Does a Mental Training Session Induce Neuromuscular Fatigue?

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ABSTRACT

ROZAND, V., F. LEBON, C. PAPAXANTHIS, and R. LEPERS. Does a Mental Training Session Induce Neuromuscular Fatigue? *Med. Sci. Sports Exerc.*, Vol. 46, No. 10, pp. 1981–1989, 2014. Mental training, as physical training, enhances muscle strength. Whereas the repetition of maximal voluntary contractions (MVC) induces neuromuscular fatigue, the effect of maximal imagined contractions (MIC) on neuromuscular fatigue remains unknown. Here, we investigated neuromuscular alterations after a mental training session including MIC, a physical training session including MVC, and a combined training session including both MIC and MVC of the elbow flexor muscles. **Methods**: Ten participants performed 80 MIC (duty cycle, 5-s MIC and 10-s rest), 80 MVC (identical duty cycle), or 80 MVC and 80 MIC (5-s MVC, 2-s rest, 5-s MIC, and 3-s rest) in three separate sessions. MVC torque was assessed five times over the course of the training and 10 min after the end of the training in the three protocols. Central activation ratio (CAR_c), reflecting central fatigue, and corticospinal excitability, at rest and during MIC, were estimated using transcranial magnetic stimulation. **Results**: Both the physical training and the combined training induced an approximately 40% drop of MVC torque, accompanied with an approximately 10% decrease of CAR_c without significant difference between the two sessions. On the contrary, the repetition of MIC did not reduce maximal force production capacity and did not alter CAR_c. Corticospinal excitability was always facilitated during MIC compared with that during rest, ensuring that the participants imagined the desired movement. **Conclusions**: These results suggested that one session of mental training alone or combined with physical training do not induce (additional) neuromuscular fatigue despite the repetitive activation of the corticospinal track. Motor imagery may be added to physical practice to increase the total workload without exacerbating neuromuscular fatigue. **Key Words:** IMAGINED CONTRACTIONS, PHYSICAL TRAINING, STRENGTH, MUSCLE ACTIVATION, MENTAL EXERTION

Motor imagery (MI) is a mental process during which an individual internally simulates body movements without actually executing them. It is now well admitted that there are two common types of MI: visual and kinesthetic imagery. Visual imagery requires self-visualization of the movement from a first- or third-person perspective, whereas kinesthetic imagery requires the mental creation of the feeling of performing the exercise from within the body. Visual imagery predominantly activates the occipital regions and the superior parietal lobules, whereas kinesthetic imagery presents more activity in motor-associated structures and the inferior parietal lobule (13). However, the authors stated that physical execution, visual imagery, and kinesthetic imagery resulted in overlapping brain activations. Indeed, imagined actions engage similar motor representations as their actual counterparts (10,15), but the CNS retains, or attenuates, the motor command before it reaches the neuromuscular level. Several neuroimaging studies have pointed out the activation of common neural structures between imagined and actual movement production (10,18,25). Notably, transcranial magnetic stimulation (TMS) studies have shown that primary motor cortex (M1) is functionally relevant for mental movement simulation and motor learning by mental practice (4,12,28). In addition, EMG responses to cortical stimulation are consistently increased during mental practice, demonstrating the involvement of the motor system to mental states of action (19–21,36).

Like physical training, mental training enhances motor performance (9–11) and muscle strength (30,41,42). For instance, in the study of Yue and Cole (41), a 4-wk mental training induced a 22% increase of the maximal voluntary force of the fifth digit, whereas the increase was 30% in the physical practice group and 4% in the control group. MI-related strength gains have also been demonstrated on both the upper limbs (31,35) and lower limbs (3,34,42). Ranganathan et al. (31), by analyzing the electroencephalogram-derived potential, have proposed that repetition of MI enhanced the

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cortical output signal. These authors suggested that MI training could increase motor units activation and/or drive the active motor units to higher intensity, leading to greater muscle force production. Furthermore, the strength gains after MI training may be due to a reduction in co-contraction of the antagonist muscles (42). However, strength or motor skill gains are lower after mental training than those after physical practice (7,9,27). Interestingly, during a combined mental/actual training, the substitution of high-intensity voluntary contractions by imagined contractions reduces muscle fatigue without decrease of muscle strength gains (32). It has also been shown that combined practice was more efficient with MI than that with neutral cognitive task and that it could also improve dynamic performances (22,23). Generally, adding mental practice to an actual training program enhances the effects of training and/or reduces muscle fatigue (for review, see reference 24). However, the effect of a single session of a mental or a combined training on neuromuscular functions remains unknown.

The repetition of maximal voluntary contractions (MVC) induces neuromuscular fatigue (16,38). For instance, Taylor et al. (38) have observed a 40%–60% drop of maximal voluntary torque after intermittent MVC of the elbow flexor (EF) muscles, with different duty cycles. In the same line, Hunter et al. (16) found a reduction of 65% of maximal voluntary torque after sustained MVC of the EF. This torque reduction after exercise was associated with a deficit of voluntary activation (reflecting central fatigue) and a reduction of twitch amplitude (indicating peripheral fatigue).

