Cerebral Hemodynamics during Maximal Muscle Contraction with Visual Feedback

—A Near-infrared Spectroscopy Study—

Makoto Fukuda*, Makoto Miyazaki, and Sunao Uchida***

*Faculty of Sport Science, Waseda University,
2-579-15 Mikajima, Tokorozawa-shi, Saitama 359-1192 Japan
makoto.fukuda@moegi.waseda.jp
**Waseda Institute for Advanced Study, Waseda University,
1-6-1 Nishi-waseda, Shinjuku-ku, Tokyo 169-8050 Japan

[Received April 9, 2008; Accepted October 21, 2008; Published online May 20, 2009]

It is well known that visual feedback of exerted force enhances muscle force during maximal voluntary contraction (MVC). Based on the previous reports on the force exertion tasks and the other tasks using the visual feedback paradigm, we hypothesized that the prefrontal cortex (PFC) is related to the enhancement of voluntary contraction force. The purpose of this study was to test the hypothesis and to identify the detail active regions in the PFC that correlates with the muscle force enhancement with visual feedback of exerted force, using near-infrared spectroscopy (NIRS). The cerebral blood flow of 11 male subjects was measured by NIRS during the MVC tasks with visual feedback of exerted torque (VFB) and without visual feedback (nVFB). As a result, both the elbow flexion torque during MVC and cerebral blood flow of the right PFC significantly increased under the VFB condition ($p<0.05$). In addition, the increased cerebral blood flow of the right PFC was correlated with the torque enhancement ($p<0.05$). The present results suggest that the right PFC is related to the increase of torque under the VFB condition. Since the PFC has a significant role in motivation, the enhancement of torque with visual feedback may be associated with such a function.

Keywords: maximal voluntary contraction, prefrontal cortex, cerebral blood flow, visual feedback, near-infrared spectroscopy

[International Journal of Sport and Health Science Vol.6, 230-237, 2008]

1. Introduction

A widely-used index for evaluating the force-generating capacity of skeletal muscles is muscle force during maximal voluntary contraction (MVC). The muscle force during MVC is known to correlate with the muscle cross-sectional area (Ikai & Fukunaga, 1968). However, the muscle force during MVC is not necessarily determined by quantitative characteristics of the muscle, such as muscle volume. Since muscles contract due to motor commands from the central nervous system (CNS), the activity of the CNS also affects the magnitude of muscle force during MVC. Behm et al. (2002) measured muscle force by activating peripheral nervous system and muscle without influence of CNS using electrical stimulation, and showed that the maximal muscle force evoked by electrical stimulation was higher than that of muscle force by MVC. In addition, previous studies reported that activation level of biceps brachii (BB) during MVC of elbow joint flexion did not achieve maximal level (Allen et al., 1998; Jakobi & Rice, 2002; Williams & Martin, 2004). From these findings, muscle force during MVC suggested not to achieve maximal level due to lower activation of CNS.

The difference between maximal voluntary force and maximal force evoked by electrical stimulation can be reduced by presenting feedback information to subjects. For example, physical performance was known to be improved by presenting physical motion or its error information (Schiffman et al., 2002). Further, presenting muscle force to subjects during MVC reported to enhance the muscle force (Peacock et al., 1981; Baltzopolous et al., 1991; Jung & Hallbeck, 2004). Since the muscle force exerted during MVC is enhanced by presenting feedback information to subjects, MVC is considered to be greatly affected by cortical activation regions related to process that information.

There is a considerable research on cortical activation regions related to force exertion tasks. In addition to known movement-related cortical regions, the primary motor cortex, premotor cortex, and supplementary motor area, the prefrontal cortex (PFC) has been reported to show extensive cortical activity during force exertion tasks. For example, according to previous studies that measured PFC activity during voluntary contraction by using functional magnetic resonance imaging (fMRI), the activation has been observed over extensive cortical regions in the PFC on the cerebral hemisphere during 80% MVC and 100% MVC of handgrip task (Dai et al., 2001; Liu et al., 2005). Liu et al. (2005) reported that the PFC during 100% MVC was activated more extensively than any other movement-related cortical regions. Further, PFC is also known to be activated by giving feedback information about task performance to subjects. Kawashima et al. (2000) reported that when subjects received appropriate feedback information and those that did not after line drawing tasks were measured for cerebral activity by positron emission tomography (PET), the latter subjects exhibited activated PFC along with improved accuracy of the line drawing task. Brunia et al. (2000) reported that subjects who were presented feedback information improved accuracy of button press timing, simultaneously PFC was activated compared with control subjects.

