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Short-Term Effects of Integrated Motor Imagery Practice on Muscle Activation and Force Performance

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Abstract

The effect of motor imagery (MI) practice on isometric force development is well-documented. However, whether practicing MI during rest periods of physical training improves forthcoming performance remains unexplored. We involved 18 athletes in a counterbalanced design including three physical training sessions scheduled over five consecutive days. Training involved 10 maximal isometric contractions against a force plate, with the elbow at 90°. During two sessions, we integrated MI practice (focusing on either muscle activation or relaxation) during the inter-trial rest periods. We measured muscle performance from force plate and electromyograms of the biceps brachii and anterior deltoideus. We continuously monitored electrodermal activity (EDA) to control sympathetic nervous system activity. MI of muscle activation resulted in higher isometric force as compared to both MI of muscle relaxation and passive recovery (respectively +2.1% and +3.5%). MI practice of muscle relaxation also outperformed the control condition (+1.9%). Increased activation of the biceps brachii was recorded under both MI practice conditions compared to control. Biceps brachii activation was similar between the two MI practice conditions, but electromyography revealed a marginal trend toward greater activation of the anterior deltoideus during MI practice of muscle activation. EDA and self-reports indicated that these effects were independent from physiological arousal and motivation. These results might account for priming effects of MI practice yielding higher muscle activation and force performance. Present findings may be of interest for applications in sports training and neurologic rehabilitation.

Keywords: mental practice, force development, training, rehabilitation

Introduction

Motor imagery (MI), i.e., the mental rehearsal of an action without any overt execution, is a cognitive operation involving executive parts of the brain motor system (for reviews, see (Lotze and Halsband, 2006; Munzert et al., 2009)). MI recruits cerebral substrates controlling the actual preparation and execution of the movement, including primary somatosensory and motor cortices (Munzert et al., 2009). In several experiments, subliminal muscle activations were detected during MI. Neuromuscular activity was primarily recorded within the prime movers of the imagined movement (Bird, 1984; Boschker, 2001). Despite challenging data (e.g., (Personnier et al., 2010)), subliminal muscle activation was found to increase according to the intensity of the imagined contraction (Bonnet et al., 1997; Boschker, 2001). The psychoneuromuscular theory early postulated that similar electromyographic patterns could occur during both physical practice (PP) and MI (Jacobson, 1930, 1932; Wehner et al., 1984), albeit with reduced magnitude (Gandevia et al., 1997). Subliminal muscle activity was even found to reflect the type of muscle contraction imagined by the participant (i.e., isometric, concentric, and eccentric (Guillot et al., 2007)), while brain activations during MI appeared to covariate with the imagined force level (Mizuguchi et al., 2014). Taken together, these data support that subliminal muscle activation during MI might result from an incomplete inhibition of the somatic motor command (see (Jeannerod, 1994) for a pioneering discussion).

Somatic motor commands addressed to muscles are paralleled by neurovegetative commands to internal organs and smooth muscles of blood vessels through the parasympathetic and sympathetic pathways. The autonomic nervous system permanently adjusts the metabolic activity to face forthcoming demands in energy. The autonomic correlates of PP are well-reproduced during MI. For instance, Decety et al. (1991) provided evidence that both heart and respiratory rates increased proportionally according to the imagined walking speed. Autonomic nervous system recordings can thus be used to monitor MI in real time (for a review, see (Collet et al., 2013)).

Due to structural and functional similarities with PP, MI practice has been used as a training method to enhance motor performance (Jackson et al., 2001; Morris et al., 2005). MI practice can facilitate motor learning and improve motor recovery after injury (for an overview, see (Guillot and Collet, 2008)). A more limited number of studies investigated its effects on strength. The pioneering study addressing this issue provided evidence that a 30-min session of MI practice increased the isometric strength of the quadriceps by 16% as compared to a control group not subjected to any form of physical or mental training (Cornwall et al., 1991). Most subsequent experiments yielded positive effects of MI practice, primarily on the development of maximal isometric strength (Yue and Cole, 1992; Smith et al., 2003; Wright and Smith, 2009). Gains usually ranged from 10% to 30% on both distal and proximal muscles of the upper limb (Yue and Cole, 1992; Wright and Smith, 2009). There is a general consensus that strength gains were of central origin, and occurred in the absence of any peripheral change, e.g., muscle hypertrophy (Yue and Cole, 1992; Ranganathan et al., 2004). Improvements may be grounded in cortical neuroplasticity, i.e., the capacity of neurons to reorganize their connectivity in response to the behavioral demand, hence leading to more efficient drive of motor units (e.g., spatial recruitment and stimulation intensities). Ranganathan et al. (2004) earlier reported a direct relationship between changes in cortical motor output and muscle performance after MI practice. Similarly, Yao et al. (2013) confirmed that kinesthetic MI practice of maximal isometric force increased the maximal isometric force of elbow flexors through

cortical motor and pre-motor neuroadaptations.

To date, most studies delivered MI practice interventions alone (Cornwall et al., 1991; Yue and Cole, 1992; Ranganathan et al., 2004), or in addition to physical training (e.g., (Wright and Smith, 2009; Reiser et al., 2011)). Only a few investigated the impact of embedding MI practice into actual strength training (e.g., (Lebon et al., 2010)). The immediate effects of MI practice during inter-trial periods of strength training sessions have not yet been investigated. This is somewhat surprising because MI practice frameworks usually recommend practicing in combination with PP and in a similar context to that of actual training (Holmes and Collins, 2001; Guillot et al., 2005; Wright and Smith, 2009). In the present experiment, we addressed whether MI practice during rest periods of physical training improved maximal isometric force. We specifically tested the selective effects of MI practice focusing either on muscle activation or relaxation on force and muscle fatigue as compared to a passive recovery condition. We hypothesized that activating MI practice would outperform both relaxing MI practice and passive recovery since it involved a specific focus on the voluntary drive addressed to the somatic effectors of the force task. MI practice focused on muscle relaxation was expected to control for attention/placebo effects. Passive recovery was finally considered the reference condition since it is the usual modality of recovery during inter-trial periods. We aimed to provide original insights into the rules of MI practice for future applications in sports and rehabilitation (e.g., (Lebon et al., 2012)).