It is of interest that both voluntary contractions and neuromuscular fatigue affect MI. For example, it has been shown that muscle fatigue could alter mental simulation of action (5,6). Precisely, mental movement was accelerated immediately after fatigue, whereas its actual production was decelerated (5). The CNS seems to integrate the current state of the motor system into the mental stimulation process. To date, the effects of the repetition of mental actions on neuromuscular capacities remain unknown. Because mental and actual movements activate common motor cortical areas, sustained mental rehearsal could alter the neural drive and induce central fatigue. Recent results seem to corroborate such a premise. It has been shown that mental fatigue due to a prolonged demanding cognitive task, as Stroop task, could alter maximal force production capacity (1). Although the authors measured only EMG activity, they suggested that voluntary activation remained stable over the course of the experiment and assumed that the decrease in MVC was due to an expenditure of cognitive resources. Therefore, one could expect that extensive mental repetition of MVC could alter maximal force production capacities.

In this context, the aim of the present study was to investigate neuromuscular alterations after a mental session with maximal imagined contractions (MIC) (mental training), a physical session with MVC (physical training), and a combined session with maximal imagined and voluntary contractions (combined training). We hypothesized that 1) mental training would alter maximal force capacities and would decrease muscle activation despite the absence of actual contractions and 2) combined training would elicit greater alteration of muscle strength compared with that in physical training alone. To test these hypotheses, we analyzed the changes in MVC and central activation ratio (CAR_c) of the EF muscles during the three types of training mentioned previously. We also assessed the level of corticospinal excitability while imagining throughout the experiment.

MATERIALS AND METHODS

Participants. Ten healthy active male subjects (age, 28 ± 10 yr; weight, = 71.6 ± 8.7 kg; height, 177.5 ± 1.6 cm), with no history of neurological diseases, took part in this study. All the participants already experienced maximal voluntary efforts before the experiment. A familiarization session with maximal voluntary and imagined contractions was performed before starting the experiment (see following section for more details). All were made aware of the protocol, and written consents were obtained before the study. Experimental protocol and procedures were approved by the Dijon Regional Ethics Committee (AEC/B90097-40) and conducted according to the Declaration of Helsinki.

Experimental setup. Subjects performed the tests in a sitting position with their dominant arm. The arm and the forearm were placed in a horizontal position, with the elbow flexed at 90°. Isometric elbow flexion torque was recorded using a dynamometer (Biodex Medical System, Inc., Shirley, NY). The arm and the wrist were firmly strapped to the dynamometer, with the axis of rotation aligned with the anatomical axis of the elbow. Two crossover shoulder harnesses and a belt cross above the abdomen limited extraneous movements of the body. Identical positioning was used for the different experimental sessions. Isometric torque was digitized online at a sampling frequency of 1 kHz using a computer and stored for future analysis using a commercially available software (AcqKnowledge 4.1.0; Biopac Systems, Inc., Goleta, CA). Subjects were verbally encouraged throughout all voluntary contractions.

Electrical recordings. EMG activity of the biceps brachii (BB) muscle was continuously recorded with pairs of bipolar silver chloride circular (recording diameter of 10 mm) surface electrodes (Controle Graphique Medical, Brie-Comte-Robert, France) positioned lengthwise over the middle of the muscle belly with an interelectrode (center to center) distance of 20 mm. The reference electrode was placed on the lateral humeral epicondyle. Low resistance between the two electrodes (<5 kΩ) was obtained by shaving the skin, and dirt was removed using alcohol. EMG signals were amplified (×1000) and recorded (acquisition rate, 2 kHz) using a software commercially available (AcqKnowledge; Biopac Systems, Inc., Goleta, CA).

TMS. Single pulses were delivered via a figure-of-eight–shaped coil (external wing diameter, 9 cm) attached to Magstim 200 stimulator (Magstim Co., Whitland, Wales, United Kingdom). The center of the junction of the coil was positioned over the left primary motor cortex to elicit motor-evoked potentials (MEP) in the right BB and oriented to deliver anterior-posterior–directed current into the brain. The coil was held tangentially to the scalp, with the handle pointing backward and 45° away from the line of the skull. The optimal position, corresponding to the stimulus site providing the greatest amplitude for the BB-evoked response, was marked and kept throughout the experiment. The head of the subjects was secured by a brace attached to the headrest to prevent head movement. An articulated arm (Otello Factory, T&O Brand, France) supported by a homemade tripod ensured stable positioning of the coil during the experiment. Rest motor threshold (RMT) of the right BB was determined as the intensity of stimulation eliciting an MEP of at least 0.05 mV in four of eight successive trials in the relaxed BB. One hundred twenty percent of the RMT (60%–85% output) was used during the experiment at rest, during mental training, and during physical training. The optimal position and the RMT were defined at the beginning of each experimental session.

