Physiology & Behavior 123 (2014) 1–10

Contents lists available at ScienceDirect

Physiology & Behavior

journal homepage: www.elsevier.com/locate/phb

Changes in cortical beta activity related to a biceps brachii movement task while experiencing exercise induced muscle damage

Kristina Plattner [a,*], Michael I. Lambert [a], Nicholas Tam [a], Robert P. Lamberts [a,b], Jochen Baumeister [c,d]

[a] UCT/MRC Research Unit for Exercise Science and Sports Medicine, Department of Human Biology, Faculty of Health Sciences, University of Cape Town, Sport Science Institute of South Africa, Newlands, South Africa
[b] Division of Orthopaedic Surgery, Department of Surgical Sciences, Faculty of Medicine and Health Sciences, Stellenbosch University, Tygerberg, South Africa
[c] Exercise & Brain Laboratory, Institute of Sports Medicine, Department of Exercise and Health, University of Paderborn, Paderborn, Germany
[d] Department of Human Movement Science, Norwegian University of Science and Technology, Trondheim, Norway

HIGHLIGHTS

- EIMD was confirmed with neuromuscular, muscle function and pain perception variables.
- Dysynchronous changes in neuromuscular function and muscle pain scores after EIMD induction.
- Increased cortical β-activity during biceps brachii movement < 36 hours after EIMD induction.
- Increased β-2 activity may be related to muscle power output and neuromuscular function.

ARTICLE INFO

Article history:
Received 22 January 2013
Received in revised form 19 August 2013
Accepted 29 August 2013

Keywords:
EIMD
Pain
Cortical activity
Neuromuscular function
EEG
EMG
Beta frequency
Cortex

ABSTRACT

Exercise-induced-muscle-damage (EIMD) is a well-described phenomenon which leads to decreased force output and altered neuromuscular function. How these symptoms of EIMD affect brain function, in particular cortical activity has not been described. Therefore the aim of this study was to investigate the relationship between the symptoms of EIMD and cortical beta (β) activity during a submaximal biceps brachii movement. Half of the subjects participated in an EIMD protocol. Control and EIMD groups were monitored for 132 h thereafter. Muscle pain scores in the EIMD group peaked after 36 h with the lowest muscle torque reported at 12 h. Beta-1 and -2 activity was increased in the frontal and parietal area in the experimental group at 12 h. This suggests an impact of EIMD induced neuromuscular changes on the cortical proprioceptive and motor perceptive networks. Beta-2 activity decreased in the control group over time suggesting a loss in focused attention and greater familiarization with the protocol as the study progressed. These data suggest that a change in β-1 and -2 activity is associated with integrating movement perception and proprioception post-EIMD.

1. Introduction

Exercise induced muscle damage (EIMD) is a well-described phenomenon which occurs after unaccustomed exercise. It includes structural damage to the muscle, symptoms of pain and changes in neuromuscular function [1]. More specifically it leads to a decrease in force and EMG output during a MVC (maximal voluntary contraction), and an increase in EMG (electromyographic) activation during submaximal contractions with these changes lasting up to 132 h after the onset of EIMD [1–5]. The change in neuromuscular function, immediately after EIMD induction, is caused by a reduction of voluntary activation either at the level of the spinal cord or motor cortex [3,6]. These changes occur independently of the soreness caused by the EIMD [3].

The interaction between the muscle and peripheral nerves with the central nervous system is most pronounced in the 15–35 Hz frequency band [7–9]. This frequency band, also known as beta (β) activity, is usually measured in the motor and somatosensory areas of the cortex and has been linked to motor performance [10–16], during isometric and dynamic muscle contractions. Beta activity consists of a large frequency range and has subsequently been divided into two sub-bands, β-1 activity at 15–20 Hz and β-2 activity at 21–35 Hz, which are both linked to movement but which display different responses to external stimuli [17–21].

* Corresponding author at: UCT/MRC Research Unit for Exercise Science and Sports Medicine, Sport Science Institute of South Africa, P.O. Box 115, Newlands, 7725, South Africa. Tel.: +27 21 6504572; fax: +27 21 6867530.
E-mail address: kristina.plattner@gmail.com (K. Plattner).

0031-9384
http://dx.doi.org/10.1016/j.physbeh.2013.08.022

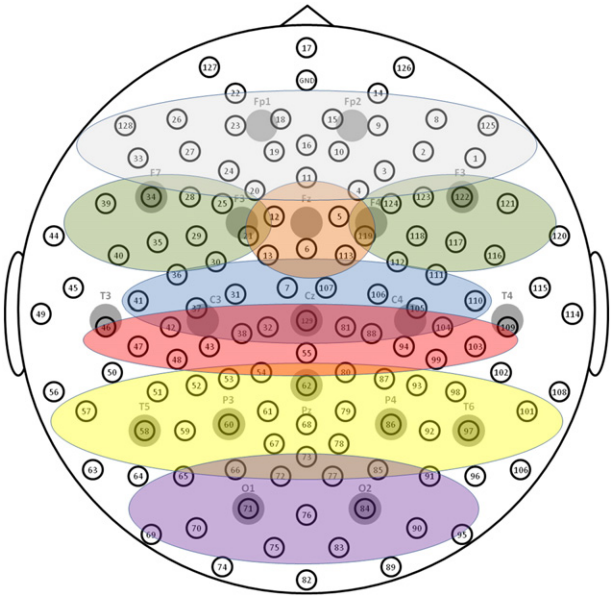


Fig. 1. A layout of the EGI 129 channel system overlaid by the 10:20 electrode system (dark gray circles). Ellipses represent the following gross cortical areas: Gray (frontal), green (premotor), orange (supplementary motor), blue (motor), red (somatosensory), yellow (parietal), purple (occipital).

Recent studies suggest that increased β-1 and -2 activity is important for the maintenance of steady state as well as low force contractions [2,3,7,8,22–25]. Increased beta activity is required for peripheral feedback to the cortex and efficient processing thereof and thereby maintaining the steadiness of the movement [23,26–29]. Further it has been shown that the coherence between the EEG (electroencephalogram) and EMG (electromyogram) activity in the 15–30 Hz range is positively correlated to force output [8,30,31].

During EIMD this peripheral feedback might be disturbed, as it has been shown that EIMD, as well as muscular pain in the biceps brachii, leads to a loss of proprioception, motor perception as well as neuromuscular function and motor recruitment [5]. These changes in turn could lead to the above mentioned compensatory increase in β activity in the associated areas [7,16,29,32,33], mainly the premotor, supplementary motor and parietal area of the cortex (Fig. 1) [16,29,32,33].

EIMD not only causes changes in neuromuscular function and proprioception but also induces muscular pain. It has been shown previously that tonic muscle pain, which is comparable to pain associated with EIMD, leads to an inhibition of movement related cortical activity and therefore leads to a reduction in cortical and spinal motor neuron excitability [34]. It has been found that tonic heat pain in the arm leads to an increase in β-1 activity in the frontal and ipsilateral temporal region [17,35,36], while β-2 activity increases globally with non-exercise induced muscle pain [18,19]. However, other studies have not shown conclusive evidence that pain has an impact on β-1 or β-2 activity at all [37].

To clarify the inconsistencies in these studies we aim to investigate the relationship between the symptoms of EIMD and cortical β-1 and -2 activity during a submaximal movement for up to 132 h following an exercise protocol designed to cause EIMD. Of special interest is not only the effect of the neuromuscular changes, but also the effect of the sensation of pain on the β-1 activity and β-2 activity. We hypothesize that β-1 and -2 activity in electrodes overlying the frontal and parietal area will be increased during EIMD to compensate for loss of neuromuscular function and to integrate the increased sensation of pain.