EXPERIMENTAL PROCEDURES

Participants

Participants ($n = 18$, mean age = 19.31 ± 1.25 years) were recruited from the Faculty of Sports Sciences of the University Claude Bernard Lyon 1 (F-69100, Villeurbanne). All were right-handed inter-regional male athletes in terrestrial sports (i.e., tennis, volleyball, handball, and climbing). They had a background of at least 2 years in upper limb muscle training in their own competing activities. No information concerning the purpose of the study was provided until after completion of the design. The local review board approved the experiment, and participants' written consent was obtained according to the statements of the Declaration of Helsinki (1982).

Experimental Design

The design was scheduled over five consecutive days and included three physical training sessions involving 10 trials of maximal isometric contractions. To avoid circadian effects, training sessions were performed at the same time of the day (12 pm before lunch), lasted 30 minutes, and were separated from each other by 48 hours (i.e., one entire day interposed between each recording day). Experimental conditions ($n = 3$) were delivered during inter-trial periods of the training session:

- MI practice of muscle activation (activating MI)
- MI practice of muscle relaxation (relaxing MI)
- Passive recovery, where the participants listened passively to three blocks of information about international sports news (12 s each; control).

Relaxing MI was expected to control for placebo effects (e.g., athletes' expectations toward the efficacy of MI practice) since it involved a specific focus on the biceps brachii recovery between force trials. The control condition aimed to control for the attention paid to audio instructions during MI conditions. To overcome carryover effects (e.g., residual muscle fatigue from one training session to another), we implemented a fully counterbalanced design with three participants assigned to each of the six possible order conditions (block randomization).

Strength Training Sessions

Participants sat on a bench, warmed up, and familiarized themselves with the experimental instructions for 15 minutes (see Appendix A, "Warm-up" and "Familiarization" for further description). They were then requested to perform 10 successive maximal flexions of their dominant elbow against an immobile force platform placed in front of them (isometric contractions) (Fig. 1A). Each effort was sustained for 12 seconds.

We used an auditory stimulus (110 Hz–50 dB) to trigger each trial start and end. Hand position and fingers were in flat contact with the force plate (Fig. 1A). Goniometers controlled that the required static position was respected across all trials (90° between the forearm and the arm). Experimenters visually controlled that the arm constantly kept contact with the trunk. Trunk position was normalized using a reclining seatback, ensuring permanent contact with the back of the head, thoracic vertebrae, and pelvis (Fig. 1A). Participants consistently fixed their gaze on a cross mark placed on the wall at the height of their eyes.

The experiment aimed to study the effect of the three recovery conditions on isometric force performance. Inter-trial periods lasted 1 minute, during which participants remained motionless with their arms resting on their thighs. For activating MI and relaxing MI, each MI trial lasted 12 seconds and was triggered by an audio stimulus (240 Hz, 50 dB). Three MI trials were completed during each recovery period of 1 minute (Fig. 1D). Participants were instructed to use kinesthetic and visual imagery concurrently (see Appendix B, "MI scripts"). Experimenters visually controlled the absence of overt motion during MI practice.

