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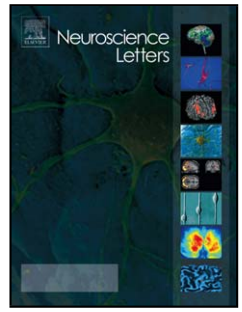

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Modulation of EMG power spectrum frequency during motor imagery

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Abstract

To provide evidence that motor imagery (MI) is accompanied by improvement of intramuscular conduction velocity (CV), we investigated surface electromyographic (EMG) activity of 3 muscles during the elbow flexion/extension. Thirty right-handed participants were asked to lift or to imagine lifting a weighted dumbbell under 3 types of muscular contractions, i.e. concentric, isometric and eccentric, taken as independent variables. The EMG activity of the agonist (long and short head of biceps brachii) and the antagonist (long portion of triceps brachii) muscles was recorded and processed to determine the median frequency (MF) of EMG power spectrum as dependant variable. The MF was significantly higher during the MI sessions than during the resting condition while the participants remained strictly motionless. Moreover, the MF during imagined concentric contraction was significantly higher than during the eccentric. Thus, the MF variation was correlated to the type of contraction the muscle produced. During MI, the EMG patterns corresponding to each type of muscle contraction remained comparable to those observed during actual movement. In conclusion, specific motor programming is hypothesized to be performed as a function of muscle contraction type during MI.

Keywords: motor imagery, EMG, mean frequency, muscle contraction types

Introduction

Motor imagery (MI) is the mental representation of a specific action without any corresponding motor output. Brain mapping techniques underlined that actual task performance and mental simulation share common neural substrate, although the cerebral networks do not fully overlap [6, 23, 30, 33]. Moreover, Transcranial Magnetic Stimulation studies showed an increase in corticomotor excitability during MI that is both muscle-specific and temporally correlated to that observed during actual execution [12, 34]. Such data support the principle of functional equivalence between imagined and actual movement. Several experiments have demonstrated previously that the electromyographic (EMG) activity recorded during MI was higher from that observed during the reference condition, i.e. basal level at rest [7]. The origin of this peripheral muscular activity is worthy of interest. Jeannerod [14] hypothesized that the residual EMG activity was due to motor command inhibition, which would remain incomplete, thus resulting in subliminal EMG activity. However, this finding was not recorded systematically [10, 12, 20, 24]. Particularly, neuroimaging studies usually used the absence of EMG activity as an indicator of immobility during scanning. Thus, EMG recordings were used as control to attest that brain activation was due to motor representation and not to retroactions from muscle spindles, and that they were, in fact, not focused specifically on the relationships between EMG and MI. Inconsistencies among publications may also result from methodological issues. EMG signal is affected by electrode geometry, location on the muscle, and distance between active fibers and electrodes [16, 31]. In addition, surface EMG recordings mainly reflect the activity of superficial muscle fibers [14].

When EMG activity was observed during MI, it was shown to be higher than rest and the magnitude of the signal was dependent on effort intensity [3, 11]. Guillot et al. [11] also demonstrated that the root mean squared value (EMGrms) was specific to each type of contraction, the eccentric condition eliciting the lowest EMG activity. In fact, the subliminal

EMG patterns recorded during MI sessions mirrored those recorded during actual conditions, thus demonstrating that the muscular activity occurring during MI was task-specific. This valuable data demonstrates that muscle activity was not due to residual tonic contraction, which would have accompanied the mental activity of MI. Thus, the similarity between mental and actual EMG patterns confirmed the structural and functional relationships between MI and actual execution [14]. Despite arguments in favour of specific muscular activity during MI, this matter has no definite answer, and the controversy would benefit from additional knowledge resulting from EMG power spectrum frequency analysis. This data processing is expected to give additional information about the correlation between MI and actual execution.