2. Methods

Thirty-seven right-handed male participants, aged 21–40 years, were recruited for this study. Handedness was determined by the *Edinburgh* handedness inventory [38]. Participants matched for age, height, weight, body fat and skinfold thickness were allocated to either the experimental or control group. All participants were free of any upper body injuries and were not participating in any upper body training 12 weeks prior to the onset of the study. This included the engagement in exercises involving specific muscle lengthening under tension movements.

Before being recruited for the study, participants signed an informed consent form and completed a Physical Activity Readiness Questionnaire (Par-Q) [39]. Further, questionnaires about their injury and training history were answered. Participants were informed about study design, familiarized with the equipment and different testing protocols before starting the experimental protocol. The Human Research Ethics Committee of the Faculty of Health Science, University of Cape Town, approved the study. The principles outlined by the Declaration of Helsinki for the use of Humans were adopted in this study [40].

2.1. Study design

Fig. 2 represents a timeline depicting the order of tests performed over the seven-day period. To minimize the effect of circadian rhythm on any of the outcome measures, all tests were scheduled at the same time of the day (within 60 min). This however was not possible for the measurement at 12 h after the exercise protocol.

Twelve hours before the start of exercise protocol (see also Fig. 2), stature, body mass, body fat percentage and skinfolds of each participant were measured. In addition resting elbow angle, elbow muscle function (maximal voluntary contraction), biceps girth and pain scores were measured. A blood sample was taken to determine baseline creatine kinase (CK) activity.

Electroencephalographic (EEG) activity was measured during a self-initiated self-paced flexion–extension movement. In contrast to all the above-mentioned measurements that were conducted at −12, 12, 36, 60, 84, 108 and 132 h EEG measurements were only captured at −12, 12, 36 and 132 h (Fig. 2). These measurements were time consuming for the participants and there were concerns about poor compliance if EEG testing was more frequent.

2.2. Exercise protocol

Twelve hours after baseline testing, the subjects in the experimental group completed an exercise protocol designed to induce muscle damage (EIMD protocol). In brief, participants were asked to resist the lengthening movement of the left bicep (5 sets of 25 movements). The

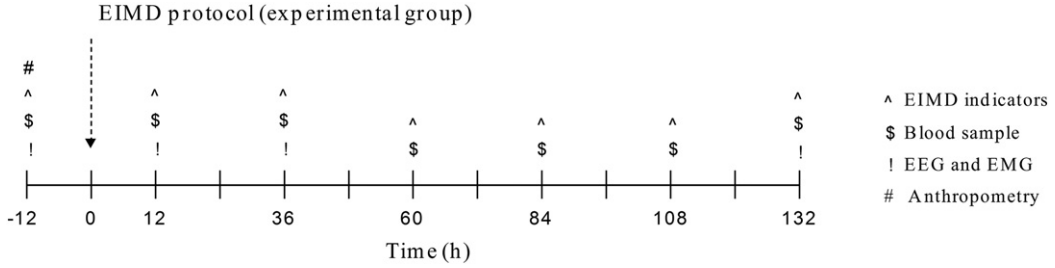


Fig. 2. Timeline of measurements. The EIMD indicators include, pain, arm circumference, elbow angle, and creatine kinase activity.

resistance to these movements was set on a Biodex dynamometer (Biodex pro 3, New York, USA) at 80% of each subject's maximum isometric contraction torque, as this has been shown to induce EIMD [1]. The control group did not perform this exercise protocol.

2.3. Muscle function tests

Participants in both groups performed the muscle function tests. These tests consisted of a maximal voluntary contraction (MVC) measurement and a self-paced submaximal flexion–extension movement. The MVC was measured using a Biodex dynamometer when performing elbow flexion of the left arm. Participants were set-up according to the methodology of Plattner et al. [1]. Participants were asked to perform three 5 s isometric elbow contractions at maximal effort, with a fixed dynamometer arm angle of 45°. This set-up resulted in an elbow angle at ±60°, within the optimal length tension curve range [41,42]. Participants were asked to perform three 5 s MVC's interspaced by 60 s recovery periods [1].

Muscle function and EMG were measured together at the same time therefore to make the timeline clear (Fig. 2) only the EMG label is used.

2.4. Electroencephalographic study procedure

The EEG data were obtained in a darkened, sound attenuated, temperature controlled room to minimize the effect of confounding factors. Participants were instructed how to perform the self paced flexion and extension movements. The flexion–extension movement was performed seated on a standard armless-chair. Their arms were relaxed and hanging by their sides. For the submaximal self-paced flexion and extension movements all participants wore a 1 kg wrist strap and movements were performed in the sagittal plane between elbow angles of 180° and 90°. During the movements subjects were ask to look at a fixed point at the wall to reduce the interference of eye movements on the EEG measurement. In addition, the upper body and upper arm were positioned as described in the MVC set-up for standardization purposes. Participants were asked to perform 75 repetitions, which were interspaced by 5–10 s recovery periods with slightly longer rest periods after each 25-repetition set, while EEG data were captured.

2.5. Electroencephalographic recording

An EEG net with 128 recording sites plus a vertex reference electrode (electrode 129) Electrical Geodesic™ system (Electrical Geodesics, Inc., Oregon, USA) [43] was fitted onto each participant (see Fig. 2 for an electrode layout). The impedance of all electrodes was maintained below 50 kΩ as suggested by the manufacture of the EGI system and different technical references [43–45] due to the high input resistance of the EEG amplifier. Specially designed amplifiers processed the high impedance signal. EEG was recorded using a 0.1–50 Hz bandpass filter (3 dB attenuation) [44]. The signals were sampled at 250 Hz [43,44]. All recordings were initially referenced to the central reference electrode (Cz/129) [43,44]. The EEG system was connected to an experimental workstation (Net Station software, Apple Inc. desktop) [43].

2.6. Electroencephalographic data analysis

Raw EEG data were processed and analyzed as previously described by Plattner et al. [46]. Although the frequency bands used in this study were as follows: β-1 (13.67–18.55 Hz) and β-2 (19.35–35.16 Hz). Thereafter the relative power (activity) for each frequency on each day was calculated with the following formula:

$$\text{Relative power} = ((\text{Power}(12\text{h or } 36\text{h or } 132\text{h}) - \text{Power}(0\text{ h}))/\text{Power}(0\text{ h})) * 100.$$

The different relative power values for each subject on the different testing days were used to calculate the statistical differences between the two different groups on the four different testing days. Matlab 6.5 (The Mathworks Inc., Massachusetts, USA) and EEGlab v 5.02 (SCCN, University of California, San Diego, USA) were used to create topographical maps of the relative power on each day in each frequency. Recorded data are represented based on the 10:20 system. All electrodes are grouped according to electrode on the 10:20 system that represents the same area. For example electrodes 5, 6, 11 and 12 represent the 10:20 electrode Fz in the Netstation system (Fig. 1). The 10–20 system is an internationally recognized system to describe and apply the location of external EEG electrodes during an experiment. It was developed to ensure standardized reproducibility so that recordings could be compared over time and between subjects. This system is based on the relationship between the location of an electrode and the underlying area of cerebral cortex [47].

2.7. Other measurements

Blood samples, biceps girth, resting elbow angle and a pain score were measured daily. For the blood sample 5 ml of blood was drawn from the right antecubital vein. These samples were stored (−20 °C) and later analyzed to determine the serum creatine kinase (CK) activity (Beckman DU-62, Beckman Instruments, Fullerton, California, USA) as described previously. The girth of the left biceps was measured with a tape measure midway between the acromion and radial bony landmarks. This site was marked with a permanent marker to ensure that all the subsequent measurements were taken in the same place. Resting elbow angles, and by implication the resting length of the biceps muscle were measured with a goniometer. Current pain perception was measured on a daily basis before the muscle function test with the use of a 10 cm visual analog scale (VAS) as previously described by Plattner et al. [1].

2.8. Statistical analysis

An independent t-test was used to compare the descriptive data between experimental and control group, using STATISTICA 8.0 data analysis software (StatSoft, Inc. Tulsa, OK, USA).

