies, we found that these extrinsic hand muscles worked together to ensure wrist joint stability in the case of the ballistic grasping task. Particularly, the EMG activity of the ECR increased gradually depending on the increase in force level and showed larger increments than those of the FCR irrespective of the grasping form, suggesting that the extensor rather than flexor muscles play a role in the grasping task.

Apart from the power grip, pinches need precise adjustment of the generated force, and the involvement of intrinsic hand muscles is considered to be important for force generation and control. The intrinsic hand muscles FDI and THENAR, which are associated with thumb and index finger movements, respectively, showed increased activity in accordance with increments of the force level. Interestingly, with side pinch the increment of EMG activities in FDI and THENAR were similar to that with power grip, while the contribution of FDI became larger when performing pulp pinch (Figure 4). Using transcranial magnetic stimulation, we previously examined the effects of training on force control in pulp pinches (Liang et al., 2007). The results showed that the improvement in force control was associated with the excitability change in the M1 of FDI but not in that of THENAR, suggesting that FDI is crucial for precise force control for holding during pulp pinch. In line with this previous study, the activation of the FDI was larger in the pulp pinch than in the side pinch, suggesting that the FDI might play a role in precision force control in pulp pinch using the thumb and index finger. Interestingly, through motor learning, the modulation of EMG activity by FDI was transferred to the untrained hand, and the contralateral M1 excitability was similarly modulated (Liang et al., 2007). This suggested that the internal models for force prediction and control were improved, therefore, it is expected that higher brain functions, aside from the M1 activity, might be involved in the force control of pinches.

The DLPFC activation in the preparatory phase of hand grips

The central mechanism related to force control consists of a feedforward signal descending from higher brain centers and a feedback signal based on afferent sensory inputs. As previous reports investigating the central mechanisms related to force generation have often provided the external feedback to the participants or used a sustained static or repetitive force generation task, they reflect the effects of not only a feedforward signal but also sensory feedback. On the other hand, under ballistic conditions without visual or auditory feedback, such as the one used in the present study, the contribution of sensory feedback might be minimized, and therefore, the feedforward control might be emphasized. Descending commands for motor output predominantly arise from the M1, and the activation of neurons in the M1 reflects the magnitude of the exerted muscle activity (Kakei et al., 1999; Perez & Cohen, 2009). However, the M1 is thought to be involved in the regulation of the force pulses production but not in the selection of force amplitude, and areas such as the basal ganglia, supplementary motor cortex, anterior cingulate cortex, and DLPFC are thought to regulate the selection of force amplitude (Vaillancourt et al., 2007). In addition, the prefrontal cortex, corresponding to the DLPFC, is activated several seconds before movement onset in volitional movement, but not in passive movement (Asahara et al., 2018; Asahara et al., 2016; Ishii et al., 2018;

Ishii et al., 2016; Pedersen et al., 1998). This suggests that the prefrontal cortex, particularly the DLPFC, is involved in the feedforward control of force selection and generation. In line with these previous studies, the present study has also demonstrated a distinct increase in the DLPFC activation from early in the preparation phase across several force levels, although it appeared to differ among the grasping forms.

The DLPFC might also be associated with the magnitude of the generated force (Ehrsson et al., 2000; Ehrsson et al., 2001; Vaillancourt et al., 2007; Wasson et al., 2010) and force control (Jin et al., 2019). Interestingly, we observed a greater increase in the pre-activation of the bilateral DLPFC when the intended target force levels were relatively lower in the pulp pinch, while it occurred when the intended target force levels were relatively high in the side pinch. In addition, there was a significant weak positive correlation between activation in the DLPFC and the actual force levels in the power grip task, and a negative correlation in the pulp pinch task. Taken together, the DLPFC activity increases when generating relatively higher forces in power grip and side pinch, which are easy to exert power, and relatively lower forces in pulp pinch, which requires more precise control of the hand (Kozin et al., 1999). This suggests that activation in the DLPFC might differ in a task precision-dependent manner.