From the findings of these previous studies, it is assumed that muscle force is enhanced by MVC when feedback information is presented and this enhancement is associated with the PFC. Thus, the present study measured muscle force on MVC tasks with visual feedback of exerted force. By measuring regional cerebral blood flow of the PFC during these tasks with near-infrared spectroscopy (NIRS) by which cerebral functions can be measured with a low degree of physical constraint regardless of exercise pattern and strength (Miyai et al., 2001; Suzuki et al., 2004), this study aimed to clarify whether the PFC is related to the enhancement of voluntary contraction force and the detail active regions in the PFC that correlates with the muscle force enhancement with visual feedback of exerted force.

Figure 1 Experimental setup.
Elbow flexion torque was measured in seated position. Both elbow and shoulder joint angle were set at 90 degree.

2. Methods

2.1. Experimental design

2.1.1. Subjects

Eleven healthy young men (9 right-handed and 2 left-handed; age, 23.8±1.1 years; height, 169.2±3.6 cm; body mass, 65.1±4.7 kg; mean±SD) provided written informed consent which was approved by Institutional Review Board of Waseda University Faculty of Sport Sciences to participate in this study.

2.1.2. Measurement environment

Measurements were conducted within a shielded, dark room, preventing direct sunlight and electromagnetic waves from measuring instruments. The subjects wore earplugs which shield high-frequency noise.

2.1.3. Body posture

The measurement was performed with subjects seated. Regardless of their dominant hand, the right upper arm and forearm of the subjects were fixed at shoulder and elbow joint flexion angles of 90 degrees (a full extension position angle of 0 degrees) to an elbow joint torque myometer (Static Torque Model Vte-002 R, Vine, Tokyo, Japan) with a cloth belt (**Figure 1**). The forearm of the subjects was at the supinated position. An oscilloscope (CS-403S, Kenwood, Tokyo, Japan) was set in front of the subject so that he could visually

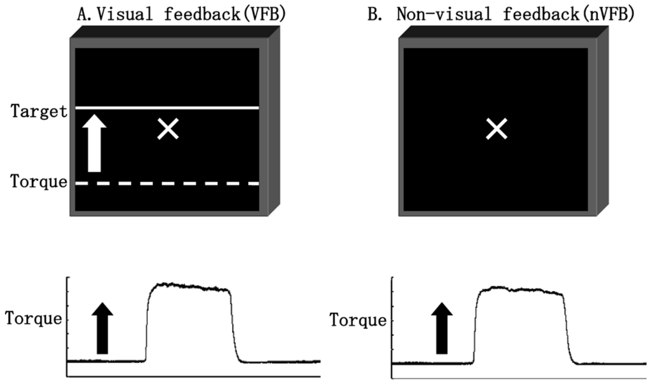

Figure 2 Display examples.
A. Visual feedback (VFB): Both target torque and real time torque were shown on the display.
B. Non-visual feedback (nVFB): No target and real time torque were displayed.

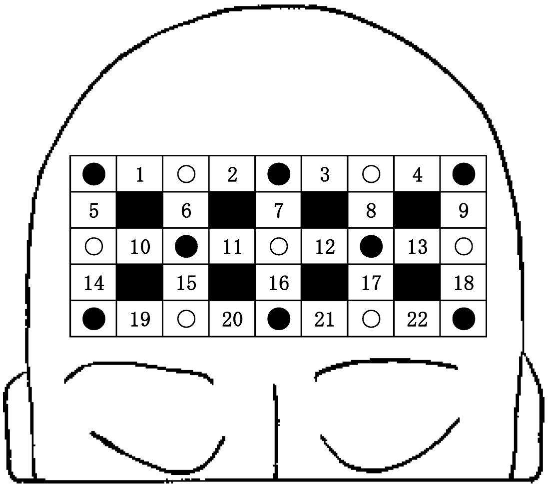

Figure 3 Measurement positions of near-infrared spectroscopy (NIRS).
NIRS measurement were performed at 22 positions (numbered) between eight irradiated probes (●) and seven receiver probes (○).

confirm his exerted torque.