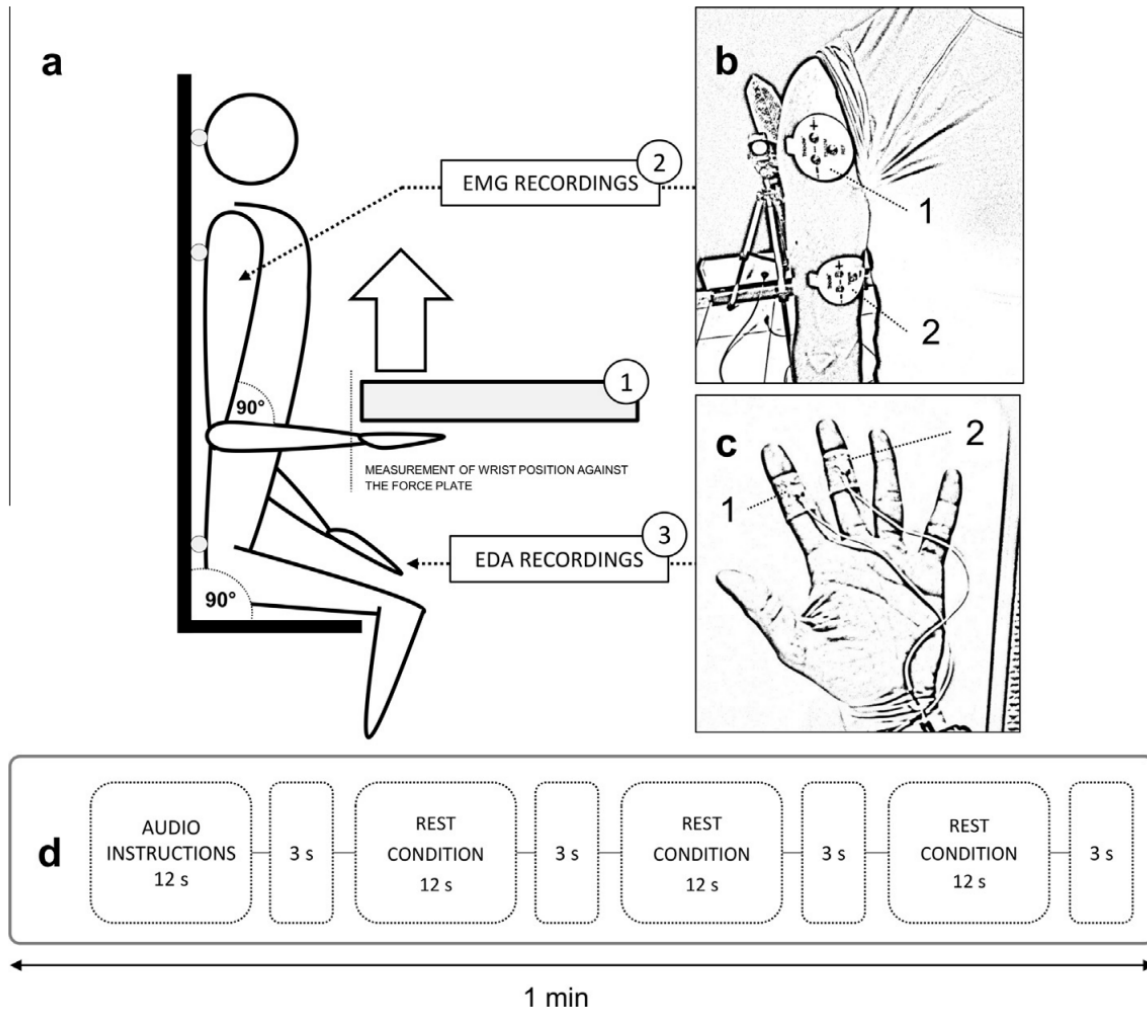


Figure 1: . (a) Representation of the experimental settings including (1) an inverted force platform on which the participants exerted maximal isometric contractions (vertical arrow indicated by the participant), (2) electromyography recordings and (3) EDA recording. Body position was standardized to prevent compensatory movements of the trunk and isolate the performance of elbow flexors. (b) Surface muscle electrodes were placed on the anterior deltoideus (1) and biceps brachii (2) of the dominant hand. (c) EDA sensors were placed on the second phalanx of the first (1) and second fingers (2) of the non-dominant hand. (d) The inter-trial period of rest was 1 min during which the three conditions were delivered

Measurements

Force performance. The elbow flexion force was measured with a force platform (AMTI, model OR6-7-2000, Watertown, Massachusetts, USA, Fig. 1A). Signals were sampled at 1000 Hz. After performing a frequency and residual analysis on raw signals, data were smoothed with a zero-lag 4th-order low-pass Butterworth filter with a cut-off frequency of 20 Hz. The sudden force increase in response to the auditory stimulus was determined with a threshold detection function (Matlab[®]) for each trial. The total force was calculated by integrating the force slope over the 12 s of each trial (trapezoid rules). Total force data were finally normalized as a percentage of the maximal isometric force trial completed

during the warm-up (see Appendix A).

After shaving and cleaning the skin with alcohol, EMG sensors were positioned according to usual recommendations of the SENIAM project (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles) (Hermens et al., 2000). Electrode edges were outlined with a marker pen, and pictures were taken to ensure reproducible electrode positioning across sessions. We collected EMG signals using the Flexcomp Infiniti system (Thought Technology, Montreal, Canada, 2048 Hz). Offline, EMG signals were rectified and smoothed with a band-pass of 20–500 Hz (Butterworth filter). The integrated EMG (iEMG) was calculated from the smoothed rectified EMG over the 12 s of sustained maximal isometric contractions. iEMG data were finally normalized in percentage of the maximal isometric force trial completed during warm-up (see Appendix A).

Autonomic nervous system recordings

We continuously recorded electrodermal activity (EDA) as an index of sympathetic activation during physical training. Changes in EDA result from the activity of eccrine sweat glands (for an exhaustive review, see Collet et al., 2013). These glands are uniquely controlled by the sympathetic branch of the autonomic nervous system through acetylcholine release, representing an exception to the principle of dual innervation (Shields et al., 1987). EDA was recorded using two 50-mm² unpolarizable Ag/AgCl electrodes (Clark Electromedical Instruments, Ref. E243) placed on the second phalanx of the second and third digits of the non-dominant hand (Fig. 1C), held by adhesive tape. We used a 5- μ A constant current to limit current density (10 μ A/cm²), and isotonic conductive paste was applied to improve skin/electrode contact.

EDA recordings were expected to provide reliable information on general physiological arousal but were not used as an index of force output. The sympathetic pathways innervating eccrine sweat glands and blood vessels of skeletal muscles are anatomically and functionally segregated (Wallin and Fagius, 1986, 1988; ?). Thus, EDA recordings controlled physiological arousal across sessions in the counterbalanced paradigm (Collet et al., 2011). We expressed EDA as skin resistance. With reference to the basal level, skin resistance tonic values were expected to decrease—or at least remain constant—if participants sustained their engagement and motivation toward task completion. Conversely, boredom or mental strain should result in increased skin resistance, reflecting reduced sympathetic activity (Collet et al., 2011). Phasic values, i.e., electrodermal responses (EDR) to various stimuli, are characterized by a sudden drop in the EDA slope, followed by a slower and steady return to baseline (for more details, see Vernet-Maury et al., 1995). EDR amplitude was standardized by reporting it to the basal level of each session.

Self-reports

After training, participants' compliance to experimental instructions was assessed through semi-structured interviews. After each session, participants reported their perceived level of motivation to complete the experimental paradigm on a 10-point Likert scale (0: no motivation, 10: very high motivation). When the training session involved MI practice, MI vividness was also measured on a 10-point Likert scale (0: no image at all, 10: vivid and accurate MI). After completing the paradigm (including the three experimental sessions), each participant was asked to indicate the training session during which he thought he performed at the highest level of force if the performance from the 10 successive trials of

each session was pooled.