Motor units' discharge frequency depends on the action potentials' waveform duration, the type of motor units, and effort intensity. The median frequency (MF) of the EMG power spectrum is poorly sensitive to noise, hence reflecting such physiological processes. Changes in MF are not only associated with the modification of the motor units' discharge frequency, but also with muscle fiber conduction velocity (CV) [2, 22, 32, 35]. The more the type II motor units are activated, the higher the CV and discharge frequency, which results in an increased MF [4, 26]. Recording MF during the mental representation may provide insight into the mechanisms underlying MI, by modulating motor units' discharge frequency and/or CV. The aim of this paper was thus to investigate the effect of muscle contraction types on the median frequency of the EMG signal during MI.

Materiel and method

Participants

Thirty right-handed students (15 men and 15 women, aged from 18 to 25, mean = 21.2 ± 2.4) took voluntarily part in this experiment after giving their informed consent. The local ethic committee agreement was also obtained. No information about the purposes or hypotheses was given to the participants until after they completed the experiment.

Experimental procedures

First, the participants were asked to perform two tests. During the week preceding the experiment, the *maximum voluntary contraction* (MVC) was determined using an incremental test, which required lifting a dumbbell by bending the elbow joint. The best grade, taken from one concentric contraction, was considered the MVC. The *isometric maximal voluntary contraction* (IMVC) was measured using a strain gauge force transducer with the elbow joint at 90°. During the experimental procedure, the subjects were seated in a comfortable armchair and were attached to the seat with a belt to prevent any body movements that could help them increase their strength.

One week later, the participants were asked to lift and imagine lifting the dumbbells under three conditions: 1) a concentric contraction (80% of MVC), 2) an eccentric contraction (120% of MVC) and 3) an isometric contraction (95% of IMVC). Each participant randomly performed 4 actual and 8 imagined trials under each condition, i.e. 16 actual movements, 32 MI trials and 32 rest-periods. Rest periods were needed to let the variables come back to their basal levels and were thus taken as controls. During MI, the participants were instructed to visualize and perceive muscular contraction and joint motion, as if movement was actually being performed. In order to insure that the participants did the correct exercise, they received the following instructions: "*Try to imagine yourself performing the motor sequence with your eyes closed, by perceiving the different movements just as if you had a camera on your head, and feel the body's sensations. You have to see and feel only what you would see and feel if you had to perform this particular skill. Imagine the movement using the most comfortable way for you, and make sure not to move your arm*". To check if the participants encountered any difficulties during the MI sessions, they were regularly asked to describe the nature of the images they perceived, and were instructed to grade MI quality after each attempt, using a 4-

points scale (1 = very easy to imagine/feel and 4 = very difficult to imagine/feel, 2 and 3 being the intermediate scores).

Dependant variables

EMG and goniometer signals were sampled at 2048 Hz and stored on a hard disk before being processed any further. The goniometer (SG110, Biometrics) was placed on the right elbow joint, to measure the angle between the arm and the forearm, to ensure that the participants remained strictly motionless during both MI and rest conditions.

The EMG signals were recorded using surface electrodes (Triodes Myoscan, interelectrodes distance: 2 cm; bandwidth: 20 Hz to 500 Hz, Flex-comp Infinity system, Thought technology, Montreal, Canada). The EMG signals were collected from 3 muscles of the dominant arm: the long and short heads of biceps brachii (the agonist muscles group) and the long portion of triceps brachii (antagonist muscle). The surface electrodes were parallel to the muscle fibers over the muscle belly. The EMG signals were differentially amplified (gain 500) at the level of the electrodes before being recorded and further band-pass filtered (12-500 Hz). Filtered signals were processed to calculate the EMGrms using a 25 ms moving rectangular window and the median frequency (MF). The EMG and goniometer signals were recorded during the MI, the rest period, and the actual contraction conditions.

A repeated measures ANOVA was then performed. The independent variables included the 3 muscle contraction types (concentric, isometric and eccentric), the 2 experimental conditions (MI and rest-period) and the 3 muscles (the long and short head of the biceps brachii and the long portion of the triceps brachii). Another ANOVA with repeated measures was run between actual and imagined contractions. The Student's paired t-test was then used to compare goniometric data under MI and rest conditions. The results are presented as a median [standard deviation] and significance level was set at $P \leq 0.05$.