2.1.4. Motor tasks

A motor task consisted of a 5-second isometric voluntary contraction for elbow joint flexion and before and after the task, a 150-second rest was assigned. The subjects performed two types of MVC exertion tasks (**Figure 2**). First, as the visual feedback (VFB) condition (**Figure 2-A**), the subject's exerted torque was displayed concurrently with his target torque in real time on the oscilloscope. Peak torque exerted without VFB that was previously measured was set as the target torque. The subjects were instructed to (1) exert torque as strong and fast as possible at the start of signal, (2) make a maximal effort to exceed their target torque, and (3) maintain their exerted maximal torque for 5 s. Meanwhile, in the non-visual feedback (nVFB) condition, neither the target torque nor the exerted torque was displayed (**Figure 2-B**). In addition, the subjects were instructed to (1) exert elbow joint flexion torque through their MVC as strong and fast as possible, and (2) maintain their exerted torque for 5 s, while staring at the fixation point (an X mark sized 1.5 by 1.5 cm) in the center of the oscilloscope screen. The order of these task conditions was randomly determined. Two trials were performed alternately for each condition.

2.2. Measured parameters

2.2.1. Elbow joint flexion torque

The elbow joint torque myometer was used for measurement of isometric elbow joint flexion torque. The signals obtained by this myometer were amplified with a strain amplifier (DPM-611B, Kyowa Electronic Instruments Co., Ltd., Tokyo, Japan), then transferred via an analog-digital converter (PowerLab/16SP, AD Instruments, Bella Vista, Australia) at a sampling frequency of 1 kHz to a personal computer (ThinkPad/T40, IBM, New York, USA).

2.2.2. Cerebral blood flow

NIRS was used for measurement of cerebral blood flow. Among three measured index of NIRS, oxygenated hemoglobin concentration (oxy-Hb), deoxygenated hemoglobin concentration (deoxy-Hb), and total hemoglobin concentration (total-Hb; the sum of the two Hb indices), the oxy-Hb which represents the cerebral hemodynamics most sensitively (Hoshi et al., 2001) was used in this study. A multichannel NIRS imaging device (NIRStation, OMM-3000, Shimadzu Co., Kyoto, Japan) was used to measure the change of oxy-Hb level during rests and tasks. NIRS signals were obtained from the 22 regions between a near-infrared light source fiber probe (8 probes in total) and a detector probe (7 probes in total) which were located alternately at 3.0 cm intervals on a cephalometric fiber holder (110 by 140 mm) mounted on the frontal region and scalp (**Figure 3**). For determination of the anatomical positions of the brain with NIRS, the international 10-20 system regarding electroencephalography (EEG) was employed (Herrmann et al., 2005; Thomas & Stephane, 2008). Based on this method, ch17 and ch15 were placed on *Fp1* and *Fp2* of each subject, respectively. The location of the NIRS probes on the scalp based on the 10-20 system corresponded to that in the Talairach coordinate axis of the standard brain, and *Fp1* and *Fp2* were both shown to be in near-field regions of Brodmann's area (BA) 10 (Okamoto et al., 2004). For *Fp1* and *Fp2*, the cerebral cortex is 1.0-2.0 cm deep from the scalp (Okamoto et al., 2004). Furthermore, a previous study has reported the measurement of 1.2-2.0 cm depth from the scalp at an inter-NIRS-probe distance of 2.7 cm (Raichle, 1999). Consequently, the present study, which measured the *Fp1* and *Fp2* region in the context of the international 10-20 system at an interprobe distance of 3.0 cm with NIRS, was considered to measure cerebral blood flow of cerebrocortical near-field regions of BA 10. The sampling frequency for NIRS signals was 160 Hz.