Imagery ability. Imagery ability was ensured in all the participants by completing the revised version of the Movement Imagery Questionnaire (MIQ-R) (14). This instrument evaluated their ability to form kinesthetic and visual mental images through eight separate movement items (e.g., jumping, knee rising) actually performed then imagined (four visual and four kinesthetic). The participants rated the vividness of their mental representation using a seven-point Likert scale (from 1 = "very hard to see/feel" to 7 = "very easy to see/feel", 2–6 being intermediate quotes).

Perceived fatigue and vigor measurements. The Brunel Mood Scale (BRUMS) developed by Terry et al. (39) was used to quantify current mood ("How do you feel right now?") before the beginning of the setup and during the recovery period after the training protocol. This questionnaire contains 24 items (e.g., "angry, uncertain, miserable, tired, nervous, energetic") divided into six respective subscales: anger, confusion, depression, fatigue, tension, and vigor. The items are answered on a five-point scale (0 = not at all, 1 = a little, 2 = moderately, 3 = quite a bit, and 4 = extremely), and each subscale, with four relevant items, can achieve a raw score in the range of 0–16. Only scores for the fatigue and vigor subscales were considered in this study.

Procedures. The participants took part in four sessions, separated by at least 48 h, with the following order: a familiarization session, a mental training session with MIC, a physical training session with MVC, and a combined training session with MVC and MIC.

Familiarization session. The participants completed the MIQ-R first. Then, they were installed on the ergometer to be familiarized with the elbow flexion movement. They tried as many submaximal contractions as they wanted and finished by performing three MVC. Afterwards, they imagined doing the same action without contracting their arm. They were instructed to imagine performing a maximal elbow flexion and feel the muscle contraction normally elicited during actual performance. A kinesthetic strategy was shown to maximally modulate corticospinal excitability (37). No specific instructions were provided regarding whether participants should perform MI with their eyes closed or open. TMS was delivered at rest and during MI to ensure that the participants were engaged in the imagined movement.

Training sessions. The mental training, the physical training, and the combined training sessions are described in Figure 1. The mental training session consisted in 80 intermittent MIC of the elbow flexors. The specific pattern used was 5 s of MIC and 10 s of rest. During the physical training session, subjects followed the same pattern, with the difference that MIC were replaced by MVC. At the beginning of the mental training protocol and every 20 MIC, subjects performed a 5-s MVC (noted $\text{MVC}^{1\text{–}5}$) to detect any physical fatigue. We also added five trials of MVC ($\text{MVC}^{1\text{–}5}$) in the 80 MVC of the physical training to have the same number of trials as that during the mental training session (5 MVC + 80 MIC). During the combined training session, subjects followed the same pattern as that during the physical training session, with the difference that a 5-s MIC was performed during the 10-s rest period (80 MVC + 80 MIC).

At the end of the three sessions, participants also performed a last MVC after 10 min of recovery (noted $\text{MVC}^{\text{post10}}$). Between the $\text{MVC}^{1\text{–}5}$, we randomly delivered five TMS pulses during the periods of rest and five TMS pulses during the periods of MIC or MVC (10 TMS × 4 blocks in each session).

Data analysis. During the mental training and the combined training sessions, the root mean square (RMS) of the BB EMG activity was analyzed at rest and during MIC to ensure that the muscle remained relaxed. RMS analysis was performed only on MIC where TMS pulses were delivered (5 TMS × 4 blocks = 20 measurements). The RMS was analyzed over 500-ms periods before the MIC at rest and over 500-ms periods before the TMS pulses during MIC.

During MVC, the short-latency excitatory response (MEP) and the subsequent profound inhibition of ongoing EMG (silent period) were analyzed from EMG responses to TMS. The peak-to-peak amplitude and the duration of MEP were measured at rest, during MIC, and during MVC for the BB muscle. Because amplitude and duration showed similar changes, only amplitude was reported. This parameter was determined by averaging five measurements for each of the four blocks in the mental training, the physical training, and the combined training sessions.

During MVC, the duration of the silent period after TMS was taken as the time interval from the stimulus artifact to the return of continuous EMG (8). The end of the silent period was determined when the RMS value of the EMG