Cortical activation during task execution may differ between power grip and precise pinches. Muri and Lemon (1983) reported a population of M1 neurons innervating the intrinsic hand muscles activate

during pulp pinch tasks but not during power grip tasks, even when similar background EMG is exhibited in primates. In humans, corticospinal excitability is greater in the pulp pinch than in the power grip, and this difference occurs at the cortical level (Tazoe & Perez, 2017). Activation in other cortical areas such as the ventral premotor cortex (PMv), the rostral cingulate motor area, and the posterior parietal and prefrontal cortices was also stronger during the pulp pinch than during the power grip (Ehrsson et al., 2000). Similar to these reports, we found differences in the DLPFC activity between power grip and pulp pinch, and further revealed that such differential increments in the excitability of the DLPFC, which depended on the force levels, could be observed at the preparatory phase of the movements. During a repetitive force-matching task using pulp pinch, Ehrsson et al. (2001) have reported that larger increases in the activation of the frontal area could be observed with smaller force (0.39 kgf, 5 % MVF) than that with larger force (1.7 kgf, 23 %MVF), both of which were relatively lower forces. We extended on previous studies by showing the force-dependent activation of the DLPFC during the preparatory phase of the motor task and over a wide range of force levels (2.1~ 4.7 kgf, 20-80 % MVF). Given the fact that the error (% MVF) of power grip and pulp pinch was similar, the absolute error (kgf) should be smaller in pulp pinch than power grip, suggesting more accurate force control in the pulp pinch. Therefore, the differences in the cortical activity between the power grip and pulp pinch might be characterized by increased activity at relatively lower force levels in the pulp pinch, just as there are neurons in the M1 and PMv with increased firing rates at weaker forces in the pulp pinch (Maier et al., 1993). Probably, it reflects that the gross hand movement of power grip might be mainly controlled at the subcortical level (Muri & Lemon, 1983), while the fine hand movement of pinches needs more cortical control, especially in the case of pulp pinch.

Moreover, we have also demonstrated, for the first time, the difference in cortical activation patterns between the side pinch and pulp pinch, although the identical thumb and index finger are used in both grasping forms. The increments in the DLPFC excitability, as well as the engagement of the intrinsic hand muscles in the side pinch were similar to those in the power grip, but were not similar to those in pulp pinches. This suggests that the side pinch is a grasping form that, no longer a precision grip, is suitable for exerting a strong force similar to a power grip, and the central mechanisms of similar pinches using the same fingers may not necessarily coincide.

Clinical relevance

Proper force generation is one of the most important factors for avoiding excessive fatigue and enabling smooth movements (Hermsdörfer et al., 2003). In daily life and rehabilitation, various grasping forms, such as power and precision grip, are used. The present study revealed that the accuracy of force generation differed depending on the grasping form, and this difference might be due to EMG engagement. Therefore, it may be necessary to pay attention to the grasping forms when assessing hand dexterity during manipulation of an object in patients with central or peripheral nerve system diseases, who often have lower dexterity due to muscle weakness and paralysis. DLPFC activation was also influenced by grasping form, especially depending on the type of grasping form. The DLPFC is a cortical area involved in both motor and cognitive functions (Faw, 2003). We have recently reported that the magnitude of grip force can be an indicator potentially reflecting the consciousness during awake craniotomy (Umaba et al., 2022), suggesting that the accuracy of force generation reflects, at least in part, the individual's cognitive state. Therefore, it might be possible to examine the relationship with cognitive function by evaluating the accuracy of force output as well as the maximum voluntary force generation.

