NEUROSCIENCE

INTERNATIONAL BRAIN RESEARCH ORGANIZATION

RESEARCH ARTICLE

F. Di Rienzo et al. / Neuroscience 418 (2019) 82–95

Effects of Action Observation and Action Observation Combined with Motor Imagery on Maximal Isometric Strength

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Abstract—Action observation (AO) alone or combined with motor imagery (AO + MI) has been shown to engage the motor system. While recent findings support the potential relevance of both techniques to enhance muscle function, this issue has received limited scientific scrutiny. In the present study, we implemented a counterbalanced conditions design where 21 participants performed 10 maximal isometric contractions (12-s duration) of elbow flexor muscles against a force platform. During the inter-trial rest periods, participants completed i) AO of the same task performed by an expert athlete, ii) AO + MI, i.e. observation of an expert athlete while concurrently imagining oneself performing the same task, and iii) watching passively a video documentary about basketball shooting (CONTROL). During force trials, we recorded the total force and integrated electromyograms from the *biceps brachii* and *anterior deltoideus*. We also measured skin conductance from two finger electrodes as an index of sympathetic nervous system activity. Both AO and AO + MI outperformed the CONTROL condition in terms of total force (2.79–3.68%, $p < 0.001$). For all conditions, we recorded a positive relationship between the *biceps brachii* activation and the total force developed during the task. However, only during AO was a positive relationship observed between the activation of the *anterior deltoideus* and the total force. We interpreted the results with reference to the statements of the psycho-neuromuscular theory of mental practice. Present findings extend current knowledge regarding the priming effects of AO and AO + MI on muscle function, and may contribute to the optimization of training programs in sports and rehabilitation. © 2019 Published by Elsevier Ltd on behalf of IBRO.

Key words: neural plasticity, neural priming, muscle function, motor cognition, conditioning.

INTRODUCTION

Dose–response relationships in the development of muscle strength have been the focus of a large body of research since the middle of the 20th century (Rhea et al., 2003; Peterson et al., 2004). Strength development originates from both structural and functional adaptations (Komi, 1986). Strength development is classically associated with hypertrophy, i.e. an increase in muscle mass (Damas et al., 2015). Muscle hypertrophy occurs as a *long-term* result of resistance training (programs scheduled within a span of several weeks), and stems from an adaptive response to the mechanical and metabolic demands elicited by training (Schoenfeld, 2010). Functional adaptations also play a key role in strength development, particularly during the early stages where *short-term* improvements occur in the absence of muscle hypertrophy (Sale, 1988; Moritani, 1993). Indeed, strength produced during maximal voluntary contractions mirrors the capacity of the central nervous system to synchronize the recruitment of motor units (Clark et al., 2014). Weighted resistance training above 90% of the maximal voluntary contraction threshold emphasizes neurophysiological adaptations yielding improved motor units recruitment (Kraemer et al., 1996).

Resistance training programs typically consist of physical exercise with progressive poundage. Nonetheless, the potential relevance of training with mental practice is gaining increased attention (Tod et al., 2003, 2015; Paravlic et al., 2018). Recent evidence supports the positive effects of motor imagery (MI), i.e. the voluntary process of mentally simulating a movement without engaging its physical execution, on strength and its inclusion within resistance training programs (Tod et al., 2015; Paravlic et al., 2018). Functional brain imag-

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https://doi.org/10.1016/j.neuroscience.2019.08.025