Results

Goniometry

Data analysis from the goniometer showed that the average deviation from the arm position to be maintained (90°) was comparable during the MI and rest conditions (0.52 [0.2] vs. 0.55 [0.2] degrees ; t = 1.39, P > 0.05, NS).

Median Frequency under Actual and MI contractions

The ANOVA showed a significant difference between actual and imagined contractions ($F_{1,264}$ = 551.47, P < 0.001), mean frequency being 72.35 Hz [12.53] and 37.08 Hz [8.65] respectively. The interaction between the muscle contraction types and the experimental conditions also reached the significant threshold ($F_{2,264}$ = 14.17, P < 0.001), the weakest MF being observed under the actual isometric contraction condition (70.01 Hz) and during the MI of eccentric contraction (35.90 Hz).

EMGrms under Rest vs. MI

The ANOVA with repeated measures showed that the EMGrms data was higher during the MI sequences than during the rest-period ($F_{1,342}$ = 7.15, P = 0.008). During concentric imagined contractions, the electrical muscular activity was higher than under eccentric in the two heads of the biceps brachii and than under isometric imagined contractions in the long head of the same muscle. The EMGrms values are presented in Table 1.

Insert Table 1 about here

Median Frequency under Rest vs. MI

The ANOVA with repeated measures showed that the median frequency was higher during the MI than during the rest-period ($F_{1,246}$ = 5.99, P = 0.016), MF values being 37.08 Hz [8.65] and 33.81 Hz [8.57] respectively. The comparison of the muscle contraction conditions did not reached significance ($F_{2, 246}$ = 0.48, P > 0.05, NS).

Median Frequency and Type of muscles contraction

Taking into account all the data, the within-subjects analysis of variance revealed a significant effect of muscle contraction types ($F_{2,246}$ = 8.18, P < 0.001). Then, each muscle contraction type was compared with each other during MI. When the data of the two heads of the biceps brachii and the triceps brachii were pooled, the concentric contraction elicited the highest MF (38.80 Hz [8.97]) and the eccentric contraction the lowest (35.90 Hz [9.25]), the isometric providing intermediate MF (36.55 Hz [7.49]). The MF during concentric contraction was significantly higher than under eccentric contraction for the long and the short head of biceps brachii (t = 3.29, P = 0.003 and t = 2.23, P = 0.036, respectively). Moreover, for the long head of biceps, the comparison of the isometric MF with the eccentric MF was close to the significant threshold (t = 1.88, P = 0.073), mean values being 36.51 Hz [8.26] and 34.53 Hz [9.42] respectively (Figure 1), whereas no significant difference emerged as a function of muscle contraction types during MI of triceps brachii (Figure 2) and during rest-period ($F_{2,114}$ = 2.80, P > 0.05, NS).

Insert Figure 1 and 2 about here

For the actual contractions condition, the MF of the eccentric contraction was significantly higher than that recorded during the isometric contraction in the long head of the biceps (t = 2.28, P = 0.007), the short head of the biceps (t = 2.54, P = 0.019) and the triceps brachii (t = 5.44, P < 0.001). Moreover, the MF of the concentric contraction was significantly lower than the eccentric for the triceps brachii (t = 3.93, P = 0.019), mean values being 62.17 Hz [7.16] and 67.89 Hz [6.62] respectively.

The ANOVA with repeated measures did not show any significant interaction between actual and imagined movements, whatever the condition, the muscle or the type of contraction.

