Perceived Exertion is Not Necessarily Associated with Altered Brain Activity during Exercise

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Abstract Previous studies have investigated the relationship between prefrontal cortex activation and perceived exertion during prolonged exercise. However, the effect of perceived exertion on prefrontal cortex activity is confounded by exercise intensity. Therefore, the changes in prefrontal cortex activity in response to perceived exertion remain unclear. The purpose of the present study was to investigate the relationship between the activation (oxygenation) of the prefrontal cortex and perceived exertion during constant work-rate elbow-flexion exercise with or without muscle-spindle stimulation. Ten healthy, right-handed subjects participated in the study. Near-infrared spectroscopy with probes positioned over the prefrontal cortex measured its activation throughout elbow-flexion exercise. Subjects performed sustained elbow-flexion exercise at 25–35% of the maximal voluntary contraction (MVC) with or without muscle-spindle stimulation (vibration), which can decrease perceived exertion. The ratings of perceived exertion were significantly lower during exercise with vibration (Ex-Vib) than during exercise without vibration (Ex) ($p < 0.05$). The oxygenation of the prefrontal cortex during Ex-Vib did not significantly differ from that during Ex ($p > 0.05$). These results indicated that perceived exertion was not necessarily associated with prefrontal cortex activation during exercise. *J Physiol Anthropol* 28(2): 63–69, 2009
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Introduction

Humans have been fascinated by prolonged exercise performance since antiquity, and numerous physiological and

psychological experiments have addressed what limits endurance, i.e., what causes fatigue. Physiological fatigue is characterized by the exercise-induced loss of the power- and force-generating ability of a muscle during the course of or after exercise (Bigland-Ritchie and Woods, 1984; Booth and Thomason, 1991; Nybo and Nielsen, 2001; Gandevia, 2001).

Fatigue may be considered an increased difficulty in maintaining a given exercise intensity, as assessed using ratings of perceived exertion (RPEs), e.g., the Borg scale (Borg, 1975, 1982), which are used for the quantification of the perception of effort (Williamson et al., 2001; Nybo and Nielsen, 2001; Dalsgaard et al., 2002; Nybo, 2003). This method of fatigue evaluation is based on a subjective sensation rather than on an objective assessment of the changes in force or power, and it does not enable a clear discrimination between the peripheral and central factors contributing to fatigue.

Previous studies have investigated the relationship between brain activation and the sensation of fatigue, as assessed using RPEs (Dalsgaard and Secher, 2007; Dalsgaard et al., 2002, Dalsgaard et al., 2003, Dalsgaard et al., 2004a, Dalsgaard et al., 2004b, Dalsgaard et al., 2004c; González-Alonso et al., 2004; Nybo et al., 2003; Nybo and Nielsen, 2001). In particular, Nybo and Nielsen (2001) reported a significant correlation between prefrontal cortex activity and RPEs during cycling exercise. However, as stated in their study, the significant relationship between RPEs and prefrontal cortex activation was influenced by not only the sensation of fatigue but also the effect of exercise intensity.

Cerebral oxygenation changes reflect cerebral functional activation (Colier et al., 1997; Colier et al., 1999; Kleinschmidt et al., 1996; Shibuya et al., 2004a, 2004b; Shibuya and Tachi, 2006; Shibuya and Kuboyama, 2007; Shibuya et al., 2008; Obrig et al., 1996), and these changes can be measured using several techniques. Near-infrared spectroscopy (NIRS) and functional magnetic resonance imaging enable the noninvasive

monitoring of regional changes in cortical tissue oxygenation in response to various stimuli (Colier et al., 1999; Kleinschmidt et al., 1996; Mehagnoul-Schipper et al., 2000; Obrig et al., 1996, Obrig et al., 2000).

NIRS permits the monitoring of changes in the oxy- ([HbO₂]), deoxy- ([Hb]), and total hemoglobin ([tHb]) levels with high temporal resolution. The NIRS method is based on changes in absorption that depend on changes in the concentrations of [HbO₂] and [Hb] in the tissue under investigation.