2.2.3. Data analysis

Under both conditions, the peak torque during MVC in the task period was used for analysis of elbow joint flexion torque. For analysis of NIRS signals at the time of peak torque, the difference between the peak torque during the task period and the averaged torque during the rest period was used, as analyzed by Miyai et al. (2001) and Suzuki et al. (2004). The analyzed period per ch was 8 s consisting of a 5-second task period and a 3-second post-task period. The rest period was 30 s, ranging from 90 s to 60 s before the task period.

2.2.4. Statistical processing

For analyses of both elbow flexion torque and oxy-Hb level, the averaged value of the two trials under each condition was used. The measured values were expressed as mean±standard error. To compare the averaged values of the exerted torque between the conditions, a paired t-test was performed. The difference in the averaged value of PFC activity between the conditions was tested by a multiple comparison, in which a paired t-test was modified by the Dubey/Armitage-Parmar method (Sankoh et al., 1997). This multiple comparison is used on the assumption that variables (oxy-Hb of each ch) correlate with each other. Herrmann et al. (2005) have used this multiple comparison to determine cerebral regions associated with motor inhibition with NIRS. In the present study, each detector probe placed close to each other in the PFC region assumed showing a correlation between each channel. Therefore, the multiple comparison modified with the Dubey/Armitage-Parmar method (Sankoh et al., 1997) was performed.

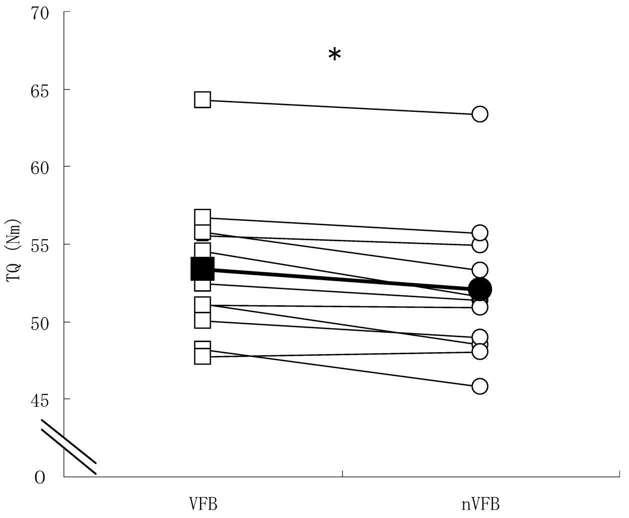

Figure 4 Maximal elbow flexion torque in each condition.
Left values (□) represent VFB condition and right values (○) represent nVFB condition. Filled square and circle (■,●) represent mean value of each condition. $*p<0.05$

3. Results

3.1. Difference in elbow joint flexion torque between conditions

The peak torque of elbow joint flexion during MVC was 53.4±1.4 Nm under the VFB condition and 52.1±1.4 Nm under the nVFB condition. The peak torque under the VFB condition was significantly higher than that of nVFB condition by 2.7%±0.7% ($p<0.05$) (**Figure 4**).

3.2. Difference in cerebral hemodynamics between conditions

Figure 5 shows a typical example of NIRS signals in frontal region from ch15 under the VFB condition. The oxy-Hb and total-Hb levels of blood flow showed similar change. These levels were lowered once from that at rest shortly after the task started, then kept rising during task period. After the task ended, these levels dropped rapidly. The deoxy-Hb level rose shortly after the task started, and then dropped in the middle of the task. All 22 chs for the NIRS-measuring probes placed over the frontal region of the subjects were compared for the peak oxy-Hb level between the conditions (**Table 1**). The peak value of the oxy-Hb level of ch11 (at the right frontal region) was significantly increased under the VFB condition compared to the nVFB condition ($p<0.05$). The peak value of ch11 under the