Discussion

The goniometric data did not show any elbow position differences during the rest and the MI conditions suggesting that changes in the EMG activity were not related to non-physiological factors [31]. Consequently, the significant difference between the EMG signals recorded during the rest and MI conditions was not due to any unexpected movement. The increase of MF may be correlated to the weak EMG activity recorded during imagined movement. Guillot et al. [11] showed that the mean EMGrms values were also higher during MI than during the rest-period. Thus, and as stated by Jeannerod [14], the motor command was probably not fully inhibited when the participants imagined the movement. Accordingly, MI has already been shown to activate the motor and premotor cortices, the supplementary motor area and the cingulare gyrus [6, 20]. The corticospinal neurones from these regions may have the ability to recruit spinal motoneurones. This may contribute to explain why the neural drive to peripheral effectors has improved the magnitude of intramuscular CV, even though the process of inhibiting the motor command remains unresolved.

During actual flexion of the elbow, Komi et al. [17] showed that the MF of the biceps brachii's concentric contraction was usually above 80 Hz, while the eccentric contraction was between 60 and 80 Hz. In the present study, the mean MF was 71.98 Hz, i.e. lower than during actual eccentric contractions (mean = 75.07 Hz). Such a difference may result from the characteristics of the experimental design: we tested at 80% of MVC with the concentric contraction, whereas Komi et al. [17] requested MVC. Furthermore, differences between types of muscular contraction may be explained by muscle length, which could affect the EMG power spectrum [27]. The increase of muscle length was shown to elicit a decrease of the muscle fiber CV [29], which is known to be closely correlated to the EMG power spectrum [2]. Komi et al. [17] showed that the lower MF recorded during actual eccentric contraction compared to concentric contractions could be explained, at least in part, by an increase in muscle length during the eccentric contraction. Thus, the decrease in MF during the eccentric contraction suggested some changes in muscle fibers CV and therefore possible derecruitment of the fastest units [17].

As far as the types of muscle contraction are concerned during imagined contractions, the difference between mean power spectrum frequencies may highlight the mechanisms underlying MI and explain the increased EMG activity. The mean level of muscle activation differentiated the MI of elbow joint bending as a function of weight [3, 11]. Indeed, higher EMGrms values were recorded when the participants imagined lifting heavier dumbbells. Furthermore, Guillot et al.'s results [11] are confirmed, by showing that during MI, the pattern of EMG activity during eccentric contractions is weaker than when it is recorded for isometric and concentric contractions. This difference may be explained by the decreased number of motor units activated during eccentric contractions compared to concentric contractions. Indeed, the EMG power spectrum analysis of the two heads of the biceps brachii showed the weakest MF during eccentric contractions. The current results provided further evidence that the EMG power spectrum patterns were similar during actual movement and MI. This finding confirms the structural relationship between MI and physical execution, even if MF recorded during simulated movements was lower than during the actual execution. The EMGrms of triceps was shown as being higher than in rest, thus attesting co-contraction. However, during MI, the MF of the triceps brachii did not differ from one muscle contraction type to another, although values were significantly higher during MI than during the rest-period. Thus, in contrast to biceps, this was not task specific. This may be caused by the increased attention on the muscles that ensure the forearm flexion on the arm.

As reported by Bouisset and Maton [4], motor units' categories and effort intensity modulate the discharge frequency and the CV. The more the type II motor units are activated, the higher the CV and discharge frequency, hence resulting in an increased MF. The current results confirmed that MF and EMGrms provide significant differences when the MI sequence was compared to the rest-period and evolved as a function of muscle contraction types. Gandevia et al. [8] argued that the motor cortex is activated by MI and that this information may, in turn, be strong enough to recruit spinal motoneurones. According to these assumptions and with reference to the current findings, we assume that, during MI, different motor units, including those of type II, may be recruited as a function of muscle contraction type, even though the number of motor units activated during MI remains unknown and probably weak. The increase of EMGrms during MI can be related to the activation of more motor units, although we do not have any information about the nature of the recruitment, e.g. spatial and/or temporal. Nevertheless, as the MF reached higher values, it may be assumed that additional type II motor units were recruited and/or the discharge frequency of these motor units was increased. According to Merletti and Lo Conte [26], action potentials travelling at a higher velocity have lower time duration, revealing type II motor units activity. As a consequence, faster motor units could be activated during MI of concentric contractions. Besides, eccentric contraction elicited the weakest MF, which is associated with a decrease of CV and frequency discharge of all the motor units and/or a lower recruitment of the fastest motor units. It may thus be hypothesized that, during MI, differences between motor programming occurred as a function of muscle contraction type and mirrored those observed during actual movements. The neurons from the motor cortex are activated selectively according to the direction and the magnitude of static force [1]. Georgopoulos et al. [9] suggested that the primary motor cortex might code the dynamic force (or the change in force). The motor command originating from the primary motor cortex integrates the movement instructions from both associative cortices and subcortical networks, specifically those from the basal ganglia and the lateral cerebellum. These signals encode movement variables, such as force and timing of the contraction [5]. The information from the central nervous system processing to the peripheral effectors might influence the recruitment of the motor units, and therefore the variables processed from the EMG signal. Indeed, information is encoded through the modulation of motor units' discharge frequency [18]. Consequently, the force, and indirectly the EMGrms recordings, is modulated by a combination of temporal and spectral changes in muscle activation [19, 25, 28].