Limitations

The present study has several limitations. First, the index of total-Hb concentration was utilized for exploring the DLPFC activation. The Total-Hb concentration consists of oxygenated-Hb and deoxygenated-Hb concentrations, and the oxygenated-Hb concentration depends on regional blood supply and is associated with increased neural activity in the corresponding brain regions. In contrast, the deoxygenated-Hb concentration has little to no affect, regardless of exercise intensity (Endo et al., 2013). Therefore, the results of the present study may mainly reflect changes in oxygenated-Hb concentrate solely on the preparation of different force levels, we could not exclude the effects of motor imagery on performance or cortical activation. Because we have shown that imagery of a cycling exercise had no significant effect on the prefrontal oxygenation (Asahara et al., 2016), it seemed that the effect of

motor imagery here would be minimum if any. Finally, the increments in DLPFC activity might be affected by paying attention to external stimuli such as the LED light (visual) and metronome (auditory) in the motor task. To exclude these possibilities, we conducted control trials in the present study and confirmed no significant changes in the DLPFC oxygenation and, therefore, suggested that the preceding DLPFC activation was devoted to movement preparation in the force generation task.

CONCLUSIONS

The present study demonstrates for the first time the central command-related and force-dependent changes in the DLPFC activity among different grasping forms. Our findings suggest that the pre-activation of DLPFC reveals a feedforward regulation for force control and it is more prominent in a precise motor task such as pulp pinch.

AUTHOR CONTRIBUTIONS

AO and NL. Conception and design of research; AO, MS, AM, TO, RS and NL. Data acquisition; AO and NL. Data analysis; AO, MS, AM, TO, RS, KI and NL. Interpretation of results; AO. Prepared the first version of the manuscript; AO, AM, TO, RS, KI and NL. Edited the manuscript; AO, MS, AM, TO, RS, KI and NL. Edited the manuscript; AO, MS, AM, TO, RS, KI and NL. Approved the final version of the manuscript.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ACKNOWLEDGEMENTS

This research was partially supported by grants from the Japan Society for the Promotion of Science (Grant-in-Aid for Scientific Research (B), 19H03974 to NL) and a Kyoto University internal grant, ISHIZUE (to NL). We would like to thank Editage (www.editage.jp) for English Language editing.

DATA AVAILABILITY STATEMENTSNOWLEDGEMENTS

The datasets analyzed in the present study are available from the corresponding author upon reasonable request.

REFERENCES

- Adewuyi, A. A., Hargrove, L. J., & Kuiken, T. A. (2016). An Analysis of Intrinsic and Extrinsic
 Hand Muscle EMG for Improved Pattern Recognition Control. *IEEE Transaction on Neural* Systems Rehabiltation Engineering, 24(4), 485-494. doi:10.1109/TNSRE.2015.2424371
- Ariani, G., Wurm, M. F., & Lingnau, A. (2015). Decoding Internally and Externally Driven Movement Plans. *Journal of Neuroscience*, 35(42), 14160-14171. doi:10.1523/JNEUROSCI.0596-15.2015
- Asahara, R., Endo, K., Liang, N., & Matsukawa, K. (2018). An increase in prefrontal oxygenation at the start of voluntary cycling exercise was observed independently of exercise effort and muscle mass. *European Journal of Applied Physiology*, 118(8), 1689-1702. <u>doi:10.1007/s00421-018-3901-4</u>
- Asahara, R., Matsukawa, K., Ishii, K., Liang, N., & Endo, K. (2016). The prefrontal oxygenation and ventilatory responses at start of one-legged cycling exercise have relation to central command. *Journal of Applied Physiology (1985)*, 121(5), 1115-1126. <u>doi:10.1152/japplphysiol.00401.2016</u>
- Chen, R., Yaseen, Z., Cohen, L. G., & Hallett, M. (1998). Time course of corticospinal excitability in reaction time and self-paced movements. *Annals of Neurology*, 44(3), 317-325. <u>doi:10.1002/ana.410440306</u>
- Cooper, D. F., Grimby, G., Jones, D. A., & Edwards, R. H. (1979). Perception of effort in isometric and dynamic muscular contraction. *European Journal of Applied Physiology and Occupational Physiology*, 41(3), 173-180. doi:10.1007/BF00430009
- Dai, T. H., Liu, J. Z., Sahgal, V., Brown, R. W., & Yue, G. H. (2001). Relationship between muscle output and functional MRI-measured brain activation. *Experimental Brain Research*, 140(3), 290-300. <u>doi:10.1007/s002210100815</u>
- Ehrsson, H. H., Fagergren, A., Jonsson, T., Westling, G., Johansson, R. S., & Forssberg, H. (2000). Cortical activity in precision- versus power-grip tasks: an fMRI study. *Journal of Neurophysiology*, 83(1), 528-536. doi:10.1152/jn.2000.83.1.528
- Ehrsson, H. H., Fagergren, E., & Forssberg, H. (2001). Differential fronto-parietal activation depending on force used in a precision grip task: an fMRI study. *Journal of Neurophysiology*, 85(6), 2613-2623. <u>doi:10.1152/jn.2001.85.6.2613</u>
- Endo, K., Matsukawa, K., Liang, N., Nakatsuka, C., Tsuchimochi, H., Okamura, H., & Hamaoka, T. (2013). Dynamic exercise improves cognitive function in association with increased prefrontal oxygenation. *Journal of Physiological Sciences*, 63(4), 287-298. <u>doi:10.1007/s12576-013-0267-6</u>
- Erdler, M., Beisteiner, R., Mayer, D., Kaindl, T., Edward, V., Windischberger, C., Lindinger, G., & Deecke, L. (2000). Supplementary motor area activation preceding voluntary movement is detectable with a whole-scalp magnetoencephalography system. *Neuroimage*, *11*(6 Pt 1), 697-707. doi:10.1006/nimg.2000.0579