Statistical analyses

We used R (?) and `lme4` (Bates et al., 2014) to perform a linear mixed effects analysis of force platform and physiological data (i.e., EMG and EDA). As a fixed effect, we entered the factor *RECOVERY CONDITION* (i.e., control, activating MI, and relaxing MI). As random effects, we included intercepts for subjects and *TRIALS* (1 to 10). A significant force decrease was expected across trials 1 to 10, particularly marked during the first trials, considering the patterns of force decreases elicited by maximal isometric contractions (Camic et al., 2013). Mixed linear models enabled us to account for inter-day variations at the participant level when testing the main *RECOVERY CONDITION* effect at the group level (in addition to the counterbalanced design). Inspection of residual plots did not reveal any obvious deviation from homoscedasticity or normality.

The p-values were obtained by likelihood ratio tests comparing the full model with a model excluding the effect in question (Winter, 2013). For post hoc investigations, mixed linear models were iterated on datasets from which classes of the factor considered were removed to allow dual comparisons. Holms' sequential Bonferroni corrections were applied, and the alpha threshold was set at $\alpha = .05$.

Self-reports were obtained using ordinal scales. Given the assumption of a non-Gaussian distribution, non-parametric tests were used. Friedman's test was conducted to compare levels of self-reported motivation and MI vividness across experimental sessions.

RESULTS

Force data

Raw total force data are provided in Appendix C. Total force was affected by the *RECOVERY CONDITION* ($\chi^2(2) = 24.99, p < .001$). Random effect coefficients for *TRIALS* confirmed the decrease in performance from trials 1 to 10, particularly between trials 1 and 2 (approximately 15%; Fig. 2). We recorded higher isometric force during *activating MI* compared to both *relaxing MI* [$2.1 \pm 0.01\%$ of fitted difference (standard error)] and *control* [$3.5 \pm 0.01\%$ of fitted difference; Fig. 2]. Total force was also $1.9 \pm 0.01\%$ higher ($p = .02$) during *relaxing MI* as compared to *control* (Fig. 2).

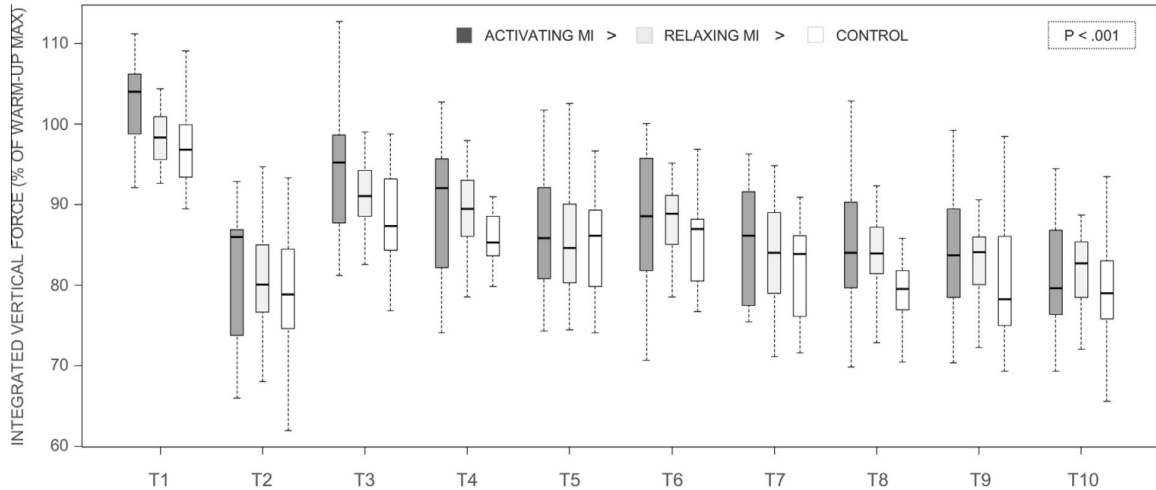


Figure 2: Integrated elbow flexion force (group level) from force trials 1 to 10 of physical training for experimental condition (see also Appendix C, “Data table”).

Electromyography data

Raw iEMG data are provided in Appendix C. iEMG from the *biceps brachii* was affected by the *RECOVERY CONDITION* ($\chi^2(2) = 31.51, p < .001$) (Fig. 3a).

Random effect coefficients for *TRIALS* for the *biceps brachii* iEMGs revealed a decrease in muscle activation from trials 1 to 10, which paralleled force data. This was particularly pronounced between trials 1 and 2 (approximately 15%; see Appendix C, “Data table”). For the *RECOVERY CONDITION*, post hoc analyses yielded higher EMG activity within the *biceps brachii* during both *activating MI* and *relaxing MI* as compared to *control* [$p = .02$ and $p < .001$, respectively, corresponding to a fitted difference of $8.2 \pm 2.0\%$ and $10.7 \pm 1.6\%$]. The difference between *activating* and *relaxing MI* was not significant ($p = .23$).

The linear mixed effect analysis revealed that the *RECOVERY CONDITION* did not affect iEMG from the *anterior deltoideus*, even though the effect approached the statistical threshold ($\chi^2(2) = 4.19, p = .12$) (Fig. 3b). Fixed effect coefficients showed that this marginal effect originated from a trend toward higher iEMG values during *activating MI* as compared to both *relaxing MI* and *control condition* ($p = .08$ and $p = .16$, respectively, corresponding to a fitted difference of $3.6 \pm 2.0\%$ and $3.8 \pm 2.7\%$).