As some of the data had an unequal variance, determined using Levene's test of homogeneity of variance, it was decided to use nonparametric statistical tests instead of the parametric ANOVA test. A Kruskal–Wallis test (H) compared the differences between the control and experimental group on each of the testing days in each electrode separately. A Friedman's test (X^2) was used to compare changes within each group over the repeated testing days in each electrode separately. A Dunn's test was used for post-hoc analysis. Statistical significance was accepted at $p < 0.01$ for EEG data and $p < 0.05$ for resultant data.

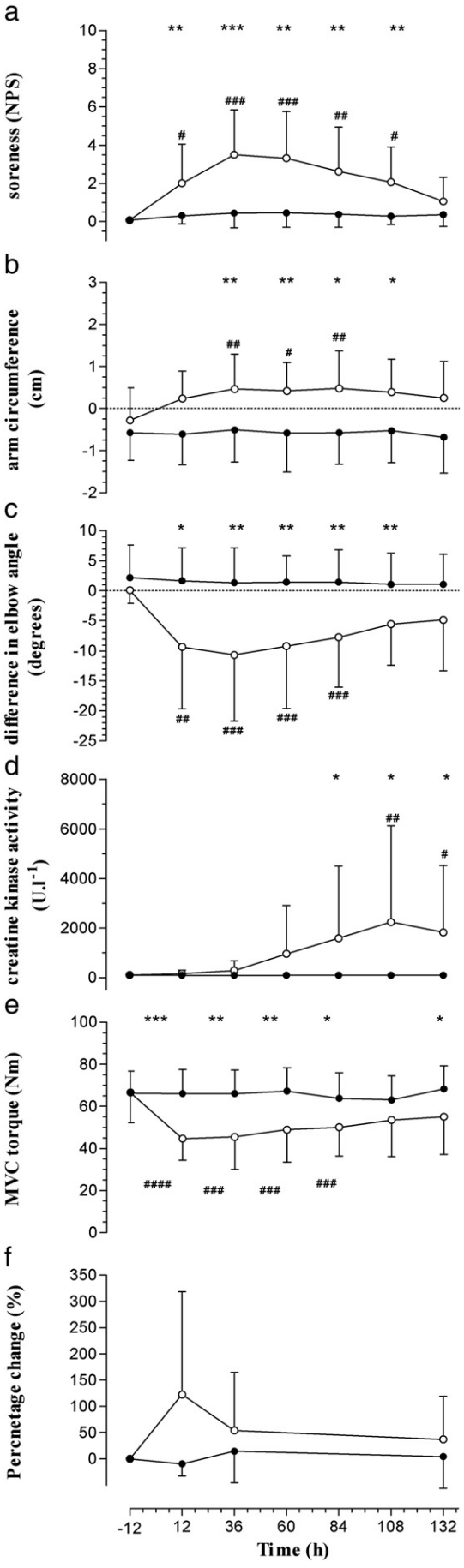
3. Results

3.1. Characteristics of subjects

One participant did not finish the entire trial and was excluded from the study. Seven other participants were also excluded because they did not have sufficient EEG data epochs for further analysis. The remaining twenty-eight participants were divided into two groups similar in weight, height, age, skinfold thickness and handedness (Table 1).

Table 1
Descriptive data for the control (n = 12) and experimental groups (n = 16). Data are expressed as mean ± SD.

Variable	Control	Experimental
Age (years)	23 ± 4	23 ± 3
Body mass (kg)	71.1 ± 8.8	72.7 ± 11.3
Stature (cm)	171.7 ± 6.8	177.4 ± 8.0
Body fat (%)	15.9 ± 4.9	13.4 ± 5.4
Skinfolds (mm)	79 ± 37	69 ± 38
Handedness (%)	73 ± 20	79 ± 19



3.2. Muscle soreness

The difference in pain in the left arm in the experimental and control group measured by the VAS scale is shown in Fig. 3a. Peak pain in the experimental group occurred 36 h after the EIMD protocol ($X2 = 53.66$ $p = 0.00001$). A difference in pain between the two groups occurred at 12 ($H = 7.48$ $p = 0.0062$), 36 ($H = 14.32$ $p = 0.0002$), 60 ($H = 10.21$ $p = 0.0014$), 84 ($H = 8.03$ $p = 0.0046$) and 108 h ($H = 8.37$ $p = 0.0038$). Significant changes in pain occurred in the experimental group compared to the baseline value at 12, 36, 60 84 and 108 h ($X2 = 53.66$ $p = 0.00001$) (Fig. 3 a).

3.3. Arm circumference

Significant changes in arm circumference were found over time in the experimental group compared to the baseline value at 36, 60 and 84 h ($X^2 = 27.04$ $p = 0.0001$). The difference between the left and right biceps girth of the control group did not change throughout the experiment. There was also a significant difference in girth between the exercised and rested arm in the experimental group when compared to the control group at 36 ($H = 7.23$ $p = 0.0072$), 60 ($H = 6.97$ $p = 0.0093$), 84 ($H = 5.36$ $p = 0.0207$) and 108 h ($H = 5.04$ $p = 0.0248$) (Fig. 3b).

3.4. Resting elbow joint angle (muscle length)

A significant decrease in elbow joint angle in the experimental group was found until 84 h post-EIMD protocol ($X^2 = 42.46$ $p = 0.0001$) (Fig. 3c). The difference in joint angle decreased in the experimental group compared to the control group and reached its minimum 36 h ($H = 7.34$ $p = 0.0067$) after the exercise protocol. It remained decreased until 108 h ($H = 6.71$ $p = 0.0096$) post-EIMD protocol.

3.5. Serum creatine kinase (CK) activity

The serum CK activity in the experimental group increased at 36 h ($H = 3.90$ $p = 0.0484$) in the experimental group and peaked when compared to the control group at 84 ($H = 3.99$ $p = 0.0456$), 108 ($H = 4.87$ $p = 0.0274$) and 132 h ($H = 5.27$ $p = 0.0217$) after the EIMD protocol. Creatine kinase activity in the experimental group was only significantly increased compared to baseline at 108 and 132 h ($X^2 = 20.27$ $p = 0.0025$) whereas no significant difference occurred in the control group (Fig. 3d).

3.6. Muscle function

Muscle function, measured by MVC (Fig. 3e), decreased significantly in the experimental group compared to the control group on all but one visit to the laboratory after the EIMD protocol ($p < 0.05$). The largest decrease in maximal force output was observed within the first 12 h post-EIMD protocol in the experimental group ($H = 14.14$ $p = 0.0002$) while no changes were observed in the control group throughout the experiment. The force output in the experimental group remained dif-

Fig. 3. a. The change in current pain measured with the VAS scale over seven days is shown the control (●) and experimental (○) group. b. The change in the difference in relaxed elbow girth (cm) between the left and right arm of the control (●) and experimental (○) group over seven days. c. The change in the difference in elbow angle (degrees) between the left and right arm of the control (●) and experimental (○) group over seven days. d. The change in creatine kinase activity ($U \cdot l^{-1}$) over seven days is shown the control (●) and experimental (○) group. e: The maximal force output produced on seven consecutive days is shown in the control (●) and experimental (○) group. (*Indicates results of the Kruskal–Wallis nonparametric test, #indicates results of the Friedman's nonparametric test. Data are presented as averages with standard deviations.) $^{*}p < 0.05$ control group versus experimental group. $^{**}p < 0.01$ control versus experimental group. $^{***}p < 0.001$ control versus experimental group. $\#p < 0.05$ post versus pre in the experimental group. $\#\#p < 0.01$ post versus pre in the experimental group. $\#\#\#p < 0.005$ post versus pre in the experimental group. $\#\#\#\#p < 0.001$ post versus pre in the experimental group.

ferent to that of the control group on all days but one until the end of the trial ($H = 5.61$ $p = 0.0179$) (Fig. 3e). A difference was also observed in the force output of the experimental group over time at 12, 36, 60 and 84 h compared to the baseline measurement ($X^2 = 48.3$ $p = 0.0001$) and no changes were observed in the control group over time.