- Farina, D., & Negro, F. (2015). Common synaptic input to motor neurons, motor unit synchronization, and force control. *Exercise and Sport Sciences Reviews*, 43(1), 23-33. <u>doi:10.1249/JES.00000000000032</u>
- Faw, B. (2003). Pre-frontal executive committee for perception, working memory, attention, longterm memory, motor control, and thinking: a tutorial review. *Consciousness and Cognition*, 12(1), 83-139. doi:10.1016/s1053-8100(02)00030-2
- Gandevia, S. C., Killian, K., McKenzie, D. K., Crawford, M., Allen, G. M., Gorman, R. B., & Hales, J. P. (1993). Respiratory sensations, cardiovascular control, kinaesthesia and transcranial stimulation during paralysis in humans. *The Journal of Physiology*, 470, 85-107. doi:10.1113/jphysiol.1993.sp019849
- Hermsdörfer, J., Hagl, E., Nowak, D. A., & Marquardt, C. (2003). Grip force control during object manipulation in cerebral stroke. *Clinical Neurophysiology*, 114(5), 915-929. <u>doi:10.1016/s1388-2457(03)00042-7</u>
- Herwig, U., Satrapi, P., & Schönfeldt-Lecuona, C. (2003). Using the international 10-20 EEG system for positioning of transcranial magnetic stimulation. *Brain topography*, 16(2). <u>doi:10.1023/b:brat.0000006333.93597.9d</u>
- Ishii, K., Liang, N., Asahara, R., Takahashi, M., & Matsukawa, K. (2018). Feedforward- and motor effort-dependent increase in prefrontal oxygenation during voluntary one-armed cranking. *The Journal of Physiology*, 596(21), 5099-5118. <u>doi:10.1113/JP276956</u>
- Ishii, K., Matsukawa, K., Liang, N., Endo, K., Idesako, M., Asahara, R., Kadowaki, A., Wakasugi, R., & Takahashi, M. (2016). Central command generated prior to arbitrary motor execution induces muscle vasodilatation at the beginning of dynamic exercise. *Journal of Applied Physiology (1985)*, *120*(12), 1424-1433. doi:10.1152/japplphysiol.00103.2016
- Jackson, A. W., & Dishman, R. K. (2000). Perceived submaximal force production in young adult males and females. *Medicine & Science in Sports & Exercise*, 32(2), 448-451. <u>doi:10.1097/00005768-200002000-00028</u>
- Jin, Y., Lee, J., Kim, S., & Yoon, B. (2019). Noninvasive brain stimulation over M1 and DLPFC cortex enhances the learning of bimanual isometric force control. *Human Movement Science*, 66, 73-83. doi:10.1016/j.humov.2019.03.002
- Kakei, S., Hoffman, D. S., & Strick, P. L. (1999). Muscle and movement representations in the primary motor cortex. *Science*, 285(5436), 2136-2139. <u>doi:10.1126/science.285.5436.2136</u>
- Kozin, S. H., Porter, S., Clark, P., & Thoder, J. J. (1999). The contribution of the intrinsic muscles to grip and pinch strength. *Journal of Hand Surgery (American Volume)*, 24(1), 64-72. <u>doi:10.1053/jhsu.1999.jhsu24a0064</u>
- Kuhtz-Buschbeck, J. P., Gilster, R., Wolff, S., Ulmer, S., Siebner, H., & Jansen, O. (2008). Brain activity is similar during precision and power gripping with light force: an fMRI study. *Neuroimage*, 40(4), 1469-1481. doi:10.1016/j.neuroimage.2008.01.037