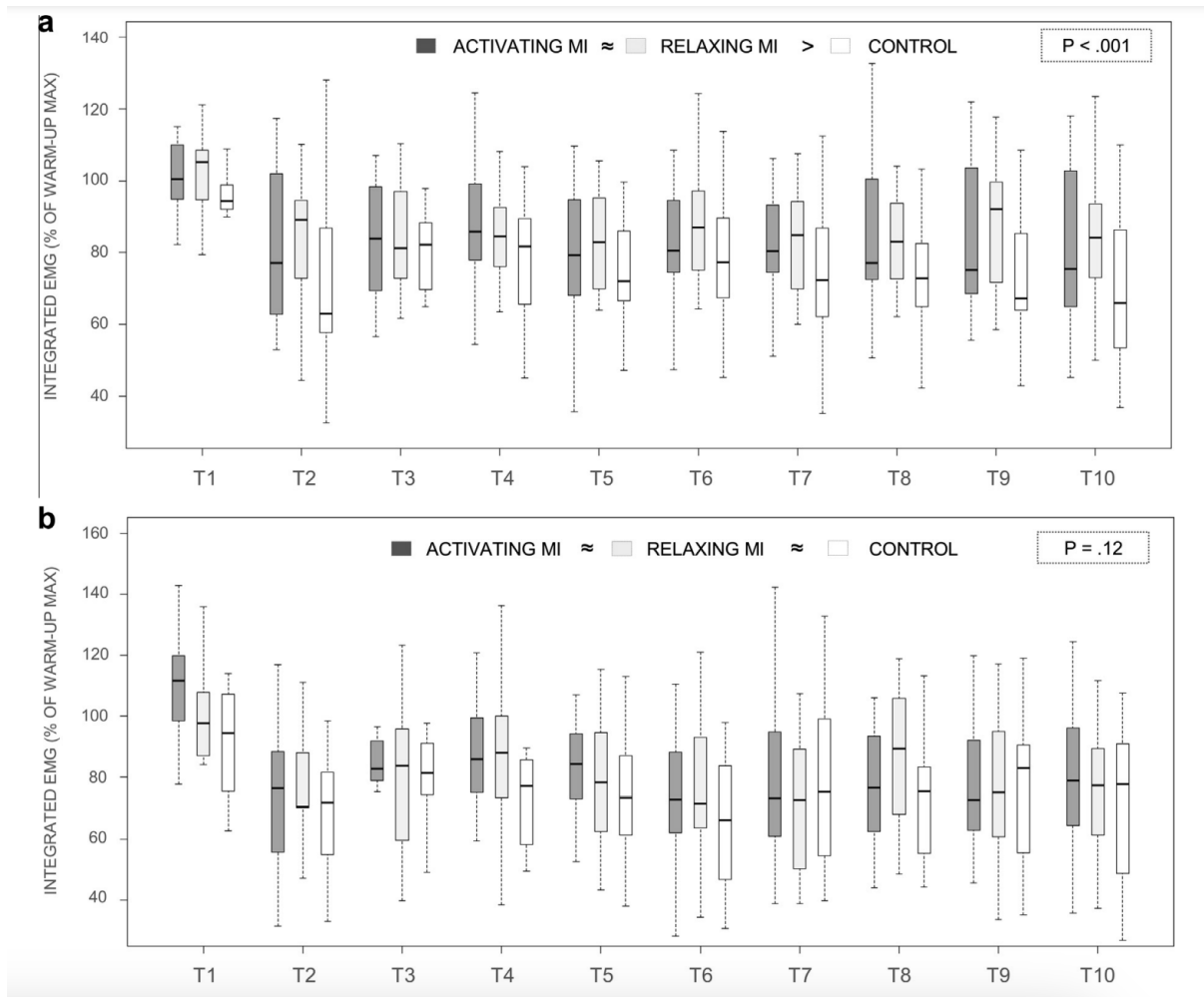


Figure 3: .(a) Integrated electromyogram (iEMG) from biceps brachii across the ten trials of physical training, for each experimental condition (Appendix C, “Data table”). (b) iEMG from the anterior deltoideus across the ten trials of physical training, for each experimental condition (Appendix C).

EDA

Tonic EDA presented a regular decrease throughout physical training from 110% to 90% of the average basal value, for all experimental conditions (Fig. 4). Standard deviation was reduced during trials 1–4 as compared to trials 5–10 (Fig. 4). Higher variability in EDA during the first trials might reflect adjustments of the autonomic nervous system to task demand to reach regular and adjusted autonomic response patterns (trials 4–7). Higher variability in EDR during trials 7–10 might reflect inter-individual variability in autonomic adaptations to physical fatigue. We also observed that basal EDA was higher under the *relaxing MI* condition ($291.47 \pm 114.99 \text{ k}\Omega$) than during both *activating MI* and *control* ($247.04 \pm 112.46 \text{ k}\Omega$ and $278.18 \pm 85.80 \text{ k}\Omega$, respectively).

Phasic EDA (i.e., EDR)

For phasic EDA (i.e., EDR), mixed linear modeling revealed that *RECOVERY CONDITION* affected the response amplitude evoked by the force trials ($\chi^2(2) = 57.92, p < .001, R^2 = .56$). Post-hoc analyses yielded higher EDR amplitudes during both *relaxing MI*

and *activating MI* as compared to *control* (48.38 ± 28.8 k Ω and 34.78 ± 23.6 k Ω vs. 29.44 ± 18.4 k Ω , both $p < .001$; Fig. 4). *Relaxing MI* was also associated with slightly higher EDR amplitudes than *activating MI* ($1.4\% \pm 0.4$ of difference, $p = .005$). EDR amplitude presented a moderate decrease from trials 1 to 10, particularly during the last trials of the session (see Fig. 4; Appendix C, “Data table”). We found no statistically significant relationship between EDR amplitude and total force decrement across trials and conditions ($\chi^2(2) = 1.94$, $p = .38$).