3.7. Electromyography (EMG)

The EMG activity during a submaximal isometric low force contraction is shown in Fig. 4.3f. The data are displayed as normalized to the EMG during the maximal force output and as a percentage change compared to 12 h pre-EIMD protocol. There was a tendency towards a difference between the groups at twelve hours ($H = 3.81$, $p < 0.051$).

3.8. Electroencephalography (EEG)

3.8.1. Beta-1

Beta-1 activity was different between the experimental and control group in the frontal, central and parietal area at 12 h post EIMD. The central differences are represented stronger on the ipsilateral compared to the contralateral side. These differences can still be seen 36 h after the EIMD protocol but were not as widespread and mainly focused in the contralateral frontal, ipsilateral central and contralateral parietal areas. Differences persisted 132 h after the start of EIMD in the contralateral frontal and the parietal areas (Figs. 4 and 6). To simplify the understanding of the results, electrodes have been placed into subgroups and labeled with the title of the closest electrode represented on the 10:20 system.

3.8.2. Differences between groups at 12 h after the EIMD protocol

At 12 h after the start of EIMD the differences between the control and experimental group were widespread over the frontal, ipsilateral central and parietal areas (Figs. 4 and 6) of the cortex. In particular the changes recorded in the frontal electrodes were widespread and recorded over the supplementary and pre-motor areas.

3.8.2.1. Frontal (Fz). Differences between groups were very pronounced in electrodes representing the frontal area. The electrode with significant differences caused by an increase in activity in the experimental group was electrode 6 ($H = 7.25$, $p < 0.01$). Further, electrodes 113 and 119 ($H = 8.02$, $p < 0.01$), which overlay the contralateral pre-motor area were also different between groups.

3.8.2.2. Central (Cz). Only electrode 107 ($H = 7.00$, $p < 0.01$) was significantly different between the groups 12 h after the EIMD protocol.

3.8.2.3. Parietal (P3). In the ipsilateral parietal area differences in activity occurred between the groups in electrodes 52 and 53 ($H = 7.76$, $p < 0.01$).

3.8.2.4. Occipital (O2). Differences occurred at electrodes 84 and 85 ($H = 9.67$, $p < 0.01$) in the occipital region of the cortex.

3.8.3. Differences over time in the control group (0 vs 12 h)

There were no differences in β-1 activity over time in the control group.

3.8.4. Differences over time in the experimental group (0 vs 12 h)

There were no significant changes in the experimental group over time.

3.8.5. Differences between groups at 36 h after the EIMD protocol

3.8.5.1. Parietal (P4). At 36 h after the EIMD protocol only electrode 92 ($H = 6.76$, $p < 0.01$) showed significant differences between groups.

3.8.6. Differences over time in the control group (0 vs 36 h)

3.8.6.1. Frontal (F4). In the control group electrode 119 ($X^2 = 1.8$, $p = 0.01$) was significantly different from baseline activity.

3.8.6.2. Parietal (P3). A decrease in activity in the control group occurred in electrodes 53 and 61 ($X^2 = 12.7$, $p = 0.01$) and 52 ($X^2 = 16.3$, $p = 0.001$), overlying the ipsilateral parietal area.

3.8.6.3. Pz. A decrease in activity when compared to baseline occurred in electrodes 54, 55 ($X^2 = 12.4$, $p = 0.01$) and 62 ($X^2 = 15$, $p = 0.001$) overlying the medial parietal area of the control group.

3.8.7. Differences over time in the experimental group (0 vs 36 h)

There were no changes in the experimental group over time.

3.8.8. Differences between groups at 100 and 32 h after the EIMD protocol

3.8.8.1. Parietal (P3 and Pz). The parietal area shows significant differences between the groups at electrode 62 ($H = 7.75$, $p < 0.01$) representing P3.

3.8.9. Differences over time in the control group (0 vs 132 h)

3.8.9.1. Parietal (P3). A difference was also observed in the β-1 activity of the control group over time compared to the baseline measurement in electrodes representing the area around P3. These electrode 52 was significant ($X^2 = 16.3$, $p = 0.01$).

3.8.10. Differences over time in the experimental group (0 vs 132 h)

There were no differences in the experimental group over time.

3.8.11. Beta-2

The differences in β-2 activity between the control and experimental group at 12 h occurred in slightly different areas than β-1 activity. Most evident differences were in the parietal areas (P3, Pz and P4). At 36 h there were only differences in the ipsilateral parietal area and at 132 h most differences were attenuated (Figs. 5 and 7).

3.8.12. Differences between groups at 12 h after the EIMD protocol

3.8.12.1. Central (C3 and Cz). In the ipsilateral motor area (C3) electrode 42 ($H = 7.50$, $p < 0.01$) activity was different between the two groups at 12 h post-EIMD induction. Also in the central area over the vertex of the head (Cz) electrode 81 ($H = 7.00$, $p < 0.01$) was different.

3.8.12.2. Parietal (P3). In the ipsilateral parietal area electrodes 52, 53 and 61 ($H = 7.50$, $p = 0.01$) were significantly different between the two groups at 12 h.

3.8.12.3. Pz. Differences between the control and experimental group were also found in electrodes 55, 68, 73, 80 ($H > 7.00$, $p < 0.01$) and 62 ($H = 11.17$, $p < 0.001$).

3.8.12.4. P4. Similarly, electrodes 79 and 87 ($H > 7.25$, $p < 0.01$) were significantly different between the two groups.

3.8.13. Differences over time in the control group (0 vs 12 h)

3.8.13.1. Frontal (F3). Electrode 20 ($X^2 = 11.8$, $p = 0.01$) overlying the pre-motor area significantly decreased between baseline and 12 h after the EIMD protocol in the control group.

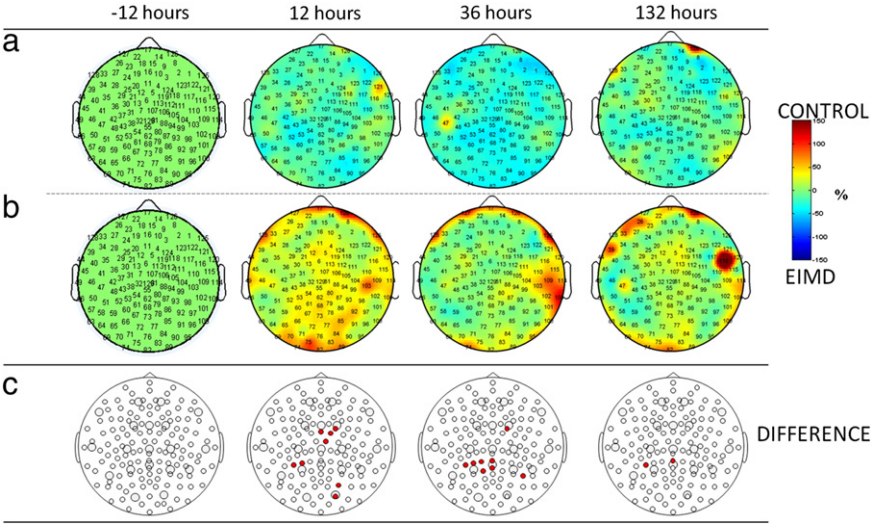


Fig. 4. The global change (%) of β-1 activity measured with 129 electrodes over the scalp is shown in the control (a) and experimental (b) group. An outline of the electrodes showing significant differences between the two groups (c) at each time point is also shown.

3.8.13.2. Parietal (Pz and P4). Differences over time also occurred in electrodes 68 ($X^2 = 12.2$, $p = 0.01$) and 79 ($X^2 = 13.0$, $p = 0.01$) located over the parietal area.