To conclude, the MF was higher when the subjects imagined lifting a dumbbell than during the rest condition, as well as during the concentric contractions, compared to other contraction types. The assumption of selecting a specific motor program as a function of muscle contraction type that requires recruitment of different motor unit during MI remains a hypothesis awaiting further experimental investigation. Direct measurement, i.e. intramuscular EMG, may provide insight regarding the differentiation of the muscle fibers recruited during MI.

References

[1] J. Ashe, Force and the motor cortex, Behav. Brain Res. 86 (1997) 1-15.

[2] L. Arendt-Nielsen, K. Mills, The relationship between mean power frequency of the EMG spectrum and muscle fiber conduction velocity, Electroencephal. Clin. Neurophysiol. 60 (1985) 130-134.

[3] F.C. Bakker, M.S.J. Boschker, T. Chung, Changes in muscular activity while imagining weight-lifting using stimulus or response propositions, J. Sport Exercise Psychol. 18 (1996) 313-324.

[4] S. Bouisset, B. Maton (Eds), Muscles, Posture et Mouvement, De l'électromyographie globale à l'étude des mouvements du répertoire. Hermann, Paris, 1995, 475 pp.

[5] P.D. Cheney, Role of cerebral cortex in voluntary movements. A review, Phys. Ther. 65 (1985) 624-635.

[6] J. Decety, D. Perani, M. Jeannerod, V. Bettinardi, B. Tadary, R. P. Woods, J.C. Maziota, F. Fazio, Mapping motor representation with positron emission tomography, Nature. 371 (1994) 600-602.

[7] R. Dickstein, M. Gazit-Grunwald, M. Plax, A. Dunsky, E. Marcovitz, EMG activity in selected target muscles during imagery rising on tiptoes in healthy adults and poststroke hemiparetic patients, J. Mot. Behav. 37 (2005) 475-483.

[8] S.C. Gandevia, L.R. Wilson, J.T. Inglis, D. Burke, Mental rehearsal of motor tasks recruits α-motoneurones but fails to recruit human fusimotor neurones selectively. J. Physiol. (London) 505.1 (1997) 259-266.

[9] A.P. Georgopoulos, J. Ashe, N. Smyrnis, M. Taira, The motor cortex and the coding of force, Science. 256 (1992) 1692-1695.

[10] E. Gerardin, A. Sirigu, S. Lehericy, J.B. Poline, B. Gaymard, C. Marsault, Y. Agid, D. Le Bihan, Partially overlapping neural networks for real and imagined hand movements, Cereb. Cortex. 10 (2000) 1093-1104.

[11] A. Guillot, F. Lebon, D. Rouffet, S. Champely, J. Doyon, C. Collet, Muscular responses during motor imagery as a function of muscle contraction types, Int. J. Psychophysiol. 66 (2007) 18-27.

[12] R. Hashimoto, J.C. Rothwell, Dynamic changes in corticospinal excitability during motor imagery, Exp Brain Res. 125 (1999) 75-81.