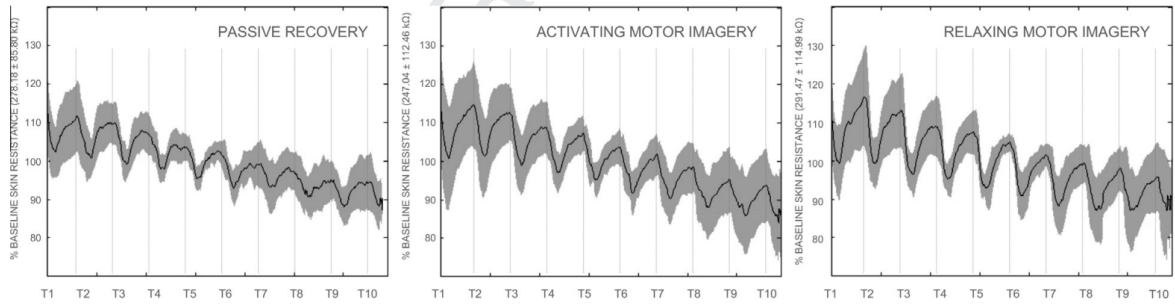


Figure 4: Averaged standardized skin resistance values (plain line) recorded during physical training with standard deviation (dotted line). Trials (from 1 to 10) are indicated by the vertical dotted lines.

Self-reports

Participants reported a strong adherence to experimental instructions, particularly concerning the requested maximal training intensities during the isometric force trials. They reported high and constant levels of motivation throughout sessions (median self-reports ranging from 8.0 to 8.5 across rest conditions on the 10-point scale; Friedman’s Chi-squared = 2.07; $p = .35$). MI ratings of vividness were comparable between *activating MI* and *relaxing MI* (median = 7 for both on the 10-point Likert scale; Friedman’s Chi-squared = 0; $p = .99$). Finally, participants felt more efficient during *activating MI* (69%) than during both *relaxing MI* and *control* (i.e., respectively 25% and 6% of self-reports; $\chi^2 = 9.87$, $p = .007$).

Discussion

The present study was designed to address the possibility of achieving short-term strength gains by embedding *MI* practice during the rest periods interposed between maximal isometric force trials. Self-reports associated with polynomial patterns of motor performance and muscle activation decrease across trials provided reliable evidence that participants engaged in a maximal isometric effort (Babault et al., 2006; Camic et al., 2013). This was somehow expected since we selected experienced athletes in upper limb force training. MI practice focused on muscle activation was expected to improve performance as compared to a passive recovery condition while MI practice of muscle relaxation was considered a placebo control condition (i.e., several participants believed that it could facilitate recovery processes and limit inter-trial strength loss). Experimental results confirmed this hypothesis. We ruled out order effects since we implemented a fully counterbalanced design. Data analysis was performed with mixed linear models. This accounted for the

inter-day variations at the participants' level when testing the effect of recovery condition at the group level. Isometric strength and surface iEMG are highly correlated variables (Moritani and deVries, 1978). During isometric force development, muscle performance is limited by central inhibition factors limiting motor units recruitment during the early stages of training (Babault et al., 2006). Rapid improvements in maximal isometric strength are due to neural adaptations, particularly a breakdown in central inhibition improving motor units recruitment and synchronization. Compared to both control and relaxing MI, activating MI yielded higher total force values. We received no feedback supporting that participants expected this condition to be more efficient than the two others. iEMG from the biceps brachii recorded during activating MI was higher than during control. However, while force performance was higher during activating MI as compared to relaxing MI, iEMGs from the biceps brachii were similar. This result somehow challenges the assumption that activating MI improved force performance through changes in muscle activation. Nonetheless, the mixed linear effects analysis yielded a statistical trend toward higher iEMG values from the anterior deltoideus during activating MI compared to both relaxing MI and control. This possibly reflects a greater synergy between the biceps brachii and the anterior deltoideus under activating MI. Indeed, compared to relaxing MI where the MI practice only focused on the biceps brachii, activating MI involved mental rehearsal of the whole upper limb coordination at maximal intensities. MI is known to replicate muscle synergies through specific patterns of corticospinal facilitation (Stinear, 2010). EMG recordings also revealed that agonist and synergist muscles coordination was adequately reproduced during MI (Guillot et al., 2007; Lebon et al., 2008). (Gandevia et al., 1997) argued that such subliminal muscle activities could trigger a feedback loop promoting more efficient neural drive during future executions of the mentally rehearsed task. The postulates of the psychoneuromuscular theory were elegantly synthesized by (Jackson et al., 2001) : "The (...) theory proposes that micronerve impulses (...) facilitate[e] (...) future performance by priming specific "mental nodes" or "patterns of movement" necessary to execute a motor task" (Jackson et al., 2001, p. 1137). Albeit this remains a working hypothesis (since iEMG was only measured during the force trials), central processing during activating MI could have "primed" neural excitability within task-specific somatic pathways, leading to increased muscle activation and intermuscular coordination through a more efficient recruitment of motor units (i.e., with reference to psychoneuromuscular theory).