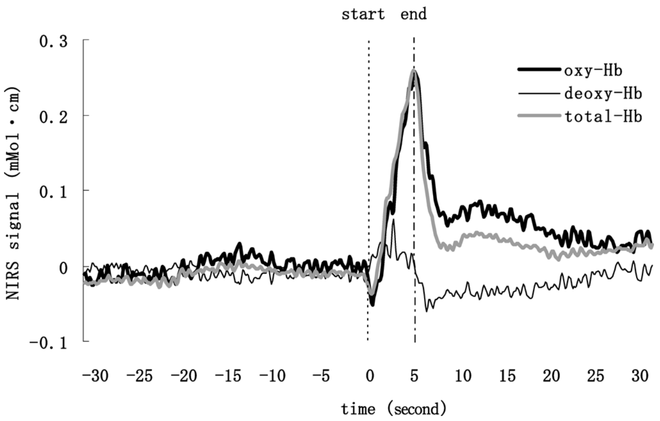

Figure 5 Hemodynamics of frontal region measured in NIRS during MVC.
Representative data from a single subject of hemodynamics in right frontal region measured in NIRS during MVC on ch15.

Table 1 Change in cerebral blood flow of frontal region in visual feedback and non-visual feedback conditions.

	VFB	nVFB	adjusted *p*-values
	mean±SE	mean±SE	
ch1	0.26±0.08	0.22±0.04	1.00
ch2	0.21±0.04	0.19±0.05	1.00
ch3	0.20±0.04	0.18±0.05	1.00
ch4	0.26±0.05	0.23±0.04	1.00
ch5	0.29±0.08	0.28±0.06	1.00
ch6	0.16±0.03	0.13±0.02	0.99
ch7	0.21±0.04	0.18±0.05	1.00
ch8	0.20±0.05	0.21±0.04	1.00
ch9	0.23±0.05	0.19±0.03	0.99
ch10	0.14±0.03	0.11±0.02	0.92
ch11	0.17±0.03	0.13±0.02	0.043*
ch12	0.20±0.05	0.23±0.05	1.00
ch13	0.23±0.04	0.24±0.04	1.00
ch14	0.13±0.02	0.13±0.02	1.00
ch15	0.17±0.02	0.14±0.02	0.32
ch16	0.13±0.02	0.13±0.02	1.00
ch17	0.23±0.05	0.23±0.05	1.00
ch18	0.17±0.03	0.16±0.02	1.00
ch19	0.16±0.02	0.16±0.02	1.00
ch20	0.17±0.02	0.18±0.03	1.00
ch21	0.21±0.04	0.22±0.05	1.00
ch22	0.17±0.02	0.18±0.03	1.00

VFB condition was 23.5%±0.2% higher on average than that under the nVFB condition. For the peak values for the oxy-Hb level of the other chs, significant increases were not observed under the VFB condition.

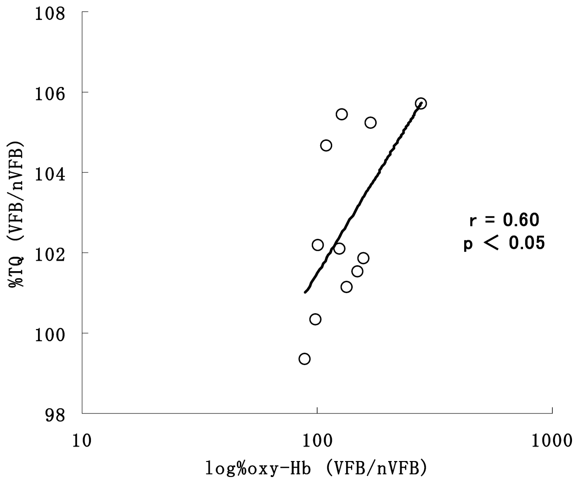

Figure 6 Relationship between cerebral blood flow (log%oxy-Hb, ch11) on the right frontal region and MVC torque in VFB condition.

3.3. Relationship between torque and frontal activity during MVC

Figure 6 shows the relationship under the VFB condition between the relative increase of oxy-Hb level of ch11 and the relative increase of exerted torque. The enhancement of the ch11 activity under the VFB condition was found to exponentially correlate with the enhancement of the exerted torque (r=0.60, $p<0.05$).