In fact, Ide et al. (1999) and Ide and Secher (2000) reported that prefrontal cortex activation (oxygenation) increased with increase in exercise intensity. To avoid the interfusion of the effects of exercise intensity and perceived exertion on prefrontal activation, the experimental design should set the exercise intensity to a stable level. The muscle-spindle stimulation technique (vibration) assists or opposes an exercising muscle group while developing a given force. The vibration technique gives the changes in the perceived exertion at the same internal- and external-workloads (Goodwin et al., 1972), and it helps in understanding the effects of the changes in perceived exertion on prefrontal cortex activity. This technique has been commonly used in previous studies (e.g., Ogoh et al., 2002; Goodwin et al., 1972). The purpose of the present study was to determine whether perceived exertion was associated with prefrontal cortex activity by using the muscle-spindle stimulation technique during static exercise.

Methods

Subjects and paradigm

Ten normal, right-handed females (age, 21.0 ± 0.7 years; height, 159.9 ± 4.8 cm; and weight, 55.6 ± 5.9 kg) participated in the present study. Informed consent was obtained from each subject after providing a detailed explanation of the procedure and the noninvasiveness of the study. The criterion for the inclusion of subjects was a medical history free of cardiovascular, pulmonary, renal, endocrinological, and neurological disorders. The subjects were instructed not to train strenuously on the day prior to testing and not to exercise on the day of testing. Moreover, they were asked to refrain from consuming food or beverages containing caffeine before the test. All subjects provided informed, written consent for the procedures.

Muscle-spindle stimulation (vibration)

A vibrator was used to induce muscle contraction by the reflex stimulation of the distal tendon of the biceps brachii. In the present study, the oscillating vibration was applied to the distal tendon of the biceps brachii, while the subjects performed sustained isometric contractions of the biceps brachii. The oscillating frequency of the vibrator was 100 Hz, and its amplitude was 0.8 mm. Vibration of the distal tendon of the biceps brachii during elbow flexion aided tension development in the biceps brachii muscle. In the resting

condition, $7.7\% \pm 3.2\%$ of the maximal voluntary contraction (MVC) was achieved by the application of vibration.

Exercise protocol

Throughout the study, the subjects sat on a comfortable chair in a quiet room. Each subject performed 2 sessions of elbow-flexion exercise with or without muscle-spindle stimulation (Ex-Vib and Ex respectively). The 2 exercise sessions were separated by a 20-min rest. The order of these sessions was randomized. The RPE (the subject rated her perceived effort on the Borg scale (Borg, 1975)) was recorded immediately after the exercise.

On the first day, in order to determine the MVC, the subjects performed maximal static elbow flexion at an angle of 90° (biceps brachii muscle exercise) with their dominant arm (right arm) for a total of 3 times. After the MVC trials, the subject was familiarized with the experimental protocol and the physiological measurements to be obtained.

On the second day, the subjects performed static elbow flexion at a 90° angle. After a preliminary 30-min resting period in the upright position, each subject performed exercises under the same protocol under 2 different conditions: (i) elbow flexion (Ex) and (ii) elbow flexion with stimulation of the distal tendon of the biceps brachii (Ex-Vib). The protocol consisted of a 3-min resting control period followed by a 2-min static contraction at 30% of the subject's pre-determined MVC. All exercise bouts were separated by a rest period of a minimum of 20 min.

Near-infrared Spectroscopy (NIRS)