ing findings support the hypothesis of a functional equivalence between MI and the physical execution of the same action. MI activates brain regions controlling the actual motor preparation and execution, albeit with reduced magnitude (Lotze and Halsband, 2006; Munzert and Zentgraf, 2009; Hétu et al., 2013). There is evidence of premotor, parietal and primary sensorimotor cortex activation during MI (Gerardin et al., 2000; Ehrsson et al., 2003; Solodkin et al., 2004; Gao et al., 2011). MI also recruits subcortical regions such as the basal ganglia and the cerebellum (Hanakawa et al., 2003; Szameitat et al., 2007; Wagner et al., 2008; Burianová et al., 2013). At the peripheral level, the effector-specific facilitation of corticospinal pathways during MI is well-established (Stinear, 2010; Grosprêtre et al., 2016, for reviews). Furthermore, both Jowdy and Harris (1990) and Gandevia et al. (1997) reported low-threshold muscle activity during MI. The subliminal muscle activation reproduced the intensity and regimen of the imagined contractions (Bakker et al., 1996; Guillot et al., 2007; Lebon et al., 2008). Henceforth, rather than a purely mental state, MI should overall better be considered a "(...) *special form of motor behaviour*" (Stephan and Frackowiak, 1996).

From an applied viewpoint, MI increases the cognitive demand on brain motor regions, which then could prompt experience-based plasticity and improve motor performance (Di Rienzo et al., 2016). Pioneering investigations of the effects of MI on strength focused on behavioral measures, sometimes associated with recordings of muscle activation (Cornwall et al., 1991; Yue and Cole, 1992). There is an emerging consensus that embedding MI within resistance training programs of several weeks yields additional strength benefits. Despite methodological differences across studies (e.g. the MI to physical practice ratio administered during the training sessions), strength typically increases from 10 to 30% (Reiser et al., 2011). Improvements occur in the absence of muscle hypertrophy, hence suggesting neural adaptation (Yue and Cole, 1992). More recently, we observed strength gains after a single-session of MI (Di Rienzo et al., 2015). These findings corroborate the proposition of the psycho-neuromuscular theory of mental practice, which posits that motor simulation can be effective to improve the cortical gain over motor units (Jacobson, 1932). While short-term changes in the cortical gain over motor units might drive most of the short-term effects (Di Rienzo et al., 2015; Grosprêtre et al., 2018), Hebbian-type plasticity comparable to that elicited by physical training may be the core process mediating improvements of motor performance through MI (Di Rienzo et al., 2016, for a review). This applies to strength development paradigms where resistance training programs with MI extend across several weeks. For instance, Ranganathan et al. (2004) demonstrated that strength improvements consecutive to MI training were associated with increased amplitudes of the cortical motor potentials generated during high-intensity strength trials (see also Yao et al., 2013; Grosprêtre et al., 2018).

Action observation (AO) is another cognitive motor process that shares common neural substrates with both MI and the actual motor preparation/execution (Tkach et al., 2007; Hardwick et al., 2018). AO and MI remain functionally dissociable and hierarchized with regard to the degree of involvement of the brain motor regions (Macuga and Frey, 2012). Nonetheless, AO consistently engages premotor, parietal and cerebellar networks. Brain networks recruited during AO have been described as part of a "*mirror neuron*" system (Rizzolatti and Craighero, 2004; Casile et al., 2011). Research in both humans and primates demonstrated that the mirror neuron system encodes relevant behavioral features of the observed actions (Agnew et al., 2007; Vogt and Thomaschke, 2007; Alaerts et al., 2012; Catmur, 2015). AO thus involves inputs to the brain motor system under the form of "*(...) Externally guided motor simulation*" (Vogt et al., 2013, p. 3). AO improves motor learning, specifically when the observer has a previous experience of the task (Rizzolatti et al., 1996; Bird et al., 2005; Mattar and Gribble, 2005; Calvo-Merino et al., 2006). However, few studies have investigated the efficacy of AO to improve strength. This is rather surprising considering the currently growing interest in mental training with AO to potentiate the recovery of muscle function (Pomeroy et al., 2005; Sale and Franceschini, 2012; Buccino, 2014). Porro et al. (2007) pioneered that daily training sessions with AO scheduled over the course of 2 consecutive weeks improved index finger abduction strength by 30%. The gains were specific to the movement observed during training. Noteworthy, the authors recorded increased excitability of corticospinal pathways targeting the first dorsal interosseous after training completion. These data support earlier findings by Ranganathan et al. (2004) suggesting that the statements of the psycho-neuromuscular theory of MI could also apply to training with AO.