3.8.14. Differences over time in the experimental group (0 vs 12 h)

There were no differences in the experimental group over time.

3.8.15. Differences between groups at 36 h after the EIMD protocol

3.8.15.1. Parietal (Pz). Only electrode 54 ($H = 7.50$, $p < 0.01$) was significantly different between the control and experimental group at 36 h after the EIMD protocol.

3.8.16. Differences over time in the control group (0 vs 36 h)

3.8.16.1. Frontal (Fz). Decreases were observed in frontal β-2 activity of the control group when compared to baseline measurement in electrode 11 ($X^2 = 10.8$, $p = 0.01$).

3.8.16.2. Parietal (Pz). Decreases, compared to baseline, occurred in electrode 55 ($X^2 = 13.5$, $p = 0.01$) in the medial parietal area.

3.8.17. Differences over time in the experimental group (0 vs 36 h)

No differences over time were observed in the experimental group.

3.8.18. Differences between groups at 100 and 32 h after the EIMD protocol

There were no differences between the two groups at 132 h post-EIMD protocol.

3.8.19. Differences over time in the control group (0 vs 132 h)

3.8.19.1. Parietal (P3). Differences were observed in the control group over time compared to the baseline measurement in electrode 53 (P3) ($X^2 = 11.8$, $p = 0.01$).

3.8.20. Differences over time in the experimental group (0 vs 132 h)

3.8.20.1. Frontal (Fz). There were decreases in electrode 6 ($X^2 = 11.1$, $p = 0.01$) in the frontal area of the experimental group over time.

3.8.20.2. Temporal (T3 and T5). In the experimental group differences over time were found in β-2 activity running along an anterior–

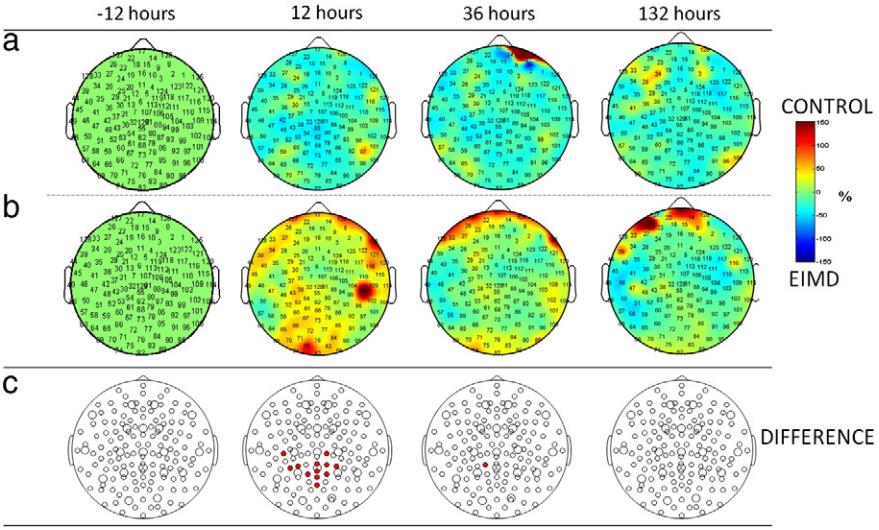


Fig. 5. The global change (%) of β-2 activity measured with 129 electrodes over the scalp is shown in the control (a) and experimental (b) group. An outline of the electrodes showing significant differences between the two groups (c) at each time point is also shown.

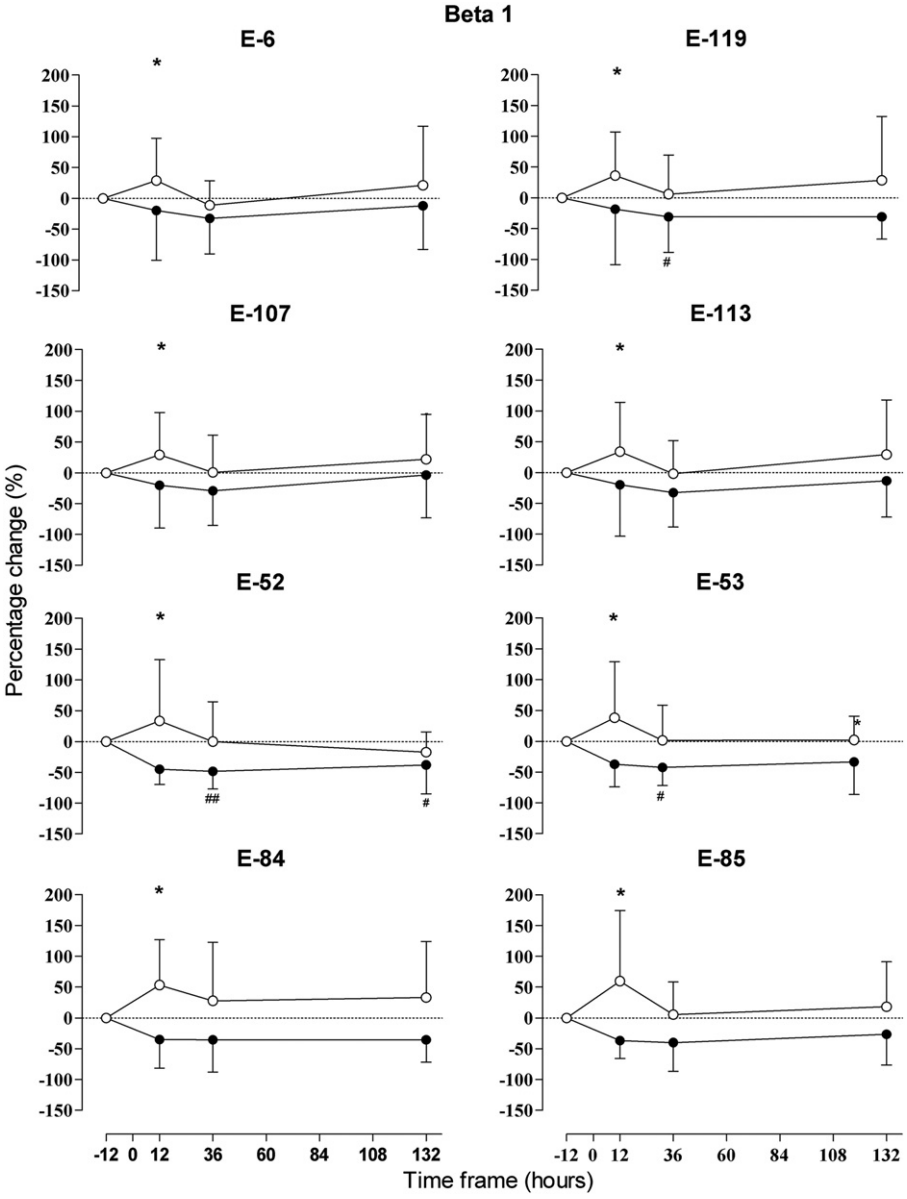


Fig. 6. Twelve different electrodes representative of the change (%) of β-1 activity in the frontal, central and parietal areas of the brain in the control (●) and experimental (○) group. Each graph is labeled with the corresponding electrode number. The horizontal dotted line represents the time of the EIMD-inducing protocol in the experimental group. The vertical gray line marks the time of the EIMD inducing protocol in the experimental subjects. (*Indicates results of the Kruskal–Wallis nonparametric test, #indicates results of the Friedman's nonparametric test.) $^{**}p < 0.01$ control versus experimental group. $\#\#p < 0.01$ at 12 h post versus pre in the control group. $\#\#\#p < 0.001$ at 36 h post versus pre in the control group.

posterior line in the ipsilateral temporal area, electrodes 41 (T3) ($X^2 = 15.23$, $p = 0.01$) and 51 (T5) ($X^2 = 12.15$, $p = 0.01$).