Prefrontal tissue oxygenation levels were recorded from the muscle and brain by using an NIRS unit (Hamamatsu NIRO-200; Hamamatsu Photonics KK, Tokyo, Japan). The theory and specifics of NIRS have been described in detail elsewhere (Elwell et al., 1994). In brief, near-infrared light is transmitted via a fiber-optic cable and passed into the tissue of interest through an emitting optode. Any light that is transmitted through the tissue is acquired by a detector optode and carried by a second fiber-optic cable to a photon detector (photomultiplier tube) in the spectrometer. The NIRO-200 uses laser diodes set at 4 different wavelengths (776, 826, 845, and 905 nm) to provide the light-source signal, which is pulsed in rapid succession and detected by the photomultiplier tube. The probes were bilaterally positioned over the motor cortex areas enclosing F3, according to the modified international electroencephalography (EEG) 10–20 system (American Electroencephalographic Society, 1994), as described in previous studies (Shibuya et al., 2004a, 2004b, 2006; Bhambhani et al., 2007). An interoptode spacing of 4 cm was used to separate the emitting from the detecting sensor. The optodes were held within a black rubber housing that maintained constant optode spacing. The housing was taped to the skin and covered with an optically dense vinyl sheet that was also affixed with tape. The housing and vinyl sheet minimized the loss of near-infrared light from the field of

interrogation as well as the intrusion of light from the environment. The full assembly was further secured with an elastic bandage that encircled the forearm and head. The levels of $[\text{HbO}_2]$, $[\text{Hb}]$, and $[\text{tHb}]$ were continuously sampled by the NIRS unit at a rate of 2 Hz. These parameters are expressed (in $\text{mM}\cdot\text{cm}$) as a change from 0. The values of $[\text{HbO}_2]$ and $[\text{Hb}]$ during exercise were calculated using the average of 10 datasets (5 s).

Pulmonary gas exchange

The subjects breathed through a face mask connected to a hot wire flowmeter that measured respiratory flow and was calibrated using a 3-L syringe. A small sample (1 mL/s) of expired gas was withdrawn continuously from the mask and analyzed for O_2 and CO_2 by using a mass spectrometer (Arco-2000, Arco Inc., Japan). The mass spectrometer was calibrated with fresh air and precision gas (O_2 , 15.04% and CO_2 , 4.957%). The time delay between the flow and gas-concentration signals was calculated to obtain breath-by-breath data. Pulmonary gas-exchange data were collected every 5 s. The heart rate (HR) was measured using leads and an electrocardiogram monitor (OEC-6201; Nihon-Kohden, Japan).

Cardiopulmonary measurements

Mean arterial pressure (MAP) was measured continuously using a photoplethysmometer (Finometer; Finapres Medical Systems, Arnhem, The Netherlands) with the cuff on the middle finger of the nondominant hand.

Statistical analysis

To compare the time-course changes, two-way ANOVA was applied to the parameters in the Ex and Ex-Vib conditions, using time and condition (with or without vibration) as fixed factors. To assess the time-course change in each condition, the changes in the parameters were subjected to post-hoc analysis using the Dunnett test. A p value less than 0.05 was considered statistically significant.

Results

The mean MVC was 14.1 ± 2.2 kp. The perceived exertions during Ex and Ex-Vib were 13.6 ± 2.2 and 11.9 ± 2.0 , respectively, and the difference between them was significant ($t=4.636$, $p<0.01$). The RPEs immediately after the exercise also significantly differed ($t=4.636$, $p<0.05$); they were 13.6 ± 2.2 in the Ex condition and 11.9 ± 2.0 in the Ex-Vib condition.

HR, MAP, and end-tidal CO_2

ANOVA revealed a significant change in the HR with time and no significant changes between the Ex and Ex-Vib conditions (time: $F=32.642$, $p<0.01$; Ex vs. Ex-Vib: $F=0.279$, $p>0.05$; and interaction: $F=0.388$, $p>0.05$), and the post-hoc tests revealed that the values from 15 s after the start

of exercise to the end of exercise were significantly higher than those at the baseline ($p<0.05$) under both the Ex and Ex-Vib conditions. Furthermore, the MAP also significantly differed with time and not with the presence or absence of vibration (time: $F=49.742$, $p<0.01$; Ex vs. Ex-Vib: $F=1.0100$, $p>0.05$; and interaction: $F=0.601$, $p>0.05$), and the post-hoc test for MAP showed that the values from the start of exercise to the end of exercise were significantly higher than those at the baseline ($p<0.05$) under both the Ex and Ex-Vib conditions (Table 1).