MI and AO have been broadly conceptualized within the field of motor cognition as motor simulation processes due to their capacity to engage the brain motor system in the absence of physical execution (Jeannerod, 1994, 2001). Previously, Shepard (1984) suggested that MI and AO belonged to a continuum extending from passive/external (bottom-up) to active/internal (top-down) motor simulation (Vogt et al., 2013 for a more recent discussion). Consequently, the overlaps between MI and AO are readily exemplified in sporting situations. For instance, observing a teammate or an opponent's performance concomitantly elicits the simulation of an adapted motor response. An emergent body of research investigates training with AO and MI concomitantly (AO + MI). AO + MI was referred to as "*(...) video guided imagery*" or "*(...) imagining imitation*" in the scientific literature. Eaves et al. (2016b) underlined that combining bottom-up and top-down processing through AO + MI yields synchronized visual and kinesthetic inputs to the brain. Performing MI while observing the same movement on a video might thus facilitate the build-up of accurate motor representations by prompting attentional focus on the relevant spatial and temporal features of the coordination. Similarly, video cues provide direct inputs to the visual system and reduce the need for top-down processing of MI. The top-down processing of kinesthetic information might consequently benefit from increased allocation of attentional resources. Transcranial magnetic stimulation provided evidence of higher corticospinal excitability during AO + MI compared to either AO or MI alone (Sakamoto et al., 2009; Ohno et al., 2011; Wright et al., 2014; Mouthon et al., 2015). Functional brain imaging recordings confirmed that AO + MI was associated with increased activity in brain motor regions compared to AO and MI alone (Nedelko et al., 2012). Due to greater involvement of motor regions in the brain, AO + MI might represent a more efficient way of enhancing the motor performance compared to the isolated practice of AO and MI (Eaves et al., 2014; Taube et al., 2014; Bek et al., 2016).

Research on the effects of AO + MI on motor performance remains sparse. A limited number of experiments compared the effects of AO + MI to AO or MI *alone*. This is particularly valid when considering strength development, although recent studies have specifically compared the efficacy of AO + MI with that of MI practice alone. In a seminal study, Scott et al. (2018) reported greater effectiveness of AO + MI compared to MI alone to increase hamstring strength. The study design also included a MI-control condition (i.e. MI focused on the upper-limbs). The 3 weeks of training involved three sessions of 20 min of MI training incorporating the "*Physical, Environmental, Task, Timing, Learning, Emotion Perspective*" (PETTLEP) guidelines (Holmes and Collins, 2001). The AO + MI and MI alone session focused on Nordic hamstring exercises, while the AO component of the AO + MI condition involved an external visual perspective. Eccentric hamstring peak torque increased in the right leg in the AO + MI group (i.e. ~6% of increase compared to the baseline), whereas the ~3.5% increase in the MI alone group did not reach significance. Further analyses (magnitude-based inference) confirmed the potential superior relevance of AO + MI, specifically from a clinical perspective. Similarly, Smith et al. (2019) addressed whether the adjunct of AO to MI training improved the maximal strength on a biceps curl machine. The authors implemented a multiple-case counterbalanced design, where AO + MI and MI alone were each administered during 4 weeks after a 3-week baseline period. Surprisingly, the authors found that MI and AO + MI were both equally efficient. Notably, AO did not focus on an external model, but was built from a video capture of participants' own physical performance, filmed from the first-person perspective during a set of repetitions to failure during the baseline period. Although their findings conflicted with those reported by Scott et al. (2018), the authors did not rule out the hypothesis that AO + MI might outperform MI alone. This is primarily due to the trajectory of performance changes. When AO + MI took place before MI alone the authors systematically observed a performance increase along the course of the 4 weeks, whereas MI alone appeared to maintain the strength benefits. They also considered the possibility of delayed gains, where AO + MI would ultimately outperform MI alone if the intervention was prolonged up to 15 weeks (e.g. Wakefield and Smith, 2011). In keeping with these exploratory findings, we found no experiments that compared AO with AO + MI in a strength paradigm. Considering the limited amount of research on the development of maximal isometric strength and the growing interest in AO + MI, we designed the present study to investigate the short-term effects of AO and AO + MI on maximal isometric strength. Based on the psycho-neuromuscular theory, we hypothesized that AO + MI should outperform AO, while AO would outperform the control condition.