3.8.20.3. Parietal (P3). Differences over time were also evident in electrode 60 between 12 and 132 h ($X^2 = 15.23$, $p = 0.01$).

4. Discussion

The first finding of this study was that the EIMD protocol resulted in similar physiological responses (Fig. 3) reflecting muscle damage in the experimental group as previously reported [1].

In particular the symptoms of EIMD (swelling, muscle shortening and serum CK activity) changed in the typical way for the duration of the experiment (Fig. 3a–d). Also, muscle function (force output) was impaired immediately after the EIMD protocol and gradually recovered, but did not return to baseline by 132 h (Fig. 3e). Pain on the other hand progressively increased, peaking around 36 to 60 h and was decreasing at 132 h.

The study also showed a trend in increased submaximal EMG activity in the biceps brachii in the first 12 h after the induction of EIMD (Fig. 3f). This is in agreement with a previous study that found submaximal EMG increased 12 h after the induction of EIMD with the same protocol and a smaller cohort (25 participants of the 37) [1]. The same study also showed that a submaximal flexion–extension movement led to increased EMG activity until 132 h after the EIMD protocol [1].

It has previously been shown that EIMD, as well as muscular pain in the biceps brachii, not only leads to altered proprioception and motor-perception but also changes in neuromuscular function and motor recruitment [5]. Several studies [2,3,24,25] have also shown that movement steadiness and force output, both associated with motion perception and proprioception, are difficult to maintain during low force contractions while experiencing symptoms of EIMD [2], as observed in this study.

With the confirmation that EIMD was successfully induced in this cohort the novel findings of this study were the significant changes in cortical β activity that peaked at 12 h while the participants were

experiencing symptoms of EIMD. Due to the lower and upper β frequency (from 13.67 to 35.16 Hz) reacting to different motor and somatosensory activation, β was divided into two different frequency bands, β-1 (13.67 to 18.55 Hz) and β-2 (19.35 to 35.16 Hz) activity respectively, for analysis and discussion.

4.1. Beta 1

The most pertinent finding in β-1 activity was that differences between the experimental and control groups peaked at 12 and 36 h after the induction of EIMD, these were predominantly evident in the

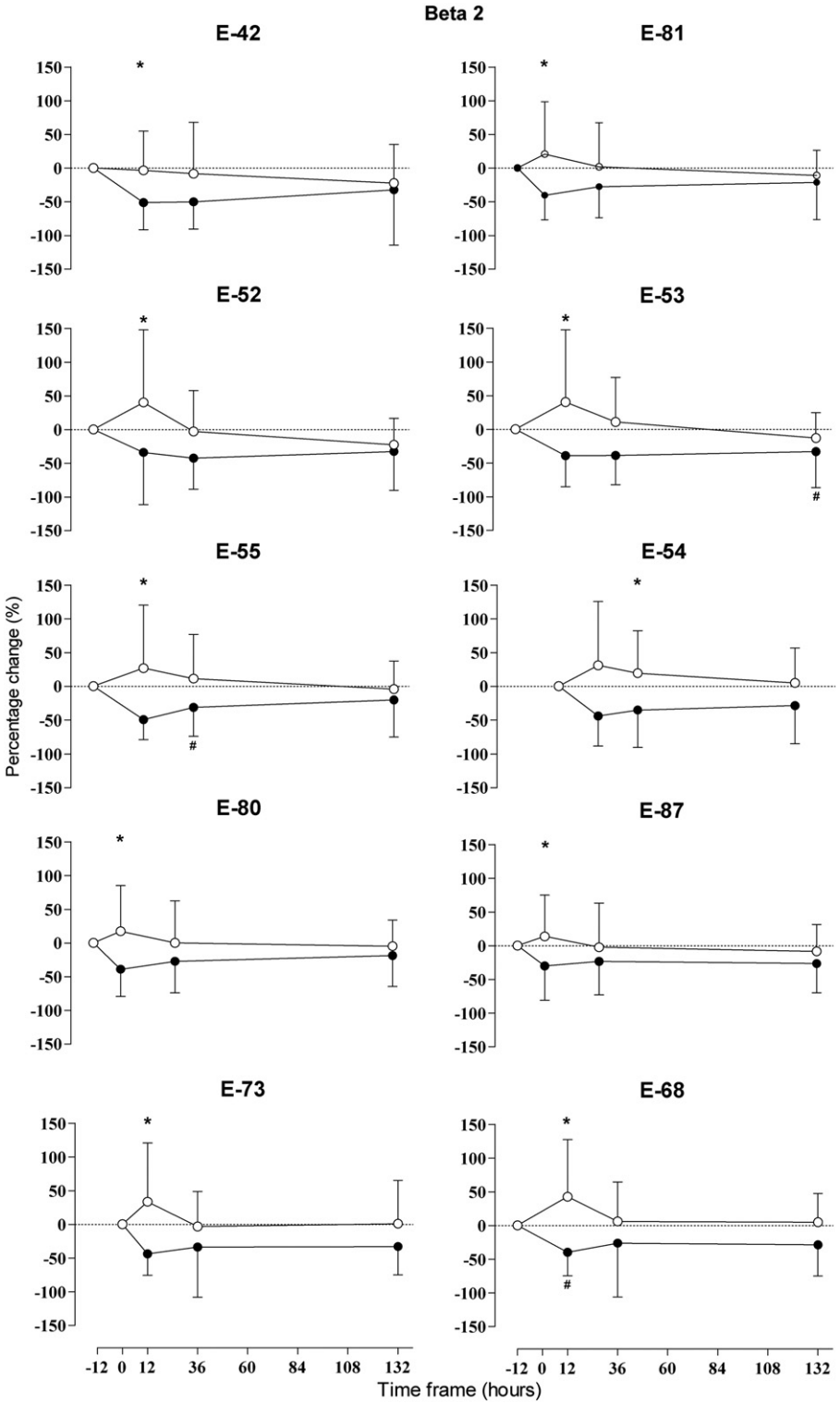


Fig. 7. Twelve different electrodes representative of the change (%) of β-2 activity in the frontal, central and parietal areas of the brain in the control (●) and experimental (○) group. Each graph is labeled with the corresponding electrode number. The horizontal dotted line represents the time of the EIMD-inducing protocol in the experimental group. The vertical gray line marks the time of the EIMD inducing protocol in the experimental subjects. (*Indicates results of the Kruskal–Wallis nonparametric test, #, †, ‡ indicate results of the Friedman's nonparametric test). $^{**}p < 0.01$ control versus experimental group. $^{***}p < 0.001$ control versus experimental group. $\#\#p < 0.01$ at 12 and 36 h post versus pre in the control group.

parietal (ipsilateral), frontal (contralateral) and occipital areas of the cortex (Figs. 4 and 5).

This increase in β-1 activity coincided with maximal changes in elbow angle, elbow girth and levels of pain (Fig. 3). At the same time a decrease in beta 1 activity was seen in the control group until 132 h after the EIMD induction protocol. These changes in activity patterns in the experimental and the control group could possibly be explained by different adaptation mechanisms to the given movement task.

Increased β-1 activity in the premotor and parietal area as seen in this study (Fig. 4) has previously been associated with movement perception (ipsilateral parietal area) or sensory motor integration (premotor area) at 12 h [16,29,32,33]. Therefore we suggest that there could be a causal relationship between increased β-1 activity in these areas and the symptoms caused by EIMD in the periphery at 12 and 36 h in the experimental group.

Most interesting are the simultaneous increases in pain, arm circumference and β-1 activity and the decrease in elbow angle (i.e. muscle shortening). Based on previous research which links increased β-1 activity to sensory motor integration and system feedback especially in chronic pain patients we hypothesize a causal interaction between the sensory output from the muscle and the parietal area in the β-1 activity range at 12 and 36 h after the EIMD protocol. This is supported by findings that show that the parietal area is associated with perception and sensory information integration [16,29,32,33] (Fig. 6).