- Kumar, S., & Simmonds, M. (1994). The accuracy of magnitude production of submaximal precision and power grips and gross motor efforts. *Ergonomics*, 37(8), 1345-1353. <u>doi:10.1080/00140139408964913</u>
- König, P., & Engel, A. K. (1995). Correlated firing in sensory-motor systems. Current Opinion in Neurobiology, 5(4), 511-519. doi:10.1016/0959-4388(95)80013-1
- Lafargue, G., & Franck, N. (2009). Effort awareness and sense of volition in schizophrenia. *Consciousness and Cognition*, 18(1), 277-289. doi:10.1016/j.concog.2008.05.004
- Li, L., Li, Y., Wang, H., Chen, W., & Liu, X. (2020). Effect of Force Level and Gender on Pinch Force Perception in Healthy Adults. *i-Perception*, 11(3), 2041669520927043. <u>doi:10.1177/2041669520927043</u>
- Liang, N., Nakamoto, T., Mochizuki, S., & Matsukawa, K. (2011). Differential contribution of central command to the cardiovascular responses during static exercise of ankle dorsal and plantar flexion in humans. *Journal of Applied Physiology (1985)*, *110*(3), 670-680. <u>doi:10.1152/japplphysiol.00740.2010</u>
- Liang, N., Takahashi, M., Ni, Z., Yahagi, S., Funase, K., Kato, T., & Kasai, T. (2007). Effects of intermanual transfer induced by repetitive precision grip on input-output properties of untrained contralateral limb muscles. *Experimental Brain Research*, 182(4), 459-467. <u>doi:10.1007/s00221-007-1004-2</u>
- Maier, M. A., Bennett, K. M., Hepp-Reymond, M. C., & Lemon, R. N. (1993). Contribution of the monkey corticomotoneuronal system to the control of force in precision grip. *Journal of Neurophysiology*, 69(3), 772-785. doi:10.1152/jn.1993.69.3.772
- Marcora, S. (2009). Perception of effort during exercise is independent of afferent feedback from skeletal muscles, heart, and lungs. *Journal of Applied Physiology (1985)*, 106(6), 2060-2062. <u>doi:10.1152/japplphysiol.90378.2008</u>
- Masakado, Y., Akaboshi, K., Nagata, M., Kimura, A., & Chino, N. (1995). Motor unit firing behavior in slow and fast contractions of the first dorsal interosseous muscle of healthy men. *Electroencephalography and Clinical Neurophysiology*, 97(6), 290-295. <u>doi:10.1016/0924-980x(95)00188-q</u>
- Miyamoto, T., Kizuka, T., & Ono, S. (2020a). Influence of preceding muscle activity on movementrelated cortical potential during superimposed ballistic contraction. *Neuroscience Letters*, 735, 135193. <u>doi:10.1016/j.neulet.2020.135193</u>
- Miyamoto, T., Kizuka, T., & Ono, S. (2020b). The Influence of Contraction Types on the Relationship Between the Intended Force and the Actual Force. *Journal of Motor Behavior*, 52(6), 687-693. <u>doi.org/10.1080/00222895.2019.1680947</u>
- Muir, R. B., & Lemon, R. N. (1983). Corticospinal neurons with a special role in precision grip. *Brain Research*, 261(2), 312-316. doi:10.1016/0006-8993(83)90635-2
- Ni, Z., Liang, N., Takahashi, M., Yamashita, T., Yahagi, S., Tanaka, Y., Tsuji, T., & Kasai, T. (2006). Motor strategies and excitability changes of human hand motor area are dependent on