The end-tidal CO_2 (ETCO_2) slightly increased, but the change was not significant; further, it did not significantly differ between the Ex and Ex-Vib conditions (time: $F=0.818$, $p>0.05$; Ex vs. Ex-Vib: $F=0.360$, $p>0.05$; and interaction: $F=0.608$, $p>0.05$) (Table 1).

Prefrontal cortex oxygenation

With regard to $[\text{HbO}_2]$, $[\text{Hb}]$, and $[\text{tHb}]$ levels, ANOVA revealed significant changes with time and no significant changes between the Ex and Ex-Vib conditions. The results of the statistical tests for these levels are as follows: (i) $[\text{HbO}_2]$: time, $F=57.397$ and $p<0.01$; Ex vs. Ex-Vib, $F=0.031$ and $p>0.05$; and interaction, $F=0.189$ and $p>0.05$ (Fig. 1). (ii) $[\text{Hb}]$: time, $F=75.781$ and $p<0.01$; Ex vs. Ex-Vib, $F=0.0004$

Table 1 ETCO_2 , HR and MAP changes in Ex and Ex-Vib conditions

		Baseline value	At the end of exercise
ETCO_2 (%)	Ex	3.71 ± 1.0	3.93 ± 1.0
	Ex-Vib	3.84 ± 1.1	4.06 ± 1.0
HR (bpm)	Ex	72.5 ± 3.5	$87.0 \pm 8.8^*$
	Ex-Vib	72.2 ± 5.7	$85.5 \pm 8.4^*$
MAP (mmHg)	Ex	80.7 ± 7.6	$94.6 \pm 11.1^*$
	Ex-Vib	79.8 ± 7.3	$98.4 \pm 6.7^*$

Asterisks shows significant difference from baseline values ($p<0.05$).

Fig. 1 Oxyhemoglobin ($[\text{HbO}_2]$) levels in the prefrontal cortex. Changes in the baseline values of $[\text{HbO}_2]$ concentration in the prefrontal cortex during exercise without (Ex) or with muscle spindle stimulation (Ex-Vib). Values are represented as means $\pm$ SD. The asterisks show significant differences from the baseline values, $p<0.05$.

Fig. 2 Deoxyhemoglobin ([Hb]) levels in the prefrontal cortex. Changes in the baseline values of [Hb] concentration in the prefrontal cortex during exercise without (Ex) or with muscle spindle stimulation (Ex-Vib). Values are represented means $\pm$ SD. The asterisks show significant differences from the baseline values, $p < 0.05$.

Fig. 3 Total hemoglobin ([tHb]) levels in the prefrontal cortex. Changes in the baseline values of [tHb] concentration in the prefrontal cortex during exercise without (Ex) or with muscle spindle stimulation (Ex-Vib). Values are represented means $\pm$ SD. The asterisks show significant differences from the baseline values, $p < 0.05$.

and $p > 0.05$; and interaction, $F = 0.4587$ and $p > 0.05$) (Fig. 2). (iii) [tHb]: time, $F = 57.394$ and $p < 0.01$; Ex vs. Ex-Vib, $F = 0.031$ and $p > 0.05$; and interaction, $F = 0.189$ and $p > 0.05$) (Fig. 3).

The post-hoc test for changes in the $[HbO_2]$, [Hb], and [tHb] levels under the Ex and Ex-Vib conditions revealed that the values from the start of exercise to the end of exercise were significantly higher than those at the baseline ($p < 0.05$).

Discussion

The present study revealed no significant difference in the prefrontal cortex activity during exercise under the Ex and Ex-Vib conditions.

Borg's RPEs have enabled the measurement of impending fatigue during exercise testing (Borg, 1982; Ekblom and Goldbarg, 1971). The RPE increases with increase in exercise intensity (Ceci and Hassman, 1991; Dunbar et al., 1992; Eston

et al., 1987; Glass et al., 1992; Kurokawa and Ueda, 1992; Ueda et al., 2006). Additionally, Nybo and Nielsen (2001) found a significant correlation between the RPEs and prefrontal cortex activity. The prefrontal cortex is most likely involved in the initiation of volitional movements (Nowak et al., 1999; Pedersen et al., 1998). The activity (oxygenation) of the prefrontal cortex increases with increase in exercise intensity (Ide et al., 1999). As such, the prefrontal cortex activity described by Nybo and Nielsen (2001) is a reflection of 2 dimensions, i.e., exercise intensity and the RPE. Thus, in order to determine the relationship between the RPE and prefrontal cortex activity, the effect of the RPE should be separated from that of exercise intensity.