4. Discussion

4.1. Effect of VFB on exerted torque

Torque during MVC under the VFB condition was significantly higher than that of nVFB condition. This result was in accordance with those of previous studies that reported enhancement of muscle force exerted during MVC with visual feedback (Peacock et al., 1981; Baltzopolous et al., 1991; Jung et al., 2004). Baltzopolous et al. (1991) and Campenella et al. (2000) have reported that knee extension force during MVC under VFB condition resulted in 8% higher than that of control condition. In the present study, the relative increase of the torque exerted during MVC by VFB was 3%, which was low compared to that of knee extension. On the other hand, McNair et al. (1996) reported that elbow flexion torque during MVC increased 5% by verbal encouragement for subjects. The previous results supported present results that feedback enhances 5% of muscle force on elbow flexion. Further, comparison of the knee extension tasks in the previous studies (Baltzopolous et al., 1991; Campenella et al., 2000) and the elbow flexion tasks in the present study suggests that the effect of the feedback during MVC may vary depending on the muscle.

4.2. Effect of VFB on cerebral hemodynamics of PFC

With the torque enhancement under the VFB condition in the present study, a significant increase was observed in the oxy-Hb level for ch11. This finding supports the present assumption that the PFC is associated with enhancement of muscle force during MVC. Furthermore, ch11 was located on the right forehead, suggesting that the right field of the PFC may be associated with torque exerted during MVC under the VFB condition. Previous studies have not clarified activated fields of the PFC associated with enhancement of torque exerted during MVC with VFB. Studies on cerebral activity during muscle force exertion have reported that the PFC on the cerebral hemisphere was activated as exerted muscle force increased gradually (Dai et al., 2001; Liu et al., 2005) and further that this field was activated most during high intensity of 80% MVC (Dai et al., 2001) and 100% MVC (Liu et al., 2005) compared to other movement-related cortical regions. Vaillancourt et al. (2003) have reported that the anterior medial prefrontal cortex of the PFC on the right hemisphere and the dorsolateral prefrontal cortex of the PFC on the left hemisphere were activated during muscle force control tasks of low intensity under the VFB condition. Also, these muscle force control tasks were related to regulation and control of muscle force aimed at exerting accurate muscle force. In the present study, on the other hand, the muscle force exertion tasks were aimed at exerting muscle force exceeding MVC. This difference might result in an activated cerebral field different from that of the previous studies. In addition, Dai et al. (2001) and Liu et al. (2005) employed handgrip tasks, which were different from the elbow joint flexion exertion tasks in the present study. These differences might also be associated with the difference of the activated region. Since torque exertion exceeding the subjects' MVC was observed under the VFB condition in the present study, the subjects were considered to be more motivated than those under the nVFB condition. An fMRI study on cerebral activity involving working memory tasks has reported that high reward was found to activate the PFC on the right hemisphere, which may be a region associated with motivation (Taylor et al., 2004). Therefore, the VFB condition in the present study, which asked subjects to exert torque exceeding 100% MVC, was considered to induce stronger motivation by presenting the torque level exceeding their MVC as the target.

4.3. Individual difference in relationship between PFC blood flow and exerted torque

The correlation analysis of the relative increase of torque and the relative increase of oxy-Hb during MVC in the subjects under the VFB condition showed that these relative increases correlated positively exponentially. In a previous study that made a similar analysis by PET, Naito et al. (2000) have reported that enhancement of activity of the anterior cingulate cortex inside the PFC and reduction of reaction time for button pressing tasks were exponentially proportional. In the context of performance during maximal effort, this finding means that the subjects having higher cerebral activity resulted in faster reaction time for the tasks and this relationship was exponential proportionality. The enhancement of the ch11 activity under the VFB condition in the present study was considered to reflect the activity at near-field regions of BA 10 in the right PFC, which may be a region associated with motivation (Taylor et al., 2004). Based on these previous results, the activation of the right PFC observed in the present study might induce stronger motivation in the subjects. In other words, the correlation between the relative increase of oxy-Hb and the relative increase of torque exerted during MVC seems to suggest that the subjects who were more motivated by the VFB condition exerted more enhanced torque.