different voluntary drives. *European Journal of Neuroscience*, *23*(12), 3399-3406. doi:10.1111/j.1460-9568.2006.04852.x

- Nicholls, M. E., Thomas, N. A., Loetscher, T., & Grimshaw, G. M. (2013). The Flinders Handedness survey (FLANDERS): a brief measure of skilled hand preference. *Cortex*, 49(10), 2914-2926. doi:10.1016/j.cortex.2013.02.002
- Okubo, M., Suzuki, H., & Nicholls, M. E. (2014). [A Japanese version of the FLANDERS handedness questionnaire]. *Shinrigaku Kenkyu*, 85(5), 474-481. doi:10.4992/jjpsy.85.13235
- Palmer, E., & Ashby, P. (1992). Corticospinal projections to upper limb motoneurones in humans. The *Journal of Physiology*, 448, 397-412. <u>doi:10.1113/jphysiol.1992.sp019048</u>
- Pedersen, J. R., Johannsen, P., Bak, C. K., Kofoed, B., Saermark, K., & Gjedde, A. (1998). Origin of human motor readiness field linked to left middle frontal gyrus by MEG and PET. *Neuroimage*, 8(2), 214-220. <u>doi:10.1006/nimg.1998.0362</u>
- Perez, M. A., & Cohen, L. G. (2009). Scaling of motor cortical excitability during unimanual force generation. *Cortex*, 45(9), 1065-1071. <u>doi:10.1016/j.cortex.2008.12.006</u>
- Rossi, S., Cappa, S. F., Babiloni, C., Pasqualetti, P., Miniussi, C., Carducci, F., Babiloni, F., & Rossini, P. M. (2001). Prefrontal [correction of Prefontal] cortex in long-term memory: an "interference" approach using magnetic stimulation. *Nature Neuroscience*, 4(9), 948-952. doi:10.1038/nn0901-948
- Semmler, J. G. (2002). Motor unit synchronization and neuromuscular performance. *Exercise and Sport Sciences Reviews*, *30*(1), 8-14. doi:10.1097/00003677-200201000-00003
- Tazoe, T., & Perez, M. A. (2017). Cortical and reticular contributions to human precision and power grip. *The Journal of physiology*, 595(8). doi:10.1113/JP273679
- Umaba, C., Mineharu, Y., Liang, N., Mizota, T., Yamawaki, R., Ueda, M., . . . Arakawa, Y. (2022). Intraoperative hand strength as an indicator of consciousness during awake craniotomy: a prospective, observational study. *Scientific Reports*, 12(1), 216. <u>doi:10.1038/s41598-021-04026-9</u>
- Vaillancourt, D. E., Yu, H., Mayka, M. A., & Corcos, D. M. (2007). Role of the basal ganglia and frontal cortex in selecting and producing internally guided force pulses. *Neuroimage*, 36(3), 793-803. doi:10.1016/j.neuroimage.2007.03.002
- Wasson, P., Prodoehl, J., Coombes, S. A., Corcos, D. M., & Vaillancourt, D. E. (2010). Predicting grip force amplitude involves circuits in the anterior basal ganglia. *Neuroimage*, 49(4), 3230-3238. <u>doi:10.1016/j.neuroimage.2009.11.047</u>
- West, S. J., Smith, L., Lambert, E. V., Noakes, T. D., & St Clair Gibson, A. (2005). Submaximal force production during perceptually guided isometric exercise. *European Journal of Applied Physiology*, 95(5-6), 537-542. <u>doi:10.1007/s00421-005-0004-9</u>
- Williams, W. N., Hanson, C. S., Crary, M. A., & Wharton, P. W. (1991). Human pinch-force discrimination. *Perceptual and Motor Skills*, 73(2), 663-672. <u>doi:10.2466/pms.1991.73.2.663</u>