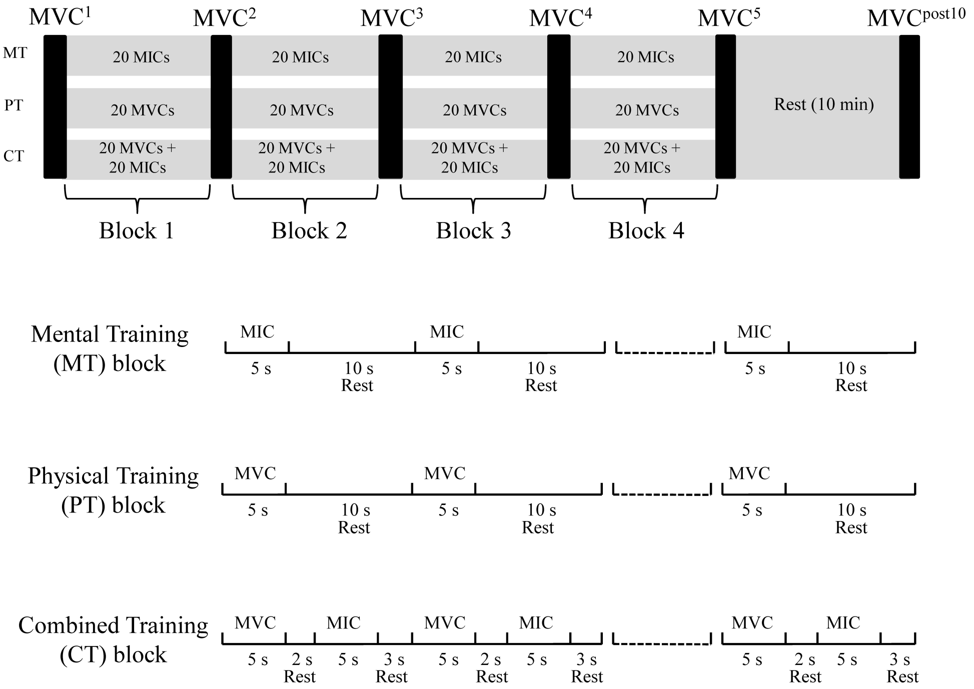

FIGURE 1—Overview of the experimental protocol for the mental training, physical training, and combined training sessions. Between the tested MVC, participants performed MIC, MVC, or combined MIC–MVC, depending on the training protocol.

signal reached two-thirds of the RMS EMG calculated over a 500-ms period before the stimulus artifact.

Muscle activation can be evaluated using TMS by the twitch interpolation technique (40). As fatiguing protocols induce poor estimation of the resting twitch (16), here, muscle activation was evaluated using the torque increment elicited by magnetic cortical stimulus during MVC (38). An increase in the torque increment represents a decrease in the level of voluntary drive. CAR cortical (CAR_c), reflecting the muscle activation, was calculated with the following formula: MVC torque/(MVC torque + superimposed twitch) × 100. CAR_c was evaluated during the first MVC (MVC^1), the last MVC (MVC^2), and after 10 min of recovery (MVC^{post10}) for each training session.

Statistical analysis. Normal distribution (Shapiro–Wilk test, $P > 0.05$) and sphericity (Mauchly test, $P > 0.05$) were respected in all variables. Changes in MEP amplitude during mental training and combined training protocols were assessed by two separate repeated-measures ANOVA, with task (MIC and rest) and block (T1–T4) as within-subjects factors.

Changes in silent period and MEP amplitude were evaluated by a two-way repeated-measures ANOVA, with condition (mental training, physical training, and combined training sessions) and contraction (MVC^1–MVC^{post10}) as within-subject factors. Similarly, changes in CAR_c were assessed by a two-way repeated-measures ANOVA, with condition (mental training, physical training, and combined training sessions) and contraction (MVC^1, MVC^5, and MVC^{post10}) as within-subject factors. Significant main or interaction effects were followed up by *post hoc* analysis (Tukey HSD), as appropriate.

Comparison of the results of the BRUMS questionnaire before and after each protocol, comparison of visual and kinesthetic scores of the MIQ-R, and comparison of RMS of the BB EMG activity before and during the MIC were analyzed using Student's paired *t*-tests. Statistical analyses were conducted using the Statistica software for Windows (Statsoft, version 6.1; Statistica, Tulsa, OK). Data are presented as mean (±SD) in the text, and a significance level of $P < 0.05$ was used for all analyses.

RESULTS

Mean MIQ-R score was 46.3 ± 6.6. The mean score was in accordance with those obtained by good imagers (13).Visual scores (24.6 ± 3.2) were significantly higher ($P < 0.05$) than kinesthetic scores (21.7 ± 4.2).

Figure 2 shows average values of BB MEP amplitude during MIC and during rest for the mental training session (Fig. 2A) and the combined training session (Fig. 2B). ANOVA revealed that MEP amplitude during MIC was significantly greater than MEP amplitude at rest (mental training, 0.42 ± 0.27 mV vs 0.26 ± 0.17 mV; combined training, 0.66 ± 0.33 mV vs 0.42 ± 0.27 mV) during the whole training session (main effect of task: mental training, $F_{1,9} = 7.99$, $P < 0.05$; combined training, $F_{1,9} = 23.41$, $P < 0.01$). This result ensures that participants were engaged in the MI task during both sessions. The values of MEP amplitude at rest and during MIC were higher for the combined training session than that for the mental training session because of the repetition of MVC, which potentiated the MEP amplitude (38). Main effect of block (mental training, $F_{3,27} = 0.78$, $P = 0.51$; combined training, $F_{3,27} = 1.91$,