4.4. Future prospects

In the present study, the PFC, which could be associated with enhancement of torque exerted during MVC, was measured as a cortical region measurement by NIRS based on the knowledge from previous studies (Brunia et al., 2000; Kawashima et al., 2000). As a result, the right field of the PFC was found to be activated under the VFB condition. With NIRS, cerebral functions can be measured with low degree of physical constraint regardless of exercise pattern and strength. However, NIRS measurements have a low spatial resolution of 3.0 cm and a measurement region of 1.2-2.0 cm depth from the surface of the cerebral cortex (Okamoto et al., 2004), so activities of deep portions of the brain and the whole brain were not clarified in the present study. Consequently, further studies will be required for details on cerebral regions activated under the VFB condition and their functions including measurement of the deep portions and the entire brain.

5. Summary

Although it is known that muscle force during maximal voluntary contraction (MVC) is enhanced by presenting visual feedback information about exerted torque to subjects, the neural mechanisms are unknown. In the present study, we forcuced on the prefrontal cortex (PFC) as a cerebral field that may be associated with enhancement of torque exerted during MVC with visual feedback (VFB), based on studies of the PFC activated with feedback and of the extensive activation in the PFC during MVC. By using near-infrared spectroscopy (NIRS), we measured hemodynamics of the PFC during the MVC task of isometric elbow flexion under the conditions where visual feedback was presented (VFB) and not presented (nVFB). As a result, the torque exerted during MVC was significantly enhanced under the VFB condition, and concurrently, significant enhancement of activity was observed in the right region of the PFC ($p<0.05$). Also, under the VFB condition, the enhancement of activity in this region had an exponential correlation with enhancement of exerted torque ($p<0.05$). These findings indicate that the enhancement of the torque exerted during MVC under the VFB condition was associated with the enhancement of PFC activity.

Acknowledgement

The functional NIRS data used in this study were supported by Shimadzu Corporation. We would like to express our gratitude to professor Fukunaga and the members of his laboratory for permission to use experimental equipment and to cooperate processing data.

References

Allen, G.M., McKenzie, D.K. & Gandevia, S.C. (1998). Twitch interpolation of the elbow flexor muscles at high forces. Muscle & Nerve, 21: 318-328.

Baltzopoulos, V., Williams, J. G. & Brodie, D. A. (1991). Sources of error in isokinetic dynamometry: Effects of visual feedback on maximum torque measurements. The Journal of Orthopaedic and Sports Physical Therapy, 13: 138-142.

Behm, D.G., Whittle, J., Button, D. & Power, K. (2002). Intermuscle differences in activation. Muscle & Nerve, 25: 236-243.

Brunia, C. H. M., Jong, B. M., van den Berg-Lessen, M. M. C. & Paans, A M J. (2000). Visual feedback about time estimation is related to a right hemisphere activation measured by PET. Experimental Brain Research, 130: 328-337.

Campenella, B., Mattacola, C. G. & Kimura, I. F. (2000). Effect of visual feedback and verbal encouragement on concentric quadriceps and hamstrings peak torque of males and females. Isokinetics and Exercises Science, 8: 1-6.

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: 290-300.

Herrmann, M. J., Plichta, M.M., Ehlis, A.C. & Fallgatter, A J. (2005). Optical topography during a Go-NoGo task assessed with multi-channel near-infrared spectroscopy. Behavioral Brain Research, 160: 135-140.

Hoshi, Y., Kobayashi, N. & Tamura, M. (2001). Interpretation of near-infrared spectroscopy signals: a study with a newly developed perfused rat brain model. Journal of Applied Physiology, 90: 1657-1662.

Ikai, M. & Fukunaga, T. (1968). Calculation of muscle strength per unit cross-sectional area of human muscle by means of ultrasonic measurement. Internationale Zeitschrift für angewandte Physiologie, 26: 26-32.

Jakobi, J. M. & Rice, C. L. (2002). Voluntary muscle activation varies with age and muscle group. Journal of Applied Physiology, 93: 457-462.

Jung, M. C. M. & Hallbeck, S. (2004). Quantification of the effects of instruction type, verbal encouragement, and visual feedback on static and peak handgrip strength. International Journal of Industrial Ergonomics, 34: 367-374.