- Yao, W., Fuglevand, R. J., & Enoka, R. M. (2000). Motor-unit synchronization increases EMG amplitude and decreases force steadiness of simulated contractions. *Journal of Neurophysiology*, 83(1). doi:10.1152/jn.2000.83.1.441
- Yoneda, T., Oishi, K., & Ishida, A. (1983). Variation of amount of muscle discharges during ballistic isometric voluntary contraction in man. *Brain Research*, 275(2), 305-309. <u>doi:10.1016/0006-8993(83)90991-5</u>
- Zhang, N., Li, K., Li, G., Nataraj, R., & Wei, N. (2021). Multiplex Recurrence Network Analysis of Inter-Muscular Coordination During Sustained Grip and Pinch Contractions at Different Force Levels. *IEEE Transaction on Neural Systems and Rehabiltation Engineering*, 29, 2055-2066. doi:10.1109/TNSRE.2021.3117286

FIGURE LEGENDS

Fig. 1 Experimental setup and positioning for each grasping form.

Fig. 2 (A) The time course in Protocol 2. The participants were asked to perform volitional force generation at their own pace more than 10 s after the Go cue (the LED light). The duration of force generation was within 1 s. (B) The specific target force level to generate was instructed randomly using this illustration. Only the target force level to generate was colored (for example, 60% of the maximum voluntary force).

Fig. 3 (A) The numerical value, (B) the relative value to 100 % MVF, and (C) the error from each target level in power grip, side pinch, and pulp pinch without visual feedback. MVF; maximum voluntary force. * P < 0.005.

Fig. 4 The correlation between the EMG activity and the actual force levels. Data are presented for each (A) intrinsic (FDI and THENAR) and (B) extrinsic (ECR and FCR) hand muscles. The dotted lines indicate the approximate straight lines for each participant, and the bold lines indicate the approximate straight lines for whole participants. FDI; first dorsal interosseous muscle, THENAR; thenar muscle, ECR; extensor carpi radialis muscle, FCR; flexor carpi radialis muscle, EMG; electromyography, MVC; maximum voluntary contraction, MVF; maximum voluntary force.

Fig. 5 (A) The time course of the averaged changes in the total-Hb at 1 s intervals. The EMG onset was defined as the time of 0 s, and the preparation phase was defined as the time from the Go cue to the EMG onset. (B) Averaged value during the preparatory phase (-10 s to 0 s). DLPFC; dorsolateral prefrontal cortex, total-Hb; total-hemoglobin, MVF; maximum voluntary force, EMG; electromyography.

Fig. 6 (A) The averaged value during the preparatory phase. (B) The correlation between the averaged value of total-Hb changes (above; left DLPFC, below; right DLPFC) and the actual force levels. The circles indicate relative low force levels (20-40% MVF) and the triangles indicate relative high force levels (60-80% MVF). There was a positive weak correlation with both the DLPFC in the grip task, and a negative weak correlation with the left DLPFC in the pulp pinch task. MVF; maximum voluntary force, total-Hb; total- hemoglobin, DLPFC; dorsolateral prefrontal cortex. * P < 0.05.