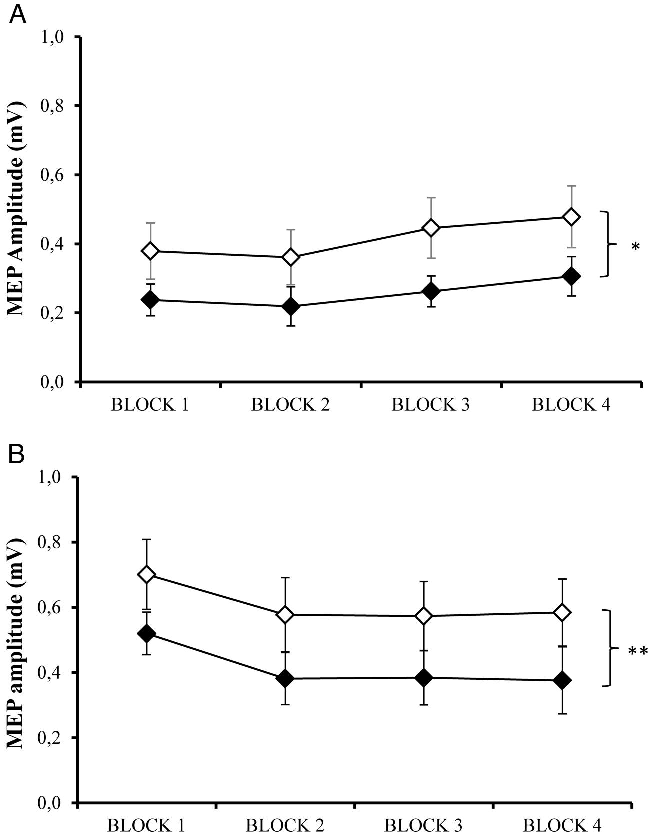

FIGURE 2—MEP amplitude (±SE) at rest (*black*) and during MIC (*white*) for the mental training session (A) and the combined training session (B). Blocks 1, 2, 3, and 4 refer to average MEP amplitude value of five TMS trials at rest and five TMS trials during MIC between each MVC. *Significant task effect, $P < 0.05$. **Significant task effect, $P < 0.01$.

$P = 0.15$) and interaction effects between task and block (mental training, $F_{3,27} = 0.33$, $P = 0.80$; combined training, $F_{3,27} = 0.52$, $P = 0.67$) were not significant. Note that RMS values of BB EMG activity during MIC (on average, 0.004 mV) were not different ($P = 0.33$, $t = 1.26$) from RMS values at rest (on average, 0.003 mV) during both mental training and combined training sessions and thus cannot explain the increase in MEP amplitude during MIC.

Table 1 shows evolution of MEP amplitude and silent period of BB muscle during MVC for the mental training, the physical training, and the combined training sessions. MEP amplitudes of BB muscle during MVC were similar in the three sessions (no main effect of condition, $F_{2,18} = 0.42$, $P = 0.66$) and remained stable during both conditions (no main effect of contraction, $F_{5,45} = 0.99$, $P = 0.43$), nor was condition–contraction interaction effect observed ($F_{10,90} = 0.98$, $P = 0.47$). Likewise, silent period was similar in the mental training and physical training sessions (main effect of condition, $F_{2,18} = 2.59$, $P = 0.10$), and remained stable during both conditions (main effect of contraction, $F_{5,45} = 0.98$, $P = 0.44$). There was no condition–contraction interaction effect ($F_{10,90} = 0.84$, $P = 0.60$).

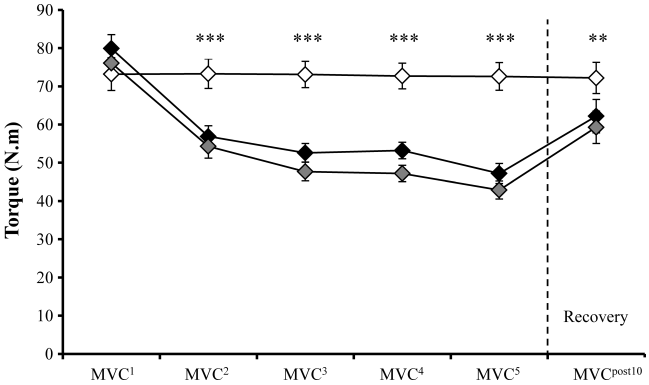

FIGURE 3—Maximal voluntary torque (±SE) during the mental training (*white*), the physical training (*black*), and the combined training (*gray*) sessions. **Significant difference between mental training session and both physical and combined training sessions, $P < 0.01$. ***Significant difference between mental training session and both physical and combined training sessions, $P < 0.001$.

Figure 3 illustrates average values of MVC torque for the mental training, the physical training, and the combined training sessions. MVC^1 torque at the beginning of the sessions was similar for the three conditions ($P > 0.24$), ensuring that subjects were in similar conditions to start the protocol. ANOVA revealed an interaction effect between condition and contraction for MVC torque ($F_{10,90} = 17.82$, $P < 0.001$) (Fig. 3) and CAR_c ($F_{4,36} = 16.35$, $P < 0.001$) (Fig. 4). The repetition of intermittent MIC did not induce any change in MVC torque (all, $P > 0.99$) and in CAR_c ($P > 0.99$) over the mental training session. In contrast, MVC torque significantly decreased over the physical training (all, $P < 0.001$) and the combined training (all, $P < 0.001$) sessions. There was a 40.4% ± 10.6% drop of MVC torque between MVC^1 and MVC^5 in the physical training session and a 41.0% ± 9.3% drop in the combined training session. The MVC torque reduction was similar in the physical training and the combined training sessions (all, $P > 0.43$).