[13] P.L. Jackson, M.F. Lafleur, F. Malouin, C.L. Richards, J. Doyon, Functional cerebral reorganization following motor sequence learning through mental practice with motor imagery, Neuroimage. 20 (2003) 1171-1180.

[14] M. Jeannerod, V. Frak, Mental imaging of motor activity in humans, Curr. Opin. Neurobiol. 9 (1999) 735-739.

[15] M. Jeannerod, The representing brain: neural correlates of motor intention and imagery, Behav. Brain Sci. 17 (1994) 187-245.

[16] R.F.M. Kleissen, J.H. Buurke, J. Harlaar, G. Zivold, Electromyography in the biomechanical analysis of human movement and its clinical application, Gait Post. 8 (1998) 143-158.

[17] P.V. Komi, Strength and power in sport, Part II: Biological basis for strength and power. The encyclopaedia of sports medicine (Vol 3), Blackwell Science, Oxford, 2003, 523 pp.

[18] P.V. Komi, V. Linnamo, P. Silventoinen, M. Sillanpää, Force and EMG power spectrum during eccentric and concentric actions, Med. Sci. Sports Ex. 32 (2000) 1757-1762.

[19] C.G. Kukulka, H.P. Clamann, Comparison of the recruitment and discharge properties of motor unit in human brachial biceps and adductor pollicis during isometric contractions, Brain Res. 219 (1981) 45-55.

[20] M.G. Lacourse, E.L.R. Orr, S.C. Cramer, M.J. Cohen, Brain activation during execution and motor imagery of novel and skilled sequential hand movement, NeuroImage. 27 (2005) 505-519.

[21] M.F. Lafleur, P.L. Jackson, F. Malouin, C.L. Richards, A.C. Evans, J. Doyon, 2002. Motor learning procedures parallel dynamic functional changes during the execution and the imagination of sequential foot movements, Neuroimage. 16 (2002) 142-157.

[22] L. Lindström, R. Magnusson, Interpretation of myoelectric power spectra: a model and its applications, Proc. IEEE. 65 (1977) 653-662.

[23] M. Lotze, U. Halsband, Motor Imagery, J. Physiol. – Paris. 99, (2006). 386-395.

[24] M. Lotze, P. Montoya, M. Erb, E. Hulsmann, H. Flor, U. Klose, Activation of cortical and cerebellar motor areas during executed and imagined hand movements: an fMRI study. J. Cogn. Neurosci. 11 (1999) 491-5.

[25] R. Merletti, L.R. Lo Conte, Advances in processing of surface myoelectrics signals: Part 1, Med. Biol. Eng. Comput. 33 (1995) 362-372.

[26] H.S. Milner-Brown, R.B. Stein, R. Yemm, Changes in firing rate of human motor units during linearly changing voluntary contractions, J. Physiol. (London). 230 (1973) 371-390.

[27] T. Moritani, S. Muramatsu, M. Muro, Activity of motor units during concentric and eccentric contraction, Am. J. Phys. Med. 66 (1987) 338-350.

[28] T. Moritani, M. Muro, Motor unit activity and surface electromyogram power spectrum during increasing force of contraction, Eur. J. App. Physiol. 56 (1987) 260-265.

[29] G. Rau, C. Disselhorst-Klug, J. Silny, Noninvasive approach to motor unit characterization: muscle structure, membrane dynamics and neuronal control, J. Biomechan. 30 (1997) 441-446.

[30] P.E. Roland, B. Larsen, N.A. Lassen, E Skinhoj, Supplementary motor area and other cortical areas in organisation of voluntary movements in man, J. Neurophysiol. 43 (1980) 118-136.

[31] D.M. Rouffet, C.A. Hautier, EMG normalization to study muscle activation in cycling, J. Electromyogr. Kines. (2007), doi:10.1016/j.jelekin.2007.03.008.