EXPERIMENTAL PROCEDURES

Participants

Twenty-one participants were recruited from the Faculty of Sports Sciences of the University Claude Bernard Lyon 1 (F-69100, Villeurbanne; 17 males; mean age = 22.25 ± 2.18 years). All were athletes of regional to national level in terrestrial sports (judo, karate, climbing, basket and soccer), and had a background of at least 2 years in resistance training (i.e. > 1 year of practice, 2–4 sessions of 45 min per week). Participants were also screened based on their ability to engage in MI practice using a standardized MI questionnaire, i.e. average score > 5 on the Movement Imagery Questionnaire-3 (Williams et al., 2012). The study was a relative strength contest with reference to body weight. This was expected to encourage the commitment to a maximal effort throughout experimental sessions. We did not provide any information regarding the purpose of the study until after completion of the design. The local Ethics Committee approved the study. Each participant provided written informed consent according to the statements of the Declaration of Helsinki (2013).

Experimental design

The repeated-measures design comprised three experimental sessions of 30 min, separated from each other by 48 h. We interposed a no-training day between experimental sessions, which were scheduled at 12 am before lunch to control for the potential influence of circadian rhythms. Each experimental session consisted of 10 maximal elbow flexions against a fixated force platform. Participants attempted to lift the fixated force platform from a seated position with the elbow at 90° and the hand against the platform (Fig. 1). For each trial, the voluntary maximal isometric contraction was sustained for 12 s. Each trial was separated from each other by a 60 s period allocated to recovery.

Experimental settings

Participants warmed-up for 10 min in a quiet room. They first completed 6 min of body weight exercises (i.e. lunges and squat jumps). Then, they seated on a bench equipped with a reclining seatback. They were instructed to keep permanent contact between the reclining seatback and the back of their head, the posterior apex of the thoracic spine, and the pelvis in order to standardize the trunk position (Fig. 1A). Participants constantly fixed a cross mark on the wall at eye level. From this standardized position, each participant performed five consecutive isometric