Motor learning and rehabilitation, please see Stoykov and Madhavan (2015). Integrative neuroscience underlined that actions may be organized according to hierarchical models (Schack, 2004; Zentgraf et al., 2009; Schack et al., 2014). These involve cognitive and sensorimotor levels of action control, assuming both representational and regulation functions (?). At the cognitive level, MI practice is likely to reinforce the structure of motor representations, hence yielding to increased expertise (Frank et al., 2014). More precisely, the authors argued that MI practice, by emphasizing the cognitive control of action, contributed to better structure procedural memory. Here, activating MI possibly primed performance through the structuration of recent memorial information, since it involved a conscious access to the efference copy of the somatic command addressed to the peripheral effectors (?). Studies addressing the issue of priming through MI practice remain scarce. Ramsey et al. (2010) observed that incongruent, but not congruent MI practice, hampered motor performance. This demonstrates that priming effects of MI practice require a tight congruence between the mental rehearsal content and the expected transfer to performance. Overall, in addition to the psychoneuromuscular theory,

hierarchical models of action organization provide an integrated rationale for priming effects of MI practice on performance. The relaxing MI condition was also associated with increased biceps brachii activation as compared to control. Stronger biceps brachii activation compared to control might account for focused attention paid to this muscle during MI practice, or purely reflect a placebo effect. Focused attention alone may facilitate corticospinal activation toward the relevant muscles (Stinear, 2010; Hiraoka et al., 2013). Yet, we did not find scientific data reporting that attention-related facilitation could be prolonged over time up to facilitate an upcoming force trial.

We recorded larger EDR during activating MI than during control, attesting higher sympathetic discharges. Tonic level of skin resistance was higher under the relaxing MI condition. This is congruent with literature data reporting reduced sympathetic activation in response to relaxation practice (Vempati and Telles, 2002). However, the largest EDR were recorded during relaxing MI. This finding is rather surprising and somehow difficult to interpret. EDR amplitude is dependent on the initial state of autonomic arousal (see also Wilder (1957) concerning the law of initial value, Vernet-Maury et al. (1995)), which is why EDR amplitudes were normalized. Nonetheless, EDR could have been amplified during relaxing MI in order to compensate a more relaxed pre-trial body state (relaxing MI practice involved a specific focus on muscle relaxation) as compared to both activating MI (involving MI practice of muscle activation at maximal intensities) and control (requiring sustained attention). Yet, no relationship was found between EDR amplitudes and force across trials and conditions.

Lebon et al. (2010) investigated the effect of MI practice during rest periods of physical training on the long-term development of dynamic muscle performance (i.e., 6 weeks of training including 12 sessions). They reported up to 20% of force gains, but did not record any physiological data. They attributed performance gains to skill improvement, presumably due to greater task focus, self-confidence and motivation. In the present experiment, the psychological factors likely to affect performance were rigorously controlled. Self-reports and physiological recordings revealed that participants' commitment and motivation during experimental measures remained constant throughout sessions. Indeed, we observed a regular decrease of about 20% in baseline EDA. Tonic sympathetic activity thus tended to increase on a trial-to-trial basis, potentially to compensate the occurrence of both accumulated mental strain and physical fatigue. Contrary to Lebon et al. (2010), performance gains could not result from technical improvements, since the task did not involve dynamic but isometric contractions. The reference position was rigorously controlled, thus ruling out possible skill adjustments. We advocate that higher training intensities, particularly during activating MI, could reflect priming effects of MI practice on central motor processes. Such short-term adaptations potentially improved muscle activation and isometric force.

While some studies which tested the effects of MI practice over several weeks did not report a positive effect on force (e.g., Herbert et al. (1998), see also Graham et al. (2014) for absence of short-term effects on muscle endurance), the long-term positive effects of MI practice on isometric force are well-established. Authors argued that MI practice induced, over several weeks, "neuroplastic" adaptations including increased cortical activation during voluntary isometric contractions at maximal intensities Yue and Cole (1992); Ranganathan et al. (2004); Yao et al. (2013). Here, "on-line" force gain between 2.1% and 3.5% were measured compared to the other conditions. These were associated with 8.2% of increase in biceps brachii activation compared to the control condition. Present results show an immediate influence of mental rehearsal on maximal isometric force. Present data

support that activating MI yielded to priming effects on performance. Such improvements may be grounded in short-term neuroplastic adaptations, possibly excitability changes in the motor cortex leading to more efficient drive of motor units. Indeed, as underlined by Stoykov and Madhavan (2015):

“(...) priming of the motor cortex is associated with changes in neuroplasticity that are associated with improvements in motor performance.”, p. 33.

These gains remain however weaker than those reported by Yao et al. (2013) after 6 weeks of kinesthetic MI training (i.e., about 11% increase in maximal elbow flexion).

CONCLUSIONS

Embedding MI practice during rest periods is congruent with theoretical frameworks supporting that MI should be practiced under conditions close to those of physical training Holmes and Collins (2001); Guillot and Collet (2008). Athletes' reports of self-efficacy corroborated both force and physiological data: they felt more efficient during activating MI. MI of muscle activation may be relevantly practiced during rest periods of training or physiotherapy sessions (see also Rozand et al. (2014)). However, physiotherapy sessions foremost involve submaximal contractions. The extent to which MI practice is likely to impact performance improvement remains to be more thoroughly studied. As short-term effects were measured on maximal isometric performance, testing the immediate effects of MI practice on submaximal force tasks is a perspective of the present experiment.

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APPENDIX A

Warm-up and Familiarization to Physical Training

Warm-up

Experiments took part in a quiet room. Participants first completed a 10-minute warm-up, which started with 4 minutes of physical arousal exercises. Participants then seated on the bench and adopted the standardized position of the experiment (Fig. 1). They were instructed to perform five incremental isometric contractions with a 90° elbow flexion against the force plate, each sustained for 10 seconds and separated by 50-second rest periods. They completed the warm-up with two maximal isometric flexions, each sustained for 12 seconds and separated by 1.5-minute rest periods. Experimenters visually controlled the strength increase using the signal from the force plate.