[32] P. Sbriccoli, I. Bazzucchi, A. Rosponi, M. Bernardi, G. De Vito, F. Felici, Amplitude and spectral characteristics of biceps Brachii sEMG depend upon speed of isometric force generation, J. Electromyogr. Kinesiol. 13 (2003) 139-147.

[33] K.M. Stefan, G.R. Fink, R.E. Passingham, D. Silbersweig, A.O. Ceballo-Bauman, C.D. Frith, R.S.J. Frackowiack, Functional anatomy of the mental representation of upper extremity movements in healthy subjects, J. Neurophysiol. 73 (1995) 373-386.

[34] C.M. Stinear, W.D. Byblow, Motor imagery of phasic thumb abduction temporally and spatially modulates corticospinal excitability, Clin Neurophysiol. 114 (2003) 909-914.

[35] F.B. Stulen, C.J. De Luca, Frequency parameters of the myoelectric signals as a measure of the muscle conduction velocity, IEEE Trans. Biomed. Eng. 28 (1981) 515-523.

Figure 1:

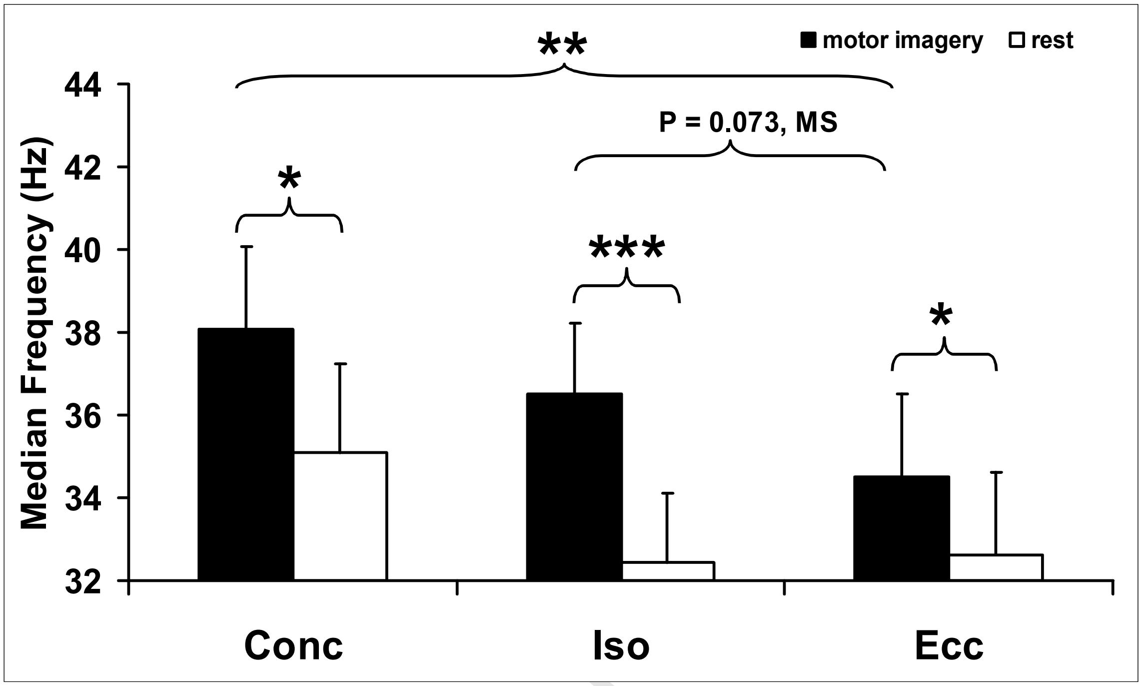

Figure 1: Comparison of the Median Frequency of the biceps brachii (long head) during rest and motor imagery, as a function of each muscle contraction type. Ecc: Eccentric contraction. Conc: Concentric contraction. Iso: isometric contractions. *: P < 0.05, **: P < 0.01, ***: P < 0.001, MS: marginally significant.