TABLE 1. Evolution of MEP amplitude and silent period of the BB muscle during MVC for mental training, physical training, and combined training sessions.

	MVC^1	MVC^2	MVC^3	MVC^4	MVC^5	MVC^{post10}
MEP amplitude (mV)						
Mental training session	5.6 (4.2)	6.2 (4.6)	5.6 (4.1)	5.8 (4.6)	6.0 (5.1)	5.0 (4.2)
Physical training session	4.9 (2.0)	4.8 (2.5)	4.7 (2.7)	4.8 (3.0)	4.1 (1.5)	4.8 (3.0)
Combined training session	4.4 (1.9)	4.8 (1.8)	4.3 (2.7)	4.1 (2.0)	4.4 (2.0)	3.9 (1.6)
Silent period (ms)						
Mental training session	119.2 (35.2)	105.0 (18.7)	108.0 (29.0)	112.4 (31.1)	103.8 (23.9)	115.5 (30.5)
Physical training session	123.9 (56.1)	103.8 (38.3)	115.5 (42.0)	103.2 (26.5)	105.3 (28.0)	119.1 (60.0)
Combined training session	92.8 (11.0)	96.4 (14.6)	97.2 (13.7)	93.8 (8.0)	91.1 (12.0)	90.1 (10.6)

MEP amplitude and silent period remained stable during the three sessions and were not significantly different between mental training, physical training, and combined training sessions. Data are presented as mean (SD) for MEP amplitude and silent period.

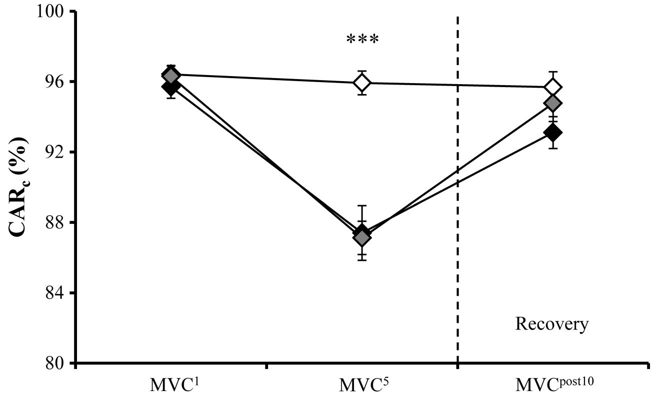

FIGURE 4—CAR$_c$ (±SE) before (MVC^1), after (MVC^5), and 10 min after (MVC^{post10}) the mental training (*white*), the physical training (*black*), and the combined training (*gray*) sessions. ***Significant difference between mental training session and both physical and combined training sessions ($P < 0.001$).

This decrease of MVC torque was accompanied by a 8.7% ± 4.1% drop of CAR$_c$ in the physical training session ($P < 0.001$) (Fig. 4) and a 9.5% ± 3.3% drop in the combined training session ($P < 0.001$) (Fig. 4). Again, this reduction was similar for both sessions ($P > 0.99$). After 10 min of rest, MVC torque significantly recovered ($P < 0.001$) but was still significantly depressed by 22.7% ± 10.2% ($P < 0.001$) in the physical training session and by 22.6% ± 8.9% ($P < 0.001$) in the combined training session compared with those in MVC^1. CAR$_c$ was similar at the beginning of the three sessions ($P > 0.99$) but was lower after the physical training and the combined training sessions than that after the mental training session ($P < 0.001$). CAR$_c$ significantly recovered after 10 min of rest for the physical training and the combined training sessions ($P < 0.001$) and was similar to MVC^1 values ($P > 0.13$).

The BRUMS questionnaire revealed a significant increase in perceived fatigue after the mental training ($P < 0.05$) (Fig. 5A), the physical training ($P < 0.001$) (Fig. 5C), and the combined training ($P < 0.001$) (Fig. 5E) protocols. Vigor significantly decreased after the physical training ($P < 0.05$) (Fig. 5D) and the combined training protocols ($P < 0.05$) (Fig. 5F) but remained stable after the mental training protocol ($P = 0.20$) (Fig. 5B).

DISCUSSION

The aim of the present study was to investigate neuromuscular alterations after a mental training session, a physical training session, and a combined training session. Contrary to our hypothesis, we found that mental training and combined training did not induce any decrease or additional decrease, respectively, in MVC torque and CAR$_C$. Interestingly, MEP during voluntary and imagined contractions remained stable, suggesting that corticospinal excitability was not modified during the three sessions.