There were no changes in β-1 activity at 12 h in the control group but a marked decrease in the parietal area at 36 and lesser decrease at 132 h. This may be a "training" effect. It is suggested that after having performed the same task three times (familiarization, 0 h and 12 h), the repetitiveness of the protocol leads to an altered movement perception and therefore decreased beta-1 activity at 36 and 132 h in the control group (Fig. 7).

4.2. Beta 2

In contrast to β-1 activity, differences in β-2 activity between the two groups were pronounced in the parietal area. Beta-2 activity differences were marked between the groups at 12 but not at 36 and 132 h after the exercise protocol. These differences may be a result of a concomitant increase in activity in the experimental group and decrease in activity in the control group. These areas are usually associated with anticipation of movement, proprioception and motor perception [16,29,32,33].

The increase in β-2 activity in the parietal area of the experimental group at 12 h is in accordance with the changed activity patterns seen in the maximal and submaximal EMG. Interestingly, the changes in neuromuscular function, seen as changes in EMG activity and force output, could act as bottom up signal from the periphery which would lead to a compensatory increase in β-2 activity in the associated parietal areas seen in our study [16,29,32,33]. This hypothesis is supported by previous studies which have not only shown cortico-motor coherence in the β frequency range [7,48], but also that β-2 activity measured in the parietal area is associated with bottom up sensory signaling from the peripheral motor system [23,49,50] to the brain. Beta-2 activity links afferent sensory information to motor planning. It has been suggested that this networking aids in the decision-making process prior to the execution of a movement [49–55].

This notion is supported by the increased EMG activity and decreased power output during the movement task. We therefore suggest that the increased β-2 activity in the experimental group is associated with the changes in power output, EMG activity and neuromuscular functioning seen 12 h post-EIMD without the specific function of this increase being known.

5. Limitations

This novel study, conducted over 132 h, explored the relationship between neuromuscular changes and pain induced by an EIMD protocol and β-1 and β-2 activity measured by EEG. Although our study investigated changes in induced β activity, rather than event related β activity, the aim was to investigate the influence of exercise-induced pain and neuromuscular changes on β activity over the entirety of a movement task. Also our data were not normalized to baseline but rather compared to pre-EIMD protocol values to identify percentage changes in β activity post- versus pre-EIMD. We also measured EMG and EEG during the same testing protocol but not at similar time points and therefore correlations and coherences can only be postulated. Further motor-cortical coherence research is required to elucidate, firstly the association between β-1 activity and motor perception and proprioception, and secondly β-2 activity and the anticipation of pain and changes in neuromuscular functioning (loss of force, stiffness and changes in EMG activation) while experiencing the symptoms of EIMD.

To elaborate further on the topic, future studies could include the use of analgesic medication and its effects on EIMD, and measuring cortical activity during rest or movement of a limb which is not affected by the EIMD. Also the use of MRI or PET scans together with EEG and EMG could lead to more conclusive results.

In conclusion this novel study found that an increased β-1 activity might be associated with the anticipation of pain induced by movement and the cognitive evaluation of neuromuscular changes associated with EIMD. Additionally our data suggest that an increased β-2 activity in the parietal area is linked to disturbed neuromuscular function, decreased force output, increased submaximal and decreased maximal EMG.

Acknowledgments

The authors would like to thank all participants of this study. This study was funded in part by the Medical Research Council of South Africa, Discovery Health and the University of Cape Town.

Ethical approval

The study was approved by the Human Ethics Committee of the Faculty of Health Science (REC REF: 090/2004), University of Cape Town, while the principles outlined by the Declaration of Helsinki were adopted in this study [40].

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] Plattner K, Baumeister J, Lamberts RP, Lambert MI. Dissociation in changes in EMG activation during maximal isometric and submaximal low force dynamic contractions after exercise-induced muscle damage. J Electromyogr Kinesiol 2011;21:642–50.
[2] Semmler JG, Tucker KJ, Allen TJ, Proske U. Eccentric exercise increases EMG amplitude and force fluctuations during submaximal contractions of elbow flexor muscles. J Appl Physiol 2007;103:979–89.
[3] Proske U, Gregory JE, Morgan DL, Percival P, Weerakkody NS, Canny BJ. Force matching errors following eccentric exercise. Hum Mov Sci 2004;23:365–78.
[4] Turner TS, Tucker KJ, Rogasch NC, Semmler JG. Impaired neuromuscular function during isometric, shortening, and lengthening contractions after exercise-induced damage to elbow flexor muscles. J Appl Physiol 2008;105:502–9.
[5] Proske U, Weerakkody NS, Percival P, Morgan DL, Gregory JE, Canny BJ. Force-matching errors after eccentric exercise attributed to muscle soreness. Clin Exp Pharmacol Physiol 2003;30:576–9.
[6] Prasartwuth O, Taylor JL, Gandevia SC. Maximal force, voluntary activation and muscle soreness after eccentric damage to human elbow flexor muscles. J Physiol 2005;567:337–48.
[7] Androulidakis AG, Doyle LM, Yarrow K, Litvak V, Gilbertson TP, Brown P. Anticipatory changes in beta synchrony in the human corticospinal system and associated improvements in task performance. Eur J Neurosci 2007;25:3758–65.
[8] Chakarov V, Naranjo JR, Schulte-Monting J, Omlor W, Huethe F, Kristeva R. Beta-range EEG–EMG coherence with isometric compensation for increasing modulated low-level forces. J Neurophysiol 2009;102:1115–20.
[9] Conway BA, Halliday DM, Farmer SF, Shahani U, Maas P, Weir AI, Rosenberg JR. Synchronization between motor cortex and spinal motoneuronal pool during the performance of a maintained motor task in man. J Physiol 1995;489(Pt 3):917–24.
[10] Ohara S, Ikeda A, Kunieda T, Yazawa S, Baba K, Nagamine T, Taki W, Hashimoto N, Mihara T, Shibasaki H. Movement-related change of electrocorticographic activity in human supplementary motor area proper. Brain 2000;123(Pt 6):1203–15.