		20 %MVF	40 %MVF	60 %MVF	80 %MVF	_
With FB (static) (n = 12)	Mean	$\begin{array}{c} 19.3 \pm 0.3 \\ [18.7 - 20.0] \end{array}$	$\begin{array}{c} 38.9 \pm 0.4 \\ [38.0 - 39.8] \end{array}$	$58.8 \pm 0.3 \\ [58.2 - 59.5]$	$\begin{array}{c} 79.0 \pm 0.5 \\ [77.9 - 80.1] \end{array}$	
	Error	-0.7 ± 0.3 [-1.3 - 0.0]	-1.1 ± 0.4 [-2.00.2]	-1.2 ± 0.3 [-1.80.5]	-1.0 ± 0.5 [-2.1 - 0.0]	
With FB (ballistic) (n = 12)	Mean	$\begin{array}{c} 20.7 \pm 0.5 \\ [19.5 - 21.8] \end{array}$	43.5 ± 1.2 [40.7 - 46.4]	61.1 ± 1.0 [58.9 - 63.3]	80.3 ± 1.1 [77.7 - 82.8]	*
	Error	$\begin{array}{c} 0.7 \pm 0.5 \\ [-0.5 - 1.8] \end{array}$	3.5 ± 1.2 [0.7 - 6.3]	1.1 ± 1.0 [-1.0 - 3.3]	0.3 ± 1.1 [-2.2 - 2.8]	l
Without FB (ballistic)	Mean	31.3 ± 4.4 [21.3 - 41.2]	45.7 ± 5.4 [33.7 - 57.7]	62.0 ± 5.4 $[49.8 - 74.2]$	77.4 ± 5.7 [64.5 – 90.2]	
(n = 14)	Error	11.3 ± 4.4 [1.3 - 21.2]	5.7 ± 5.4 [-6.3 - 17.7]	2.0 ± 5.4 [-10.1 - 14.2]	-2.6 ± 5.7 [-15.5 - 10.2]	

Table 1. The actual force levels and the error from target force levels (%MVF) for power grip with and without visual feedback.

Values are means \pm SE [95% confidence intervals]. FB; feedback, MVF; maximum voluntary force. * P < 0.05.









Fig. 4



Side pinch

Pulp pinch

Left DLPFC

Α



Power grip

Right DLPFC

















Fig. 6



	•	• • •		6		
		20 %MVF	40 %MVF	60 %MVF	80 %MVF	
FDI	Power grip	13.8 ± 2.5	17.5 ± 2.8	22.5 ± 3.9	36.0 ± 4.8	
	Side pinch	9.5 ± 1.9	16.1 ± 3.1	20.8 ± 4.8	28.1 ± 5.4	*
	Pulp pinch	15.4 ± 3.7	30.9 ± 6.2	35.9 ± 7.8	39.3 ± 7.5	 *
THENAR	Power grip	26.1 ± 2.9	32.1 ± 4.0	43.3 ± 5.6	55.6 ± 6.2	
	Side pinch	22.9 ± 4.1	26.7 ± 4.1	38.3 ± 6.2	45.7 ± 7.1	*
	Pulp pinch	13.0 ± 2.1	20.1 ± 3.1	27.3 ± 5.5	32.4 ± 4.4	*
ECR	Power grip	23.9 ± 2.9	33.1 ± 3.5	36.4 ± 3.6	49.7 ± 4.1	 _
	Side pinch	11.7 ± 1.8	14.4 ± 1.9	18.8 ± 2.6	13.0 ± 3.5	*
	Pulp pinch	8.5 ± 1.0	12.5 ± 1.6	17.4 ± 2.2	23.0 ± 3.5	I
FCR	Power grip	8.8 ± 1.8	10.9 ± 1.8	12.8 ± 2.3	16.8 ± 2.9	
	Side pinch	7.6 ± 2.3	8.3 ± 2.3	9.3 ± 2.2	10.3 ± 2.3	*
	Pulp pinch	7.5 ± 2.2	8.9 ± 2.2	9.6 ± 2.2	12.2 ± 3.0	

Table 2. The averaged EMG activity (%MVC) of each muscle at different target force levels.

Values are means \pm SE. EMG; electromyography, MVC; maximum voluntary contraction, MVF; maximum voluntary force, FDI; first dorsal interosseous muscle, THENAR; thenar muscle, ECR; extensor carpi radialis muscle, FCR; flexor carpi radialis muscle. * P < 0.005.