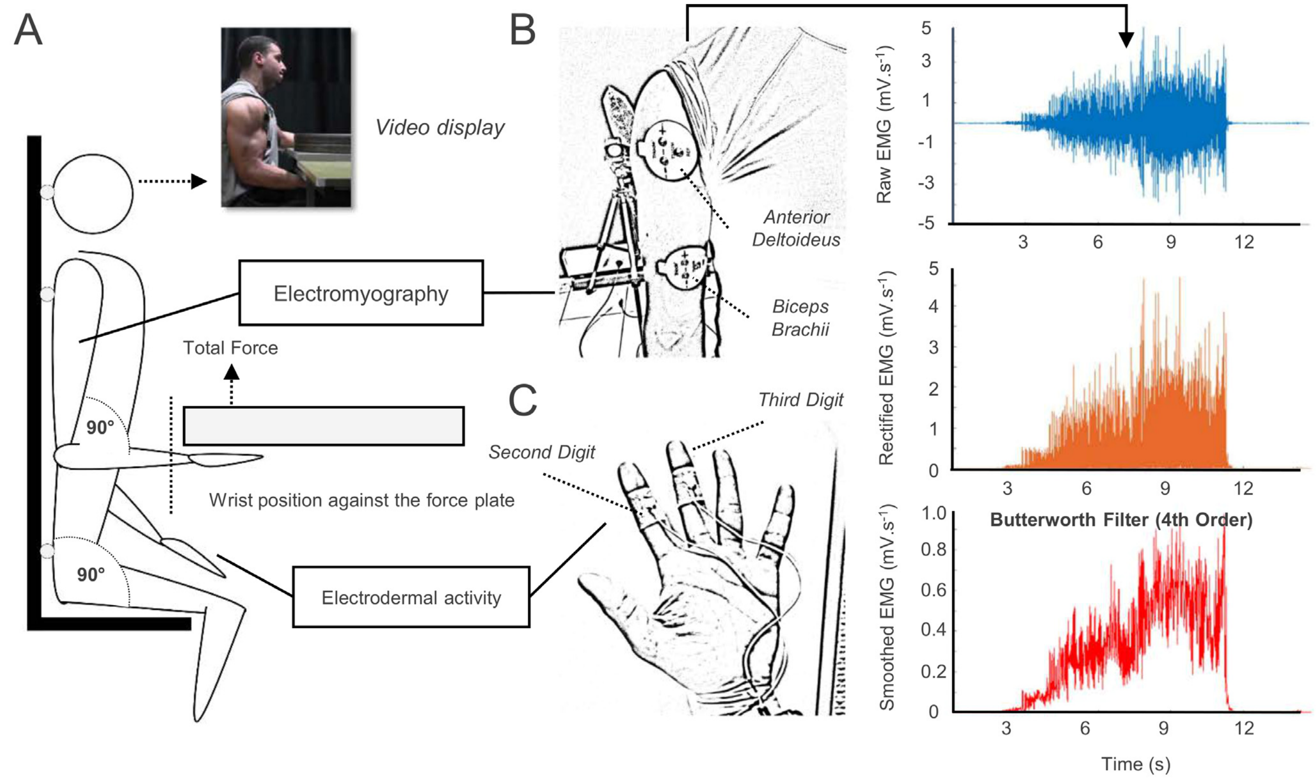

Fig. 1. Experimental session settings. (A) Experimental settings involved a standardized body position in front of a fixed force platform against which participants produced a maximal isometric contraction with the elbow at 90° (i.e. vertical arrow). The total force was used as the behavioral performance variable quantifying strength. (B) Electromyograms from the *biceps brachii* and *anterior deltoideus* of the dominant upper limb. The smoothed/rectified signal corresponding to the 12 s of each trial was integrated and used as a dependent variable quantifying voluntary muscle activation. (C) Skin conductance, with sensors on the second phalanx of the second and third digits, according to traditional recommendations. We measured the maximal amplitude of skin conductance response during each 12-s trial, as an index of the sympathetic activity.

contractions of 12 s of incremental intensity against the fixated force platform. They were instructed to achieve a self-paced increase in the intensity of the isometric contractions across the five trials, but below their maximal isometric strength threshold. Each trial was separated by recovery periods of 50 s. Participants then finished the warm-up by two maximal isometric contractions sustained for 12 s, separated by 90 s of passive recovery. Finally, the experimenter provided oral instructions corresponding to the upcoming experimental condition. While sitting on the bench, they faced a force platform under which they placed their dominant hand in supine position, with the elbow at 90°, as controlled by goniometers. We rigorously controlled the hand position at each trial, checking that the wrist, palm and fingers remained in flat contact with the force platform (Fig. 1A).

Experimental conditions

Across the repeated measures of the design, we administered the following experimental conditions during the inter-trial recovery periods: i) observation of a bodybuilder athlete performing the task (AO), ii) observation of a bodybuilder athlete performing the task combined with MI of oneself performing the task (AO + MI) and iii) watching passively a video documentary about basketball shooting (CONTROL). Experimental settings were identical to those during the warm-up. During each 60 s inter-trial recovery period, we administered three blocks (15 s each) of mental practice corresponding to the different experimental conditions. The onset and the offset of each trial and recovery periods were externally cued by audio stimuli (Presentation, Neurobehavioral systems®, 240 Hz, 50 dB). To prevent carryover effects, e.g. residual muscle fatigue from one experimental session to another, experimental conditions were administered in counterbalanced order (block randomization).