[11] Erbil N, Ungan P. Changes in the alpha and beta amplitudes of the central EEG during the onset, continuation, and offset of long-duration repetitive hand movements. Brain Res 2007;1169:44–56.
[12] Leocani L, Toro C, Manganotti P, Zhuang P, Hallett M. Event-related coherence and event-related desynchronization/synchronization in the 10 Hz and 20 Hz EEG during self-paced movements. Electroencephalogr Clin Neurophysiol 1997;104:199–206.
[13] Fukuda M, Juhasz C, Hoechstetter K, Sood S, Asano E. Somatosensory-related gamma-, beta- and alpha-augmentation precedes alpha- and beta-attenuation in humans. Clin Neurophysiol 2010;121:366–75.
[14] Del PC, Marzano N, Tilgher S, Fiore A, Di CE, Aschieri P, Lino A, Toran G, Babiloni C, Eusebi F. Pre-stimulus alpha rhythms are correlated with post-stimulus sensorimotor performance in athletes and non-athletes: a high-resolution EEG study. Clin Neurophysiol 2007;118:1711–20.
[15] Miller KJ, Leuthardt EC, Schalk G, Rao RP, Anderson NR, Moran DW, Miller JW, Ojemann JG. Spectral changes in cortical surface potentials during motor movement. J Neurosci 2007;27:2424–32.
[16] Mizelle JC, Forrester L, Hallett M, Wheaton LA. Electroencephalographic reactivity to unimodal and bimodal visual and proprioceptive demands in sensorimotor integration. Exp Brain Res 2010;203:659–70.
[17] Chang PF, Arendt-Nielsen L, Graven-Nielsen T, Chen AC. Psychophysical and EEG responses to repeated experimental muscle pain in humans: pain intensity encodes EEG activity. Brain Res Bull 2003;59:533–43.
[18] Chang PF, Arendt-Nielsen L, Graven-Nielsen T, Svensson P, Chen AC. Comparative EEG activation to skin pain and muscle pain induced by capsaicin injection. Int J Psychophysiol 2004;51:117–26.
[19] Chang PF, Arendt-Nielsen L, Graven-Nielsen T, Svensson P, Chen AC. Different EEG topographic effects of painful and non-painful intramuscular stimulation in man. Exp Brain Res 2001;141:195–203.
[20] Chen AC, Feng W, Zhao H, Yin Y, Wang P. EEG default mode network in the human brain: spectral regional field powers. Neuroimage 2008;41:561–74.
[21] Moraes H, Deslandes A, Silveira H, Ribeiro P, Cagy M, Piedade R, Pompeu F, Laks J. The effect of acute effort on EEG in healthy young and elderly subjects. Eur J Appl Physiol 2011;111:67–75.
[22] Androulidakis AG, Doyle LM, Gilbertson TP, Brown P. Corrective movements in response to displacements in visual feedback are more effective during periods of 13–35 Hz oscillatory synchrony in the human corticospinal system. Eur J Neurosci 2006;24:3299–304.
[23] Baker SN. Oscillatory interactions between sensorimotor cortex and the periphery. Curr Opin Neurobiol 2007;17:649–55.
[24] Weerakkody N, Percival P, Morgan DL, Gregory JE, Proske U. Matching different levels of isometric torque in elbow flexor muscles after eccentric exercise. Exp Brain Res 2003;149:141–50.
[25] Carson RG, Riek S, Shahbazpour N. Central and peripheral mediation of human force sensation following eccentric or concentric contractions. J Physiol 2002;539:913–25.
[26] Gilbertson T, Lalo E, Doyle L, Di LV, Cioni B, Brown P. Existing motor state is favored at the expense of new movement during 13–35 Hz oscillatory synchrony in the human corticospinal system. J Neurosci 2005;25:7771–9.
[27] Klostermann F, Nikulin VV, Kuhn AA, Marzinzik F, Wahl M, Pogosyan A, Kupsch A, Schneider GH, Brown P, Curio G. Task-related differential dynamics of EEG alpha- and beta-band synchronization in cortico-basal motor structures. Eur J Neurosci 2007;25:1604–15.
[28] Brown P. Abnormal oscillatory synchronisation in the motor system leads to impaired movement. Curr Opin Neurobiol 2007;17:656–64.
[29] Lalo E, Gilbertson T, Doyle L, Di LV, Cioni B, Brown P. Phasic increases in cortical beta activity are associated with alterations in sensory processing in the human. Exp Brain Res 2007;177:137–45.
[30] Kilner JM, Baker SN, Salenius S, Hari R, Lemon RN. Human cortical muscle coherence is directly related to specific motor parameters. J Neurosci 2000;20:8838–45.
[31] Kilner JM, Baker SN, Salenius S, Jousmaki V, Hari R, Lemon RN. Task-dependent modulation of 15–30 Hz coherence between rectified EMGs from human hand and forearm muscles. J Physiol 1999;516(Pt 2):559–70.
[32] Vaina LM, Solomon J, Chowdhury S, Sinha P, Belliveau JW. Functional neuroanatomy of biological motion perception in humans. Proc Natl Acad Sci U S A 2001;98:11656–61.
[33] Altamura M, Goldberg TE, Elvevag B, Holroyd T, Carver FW, Weinberger DR, Coppola R. Prefrontal cortex modulation during anticipation of working memory demands as revealed by magnetoencephalography. Int J Biomed Imaging 2010;2010.
[34] Le Pera D, Graven-Nielsen T, Valeriani M, Oliviero A, Di LV, Tonali PA, Arendt-Nielsen L. Inhibition of motor system excitability at cortical and spinal level by tonic muscle pain. Clin Neurophysiol 2001;112:1633–41.
[35] Huber MT, Bartling J, Pachur D, Woikowsky-Biedau S, Lautenbacher S. EEG responses to tonic heat pain. Exp Brain Res 2006;173:14–24.
[36] Chen AC, Herrmann CS. Perception of pain coincides with the spatial expansion of electroencephalographic dynamics in human subjects. Neurosci Lett 2001;297:183–6.
[37] Chang PF, Arendt-Nielsen L, Chen AC. Differential cerebral responses to aversive auditory arousal versus muscle pain: specific EEG patterns are associated with human pain processing. Exp Brain Res 2002;147:387–93.
[38] Oldfield RC. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia 1971;9:97–113.
[39] American College of Sports Medicine. Preparticipation health screening and risk stratification. In: Whaley Mitchell H, editor. ACSM's guidelines for exercise testing and prescription. 7th ed. Indiana: Lippincott William & Wilkins; 2007. p. 19–35.
[40] World Medical Association Declaration of Helsinki. Nurs Ethics 2002;9:105–9.
[41] Chang YW, Su FC, Wu HW, An KN. Optimum length of muscle contraction. Clin Biomech (Bristol, Avon) 1999;14:537–42.
[42] Saxton JM, Donnelly AE. Length-specific impairment of skeletal muscle contractile function after eccentric muscle actions in man. Clin Sci (Lond) 1996;90:119–25.
[43] Bernier R, Dawson G, Webb S, Murias M. EEG mu rhythm and imitation impairments in individuals with autism spectrum disorder. Brain Cogn 2007;64:228–37.
[44] Murias M, Swanson JM, Srinivasan R. Functional connectivity of frontal cortex in healthy and ADHD children reflected in EEG coherence. Cereb Cortex 2007;17:1788–99.
[45] Keil A, Muller MM. Feature selection in the human brain: electrophysiological correlates of sensory enhancement and feature integration. Brain Res 2010;1313:172–84.
[46] Plattner K, Lambert MI, Tam N, Baumeister J. The response of cortical alpha activity to pain and neuromuscular changes caused by exercise-induced muscle damage. Scand J Med Sci Sports 2012. http://dx.doi.org/10.1111/j.1600-0838-2012-01486.x [Epub ahead of Print].
[47] Niedermeyer E, Lopes da Silva FH. Electroencephalography: basic principles, clinical applications, and related fields. fifth ed. Philadelphia, Baltimore, New York, London, Buenos Aires, Hong Kong, Sydney, Tokyo: Lippincott Williams & Wilkins; 2005.
[48] Gross J, Tass PA, Salenius S, Hari R, Freund HJ, Schnitzler A. Cortico-muscular synchronization during isometric muscle contraction in humans as revealed by magnetoencephalography. J Physiol 2000;527(Pt 3):623–31.
[49] Lamb GD. Mechanisms of excitation–contraction uncoupling relevant to activity-induced muscle fatigue. Appl Physiol Nutr Metab 2009;34:368–72.
[50] Siegel M, Engel AK, Donner TH. Cortical network dynamics of perceptual decision-making in the human brain. Front Hum Neurosci 2011;5:21.
[51] Donner TH, Siegel M, Oostenveld R, Fries P, Bauer M, Engel AK. Population activity in the human dorsal pathway predicts the accuracy of visual motion detection. J Neurophysiol 2007;98:345–59.
[52] Murthy VN, Fetz EE. Coherent 25- to 35-Hz oscillations in the sensorimotor cortex of awake behaving monkeys. Proc Natl Acad Sci U S A 1992;89:5670–4.
[53] Brovelli A, Ding M, Ledberg A, Chen Y, Nakamura R, Bressler SL. Beta oscillations in a large-scale sensorimotor cortical network: directional influences revealed by Granger causality. Proc Natl Acad Sci U S A 2004;101:9849–54.
[54] Engel AK, Fries P. Beta-band oscillations — signalling the status quo? Curr Opin Neurobiol 2010;20:156–65.
[55] Wang XJ. Probabilistic decision making by slow reverberation in cortical circuits. Neuron 2002;36:955–68.