Familiarization

Immediately after the warm-up, participants received the experimental instructions for the forthcoming physical training session. The organization of rest periods was carefully explained to them. For the training session involving passive recovery, participants were instructed to remain motionless and listen to audio instructions during rest periods.

Immediately before the first force trial of the physical training, participants were broadcasted a 1-minute audio sequence involving three sequences of 12 seconds of information concerning international sports news.

When rest periods involved MI training, participants were carefully instructed to perform either activating or relaxing MI as accurately as possible. Immediately before the first trial of physical training, they were requested to complete three MI trials of 12 seconds over a period of 1 minute, using a similar audio soundtrack to that used during the rest periods of the physical training session.

APPENDIX B

MI Scripts

For the **activating MI** condition, the following script was broadcasted to participants:

“Mentally represent yourself in the standardized experimental position. Perceive the intense contraction of your biceps in response to the auditory tone. Feel the maximal muscle activation, and focus on the contraction of all muscle fibers. Visualize your arm sustaining this maximal effort.”

For **relaxing MI**, the following script was broadcasted to participants:

“Mentally represent yourself in the standardized experimental position. Perceive the profound relaxation of your biceps after trial completion. You feel complete muscle easing and calmness accompanying relaxation of all muscle fibers. Visualize your arm sustaining this relaxed state.”

APPENDIX C

Parameter	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Vertical force (N s)										
ACTIVE MI	2593.88 ± 130.83	2343.76 ± 111.03	2252.58 ± 119.87	2178.07 ± 98.13	2137.62 ± 104.76	2134.62 ± 110.59	2123.83 ± 107.95	2101.69 ± 100.07	2053.99 ± 99.20	2067.68 ± 109.09
RELAXING MI	2596.44 ± 127.48	2268.20 ± 135.15	2231.19 ± 125.34	2155.57 ± 112.88	2167.29 ± 113.38	2103.68 ± 125.50	2088.92 ± 103.12	2053.15 ± 105.36	2035.74 ± 107.20	2021.60 ± 111.43
PASSIVE RECOVERY	2493.77 ± 115.69	2264.47 ± 138.77	2187.06 ± 121.85	2165.48 ± 126.50	2167.41 ± 118.86	2079.72 ± 108.82	2042.44 ± 111.08	2058.82 ± 107.15	2037.26 ± 117.97	1996.35 ± 117.05
EMG electromyogram from the biceps brachii (mV s)										
ACTIVE MI	10224.39 ± 1306.35	8601.81 ± 1136.15	8097.61 ± 1211.06	8105.28 ± 1137.92	8343.57 ± 1244.04	8369.78 ± 1128.36	8246.46 ± 1057.12	8343.33 ± 1026.25	8331.30 ± 1081.06	8291.81 ± 1106.31
RELAXING MI	10534.59 ± 1348.80	8428.22 ± 1096.86	8596.71 ± 1030.31	8148.78 ± 1068.64	8442.42 ± 963.07	8470.13 ± 1035.62	8267.26 ± 995.90	8518.53 ± 1003.60	8333.97 ± 1027.06	8566.31 ± 1147.80
CONTROL	9046.59 ± 1101.95	7741.13 ± 1062.60	7696.86 ± 1078.12	7771.68 ± 1026.61	7476.69 ± 983.80	7254.75 ± 1019.41	7293.22 ± 1004.62	7591.92 ± 1044.83	7108.99 ± 1151.68	7098.26 ± 1124.71
Integrated electromyogram from the anterior deltoid (mV s)										
ACTIVE MI	4471.06 ± 821.05	3985.51 ± 629.90	3988.87 ± 619.05	4169.08 ± 567.09	4063.86 ± 609.15	4025.32 ± 628.88	3862.32 ± 609.01	3925.31 ± 628.63	4092.78 ± 666.16	3890.05 ± 668.77
RELAXING MI	4794.81 ± 884.55	3968.74 ± 671.84	4134.92 ± 666.24	3798.13 ± 637.59	3726.92 ± 680.92	3506.55 ± 593.83	4130.94 ± 617.40	3762.62 ± 685.03	3672.60 ± 660.80	3446.63 ± 562.40
CONTROL	4392.07 ± 729.18	3759.08 ± 626.76	3585.48 ± 611.66	3526.39 ± 616.35	3241.84 ± 623.71	3242.32 ± 618.78	3461.35 ± 653.06	3765.74 ± 691.72	3248.52 ± 589.96	2759.84 ± 454.64
Skin resistance response amplitudes (% of basal value in K)										
ACTIVE MI	15.48 ± 3.29	15.93 ± 3.69	15.81 ± 3.59	15.91 ± 3.29	14.82 ± 3.48	13.69 ± 3.36	14.13 ± 3.38	14.05 ± 3.46	13.80 ± 3.49	13.63 ± 3.35
RELAXING MI	17.63 ± 5.88	19.40 ± 3.67	17.69 ± 2.41	15.38 ± 2.13	17.22 ± 2.44	16.83 ± 2.11	16.63 ± 1.98	15.74 ± 1.74	14.09 ± 1.79	14.29 ± 1.68
CONTROL	16.08 ± 2.43	11.06 ± 1.88	12.43 ± 1.57	10.05 ± 1.40	9.35 ± 1.41	10.33 ± 1.23	9.81 ± 1.24	7.03 ± 1.16	8.91 ± 1.52	10.28 ± 1.79

Table 1: Group mean ± standard errors recorded for each dependent variable of interest (see Experimental procedures), during each of the ten trials of physical training (from left to right). MI: Motor imagery