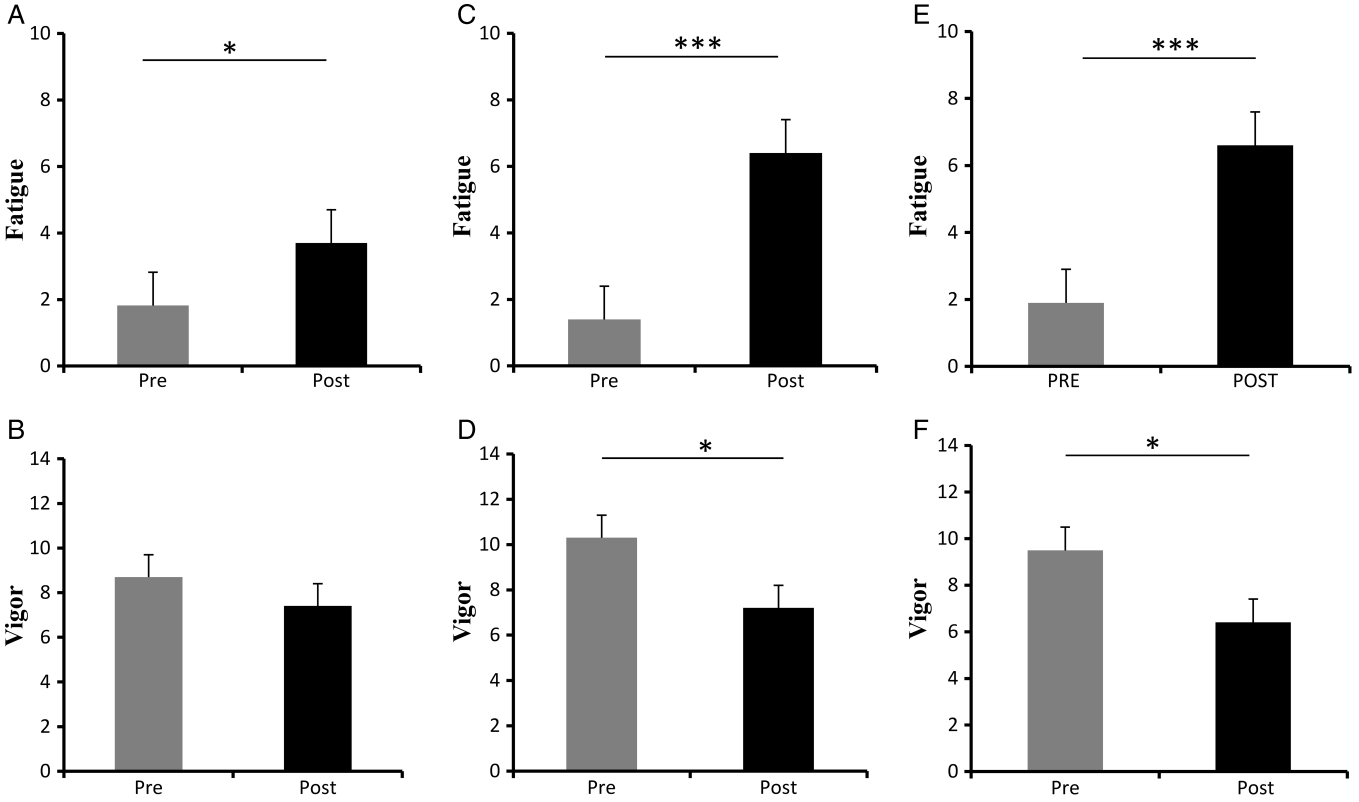

FIGURE 5—Psychological state before (pre) and after (post) the two sessions. A, Fatigue for the mental training session. B, Vigor for the mental training session. C, Fatigue for the physical training session. D, Vigor for the physical training session. E, Fatigue for the combined training session. F, Vigor for the combined training session. *$P < 0.05$ and ***$P < 0.001$. Data are represented as means ± SE.

Fatigue and failure in muscle activation during the physical training session. In accordance with previous studies, the repetition of 80 MVC induced a 40% reduction in MVC torque (16,38). As MVC torque decreased, torque increments elicited by TMS increased, suggesting that subjects were unable to maximally activate their elbow flexor muscles. MVC torque recovered after a 10-min rest but still remained at 80% of the pre-value. Muscle activation completely recovered after 10 min of rest, according to Taylor et al. (38) who found a complete recovery after 1-min rest after repetitive MVC. Although muscle activation was altered by MVC repetition, neither MEP amplitude nor silent period was altered. These findings are in contrast with previous observations by Taylor et al. (38) who found an increase in MEP amplitude and silent period. The discrepancy could be explained by the different duty cycles used in the two studies. Indeed, Taylor et al. (38) reported that the changes in MEP and silent period during 15-s or 30-s contractions occurred sooner than the ones during 5-s contractions. Furthermore, there was no recovery after a 5-s rest but a partial recovery after a 10-s rest. Here, we assumed that the 5-s/10-s duty cycle did not induce a cumulative effect of the maximal contractions on MEP and silent period. It is plausible that the contraction time was too short and the rest period allowed fully recovering MEP and silent period changes. The present results suggest that the repetition of MVC (5-s contraction/10-s rest) induced a reduction in the voluntary drive without change in corticospinal excitability.