The exercise design in the present study differed from that in a previous study (Nybo and Nielsen, 2001), and it successfully separated the effects of RPE from those of exercise intensity by using the muscle-spindle stimulation technique. We detected no significant difference in the activity of the prefrontal cortex in the Ex and Ex-Vib conditions. This result indicates that the RPEs are not associated with prefrontal cortex activity. The RPEs reflect the sensation of physical fatigue (Borg, 1982; Ekblom and Goldbarg, 1971). Information regarding physical fatigue might be transmitted from the peripheral nervous system to the sensory cortex and not to the prefrontal cortex. As mentioned by Ueda et al. (2006), the RPE scale might be influenced by multiple psychological factors since perceived exertion is induced by central pain and several peripheral factors, namely, arm pain, leg pain, breathing difficulty, and heart pain. On the other hand, the activity of the prefrontal cortex might not reflect multiple factors. In the present study, we proposed the linear increase in the oxygenation in the prefrontal cortex during steady-state exercise (Figs. 1, 2, 3). The reasons for the increase in the oxygenation remain unclear in the present study. Further studies are needed to clarify the reasons for the increase in prefrontal cortex oxygenation even during steady-state exercise.

In the present study, no significant differences were detected in the central circulation parameters (i.e., HR and MAP) in the Ex and Ex-Vib conditions. Additionally, the $ETCO_2$ did not vary from the baseline value in both conditions. $ETCO_2$ is a key factor for the regulation of cerebral blood volume (Harris et al., 2006). Thus, this indicated that cerebral blood volume was not substantially altered. The significant increase in the prefrontal cortex activity in both conditions suggests that cerebral autoregulation occurred in the present study.

We used NIRS to investigate human brain activation. NIRS can noninvasively measure cerebral hemoglobin oxygenation (Jobsis, 1977) and has been used to assess functional brain activation in adults (Chance et al., 1993; Hoshi and Tamura 1993; Villringer et al., 1993) and infants (Taga et al., 2003; Taga and Asakawa, 2007). NIRS signals reflect the fact that blood flow response to functional activation is larger than the increase in oxygen consumption, similar to the blood oxygenation level-dependent (BOLD) contrast in fMRI

(Villringer and Change, 1997). The oxygenation response typically consists of an increase in oxygenated hemoglobin (oxy-Hb) and a slight decrease in deoxygenated hemoglobin (deoxy-Hb) over an activated cortical region (Obrig and Villringer, 2003). Because NIRS imposes fewer body constraints, the technique has been used to investigate brain activation in relation to motor function (Colier et al., 1999; Franceschini et al., 2003; Hatakenaka et al., 2007; Hirth et al., 1996; 1997; Hupper et al., 2006; Jaszewski et al., 2003; Klinschmit et al., 1996; Maki et al., 1995; Obrig et al., 1996; Sato et al., 2005, 2006; Shimada et al., 2004; Watanabe et al., 1996; Wolf et al., 2002). It should be noted that the Hb signals reflect the products of the molar concentration changes and the optical path lengths. The optical path lengths may vary between brain regions. Since we performed the group analysis on a channel-by-channel basis, the statistical results were not affected by the regional-dependent differences of the optical path lengths. Although the optical path lengths may vary between participants, consistent changes in the Hb signals are good approximations of those in the Hb concentrations that are induced by brain activation.

In conclusion, the present study revealed that oxygenation of the prefrontal cortex did not significantly differ in the Ex and Ex-Vib conditions. The results of the present study suggest that perceived exertion is not necessarily associated with prefrontal cortex activity.

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