Kawashima, R., Tajima, N., Yoshida, H., Okita, K., Sasaki, T., Schormann, T., Ogawa, A., Fukuda, H. & Zilles, K. (2000). The effect of verbal feedback on motor learning-A PET Study. NeuroImage, 12: 698-706.

Liu, J.Z., Zhang, L., Yao, B., Sahgal, V. & Yue, G.H. (2005). Fatigue induced by intermittent maximal voluntary contractions is associated with significant losses in muscle output but limited reductions in functional MRI-measured brain activation level. Brain Research, 1040: 44-54.

McNair, P. J., Depledge, J., Brettkelly, M. & Stanley, S. N. (1996). Verbal encouragement: effects on maximum effort voluntary muscle action. British Journal of Sports Medicine, 30: 243-245.

Miyai, I., Tanabe, H. C., Sase, I., Eda, H., Oda, I. C., Konishi, I., Tsunazawa, Y., Suzuki, T., Yanagida, T. & Kubota, K. (2001). Cortical mapping of gait in humans: A near-infrared spectroscopic topography study. NeuroImage, 14: 1186-1192.

Naito, E., Kinomura, S., Geyer, S., Kawashima, R., Roland, P.E. & Zilles, K. (2000). Fast reaction to different sensory modalities activates common fields in the motor areas, but the anterior cingulate cortex is involved in the speed of reaction. Journal of Neurophysiology. 83: 1701-1709.

Okamoto, M., Dan, H., Sakamoto, K., Takeo, K., Shimizu, K., Kohno, S., Oda, I., Isobe, S., Suzuki, T., Kohyama, K. & Dan, I. (2004). Three-dimensional probabilistic anatomical cranio-cerebral correlation via the international 10-20 system oriented for transcranial functional brain mapping. Neuroimage, 21: 99-111.

Peacock, B., Westers, T., Walsh, S. & Nicholson, K. (1981). Feedback and maximal voluntary contraction. Ergonomics, 24: 223-228.

Raichle, M. E. (1999). Modern phrenology: Maps of human cortical function. Annals of the New York Academy of Sciences, 882: 107.

Sankoh, A.J., Huque, M.F. & Dubey, S.D. (1997). Some comments on frequently used multiple endpoint adjustment methods in clinical trails. Statistics in Medicine, 16: 2529-2542.

Schiffman, J. M., Luchies, C. W., Richards, L. G. & Zebas, C. J. (2002). The effects of age and feedback on isometric knee extensor force control abilities. Clinical Biomechanics, 17: 486-493.

Suzuki, M., Miyai, I., Ono, T., Oda, I., Konishi, I., Kochiyama, T. & Kubota, K. (2004). Prefrontal and premotor cortices are involved in adapting walking and running speed on the treadmill: An optical imaging study. NeuroImage, 23: 1020-1026.

Taylor, S. F., Welsh, R.C., Wager, T. D., Phan, K. L., Fitzgerald, K. D. & Gehring, W. J. (2004). A functional neuroimaging study of motivation and executive function. NeuroImage, 21: 1045-1054.

Thomas, R. & Stephane, P. (2008). Prefrontal cortex oxygenation and neuromuscular responses to exhaustive exercise. European Journal of Applied Physiology, 102: 153-163.

Vaillancourt, D.E., Thulborn, K.R. & Corcos, D.M. (2003). Neural basis for the processes that underlie visually guided and internally guided force control in humans. Journal of Neurophysiology, 90: 3330-3340.

Williams, D.M. & Martin, B. (2004). Assessment of voluntary activation by stimulation of one muscle or two synergistic muscles. Muscle & Nerve, 29: 112-119.

Name:
Makoto Fukuda

Affiliation:
Graduate School of Sport Sciences, Waseda University

Address:
2-579-15, Mikajima, Tokorozawa-shi, Saitama 359-1192 Japan

Brief Biographical History:

2003-2005 Master's Programs in Graduate School of Human Sciences, Waseda University

2005-2008 Doctoral Programs in Graduate School of Sport Sciences, Waseda University

Membership in Learned Societies:

- Japan Society of Physical Education, Health and Sport Sciences