Effects of mental training and combined training sessions on corticospinal excitability. During the mental training and the combined training sessions, MEP amplitude of the BB muscle was greater during MIC than that at rest, suggesting a higher corticospinal excitability. This result confirms previous studies that demonstrated an increase in primary motor cortex excitability above resting levels during imagery of target muscle contraction, evidenced by a decrease in motor threshold and an increase in response amplitude (19,20,29). No increase of EMG activity of the elbow flexors was observed during the imagination of the movement compared with that during baseline, attesting that the subjects remained relaxed and did not contract their muscle. These results ensured that participants were engaged in the imagined movement and carried out the exercise correctly.

Effects of mental training and combined training sessions on maximal force production. In contrast to our hypothesis, mental rehearsals of an acute session of mental imagery did not alter maximal force production capacity and did not reduce muscle activation, although subjects reported greater perceived fatigue at the end of the mental training session. These findings suggest that neuromuscular properties remained stable over the course of the experiment despite greater perceived fatigue. Furthermore, an additional MI task to a physical exercise did not induce a supplementary decrease in MVC torque, nor in voluntary activation, and the participants recovered similarly to the physical training session after a 10-min rest. These findings corroborate those of previous studies that showed no effects of mental tasks on motor performance. For example, on the lower limb, Pageaux et al. (26) did not observe any decrease in MVC torque after a 90-min mentally fatiguing task. In contrast, Bray et al. (1) observed a decrease in maximal force production on the upper limb after a prolonged cognitive task, but the physiological and/or psychological mechanisms remained unknown. In the present study, the absence of significant effects on maximal force capacity may be explained either by the short duration of the training sessions and/or by a lower activation of the cortical areas. Indeed, primary motor cortex activation reported during MI amounts to about 30% of the level observed during execution (30). Furthermore, MI is accompanied by a subthreshold activation through the motor pathway (17). Differences in the intensity of the activation of motor pathways between mental practice and physical practice may also explain differences in central fatigue induced by the two training methods.

Practical applications. It has been previously demonstrated that imagery training induced strength gains (31,34,42). The duty cycle and the session duration used in the present study were similar with imagery training sessions used in the previously cited studies. In our study, participants performed 80 MIC with a 5-s/10-s duty cycle. For their training sessions, Ranganathan et al. (31) used a 5-s/5-s duty cycle to perform 50 imagined trials, Yue and Cole (41), a 15-s/20-s duty cycle for 15 imagined trials, and Sidaway and Trzaska (34), a 10-s/10-s duty cycle for 50 imagined trials. Our data suggest that one session of MI training alone is not sufficient to induce muscular strength gain in proximal muscles of the upper limb and does not induce neuromuscular fatigue. MI does not outperform actual training (7,9,27). MI can be used as a complement but cannot replace physical training to obtain same strength gains (32).

During combined MI and physical practice, athletes alternate imagined and voluntary contractions during each session. Although a previous study showed that the substitution of high-intensity voluntary contractions by imagined contractions reduces muscle fatigue (32), the present study showed that MI added to a physical training did not induce additional muscle fatigue. Performing MI before or during a physical practice would activate the corticospinal pathways and would improve intrinsic motivation and arousal level of the athletes without having negative effects on their future performances. The alternation of MI and voluntary contractions could enhance the volume of training and limit the development of muscle fatigue (32). Interestingly, this higher volume of training would improve performances (22,23) without additional muscle fatigue and with a similar recovery. Then, the amount of physical training can be maintained. As physical practice, the strength gains will not appear at short term (single session) but after a few weeks of mental or combined training (22,31,41). However, the repetition of MIC induced perceived mental fatigue. Further researches have to be carried out to investigate the effects of mental fatigue on imagery quality with objective neurophysiological criteria as the MI index (2). If mental fatigue may deteriorate imagery ability, mental training should not last more than 20 min, as suggested previously (33). Moreover, it would be interesting to examine the long-term effects of the three different trainings (imagined vs physical vs combined) to compare the strength gains after the three methods of training.

CONCLUSIONS

The current study demonstrated that a single mental training session did not induce any neuromuscular fatigue of the EF muscles, contrary to actual contractions. In addition, the results showed that a combined training session did not induce additional fatigue compared with that in physical training. Although participants reported greater perceived fatigue after the repetition of MIC, maximal muscle activation was not altered in the mental training session and was not exacerbated in the combined training session. This absence of neuromuscular changes after the mental training and the combined training sessions compared with those after the physical training session could be due to the weaker activation of the cortical areas and corticospinal pathway during MI compared with that during actual movement. MI may be used to increase total workload during a strength training session and thus to obtain higher strength gains without exacerbating neuromuscular fatigue.

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