Figure 2:

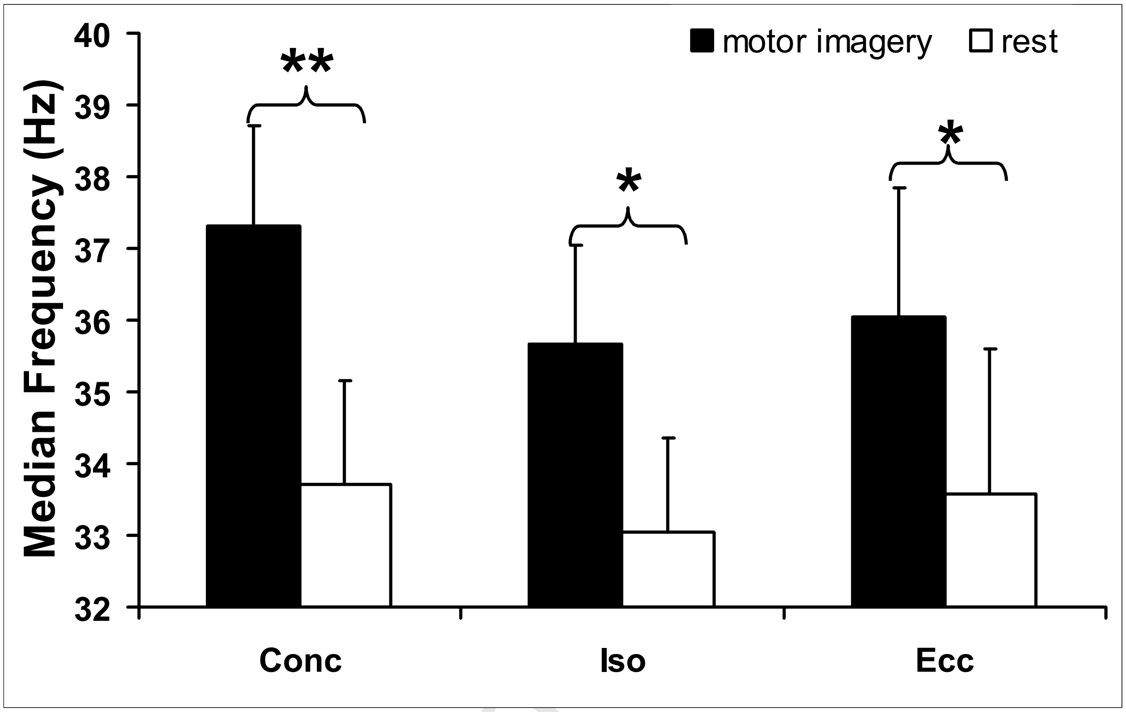

Figure 2: Comparison of the Median Frequency of the triceps brachii (long portion) during the rest and the motor imagery conditions, as a function of each muscle contraction type. Iso: isometric contraction. Conc: concentric contraction. Ecc: eccentric contractions. *: $P < 0.05$, **: $P < 0.01$.

Table 1

EMG activity (mV)	Motor imagery		
	Concentric	Isometric	Eccentric
Biceps brachii Long Head	1.657 (0.08) **	1.527 (0.08) #	1.242 (0.08)
Biceps brachii Short Head	1.701 (0.06) *	1.500 (0.07)	1.370 (0.07)
Triceps Brachii	1.310 (0.06)	1.293 (0.06)	1.282 (0.07)
	Rest		
	Concentric	Isometric	Eccentric
Biceps brachii Long Head	1.235 (0.08)	1.234 (0.07)	1.106 (0.08)
Biceps brachii Short Head	1.278 (0.07)	1.208 (0.06)	1.179 (0.07)
Triceps Brachii	1.118 (0.07)	1.121 (0.07)	1.118 (0.07)

Table 1: EMG activity (mV) and Standard Deviation during Motor Imagery and Rest as a function of muscular contraction type. **: difference between concentric and eccentric contraction ($P < 0.01$); *: difference between concentric and eccentric contraction ($P < 0.05$); #: difference between eccentric and isometric contraction ($P < 0.05$).