During inter-trial recovery periods, participants watched a 15-s video displayed on a screen in front of them. During AO and AO + MI, the video displayed a bodybuilder athlete (79 kg, 7.63% of body fat, 22 years old) completing the maximal isometric strength task in identical experimental settings. The video showed the bodybuilder from a lateral view (Fig. 1A). During AO, the experimenter gave participants the following instructions: *"Watch carefully the athlete performing the maximal voluntary contraction. Focus on the effort produced by the athlete trying to lift the platform. Focus your attention on his upper limb and observe the intense muscles contractions all along with the maximal effort intensity*". The experimenter explicitly instructed participants not to engage in MI during the AO condition. This method is comparable to that described by Eaves et al. (2016a), where the authors requested: "*Please refrain from undertaking any MI during (...) observation in this pure AO condition*" (p. 94). During AO + MI, participants performed the same action observation task as during AO while simultaneously engaging in MI. When watching the video, the participants were instructed to: "*Imagine yourself in an attempt to lift the platform. Feel the intense contraction of your biceps and your shoulder muscles during the maximal effort. Focus on the total recruitment of muscle fibres throughout the duration of the effort*". Participants were prompted by such instructions to engage in the kinesthetic modality of MI. During Control, participants remained motionless and watched the video documentary for 15 s.

Dependent variables

Psychometric recordings. Functions of Observational Learning Questionnaire. Before the first experimental session, participants completed the Functions of Observational Learning Questionnaire (FOLQ; Cumming et al., 2005). This is a qualitative tool investigating participants' uses of action observation with the aim to improve performance in their sporting activities (Cumming et al., 2005). The FOLQ investigates the uses of AO with reference to the cognitive and motivational functions of MI earlier described by Paivio (1985) to improve sporting performance. Participants reported each item on a Likert-type scale ranging from 1 ("*I never use*") to 7 ("*I often use*"). The FOLQ specifically investigates two cognitive (Strategy and Skills) and one motivational (Performance) functions of AO. Strategy refers to uses of AO to improve cognitive processing related to tactical aspects mediating performance (e.g. "*I use observational learning to determine how a strategy will work in an event/game*"). Skills refer to uses of AO to improve cognitive processing related to technical execution mediating performance (e.g. "*I use observational learning to understand how to perfectly perform a skill*"). Finally, Performance refers to uses of AO to achieve optimal arousal and anxiety appraisal in sporting situations (e.g. "*I use observational learning to know how to respond to the excitement associated with performing well*"). The FOLQ showed high internal consistency with Cronbach's alphas ranging from 0.84 to 0.90 (Cumming et al., 2005).

Likert ratings. After each experimental session, participants rated their perceived strength throughout the maximal isometric strength trials on a Likert-type scale ranging from 1 ("*Very low level of strength output*") to 10 ("*Very high level of strength output*"). Participants also rated their motivation to complete the experimental session on a Likert-type scale ranging from 1 ("*Very low level of motivation*") to 10 ("*Very high level of motivation*"). We also evaluated the perceived difficulty to complete the experimental session with self-reports using a Likert-type scale ranging from 1 ("*Very low level of difficulty*") to 10 ("*Very high level of difficulty*"). After completion of the AO + MI condition, we finally evaluated MI vividness with self-reports with a Likert-type scale ranging from 1 (i.e. "*Absence of visual/kinesthetic information during imagination*") to 10 (i.e. "*Comparable visual/kinesthetic information during imagination as during physical practice*").

Behavioral recordings. We measured the elbow flexion strength with a force platform (AMTI, model 0R6-7-2000, Watertown, Massachusetts, USA). Data were continuously recorded and synchronized by LabChart Pro V8© (ADInstruments Pty Ltd., 2014) at 1000 Hz. Data were smoothed with a zero-lag fourth-order low-pass Butterworth filter with a 20-Hz cut-off frequency. During each trial, the sudden force increase in response to auditory stimulus was detected using a threshold detection function (Matlab®). We then calculated the total force by integrating the force slope with respect to the duration of each trial (12 s, trapezoid rules). We finally normalized the total force in percentage of the total force value recorded during the maximal isometric force trial of the warm-up:

$$TotalForce_{(Normalized)} = \left(\frac{TotalForce(\text{Maximal isometric strength trial 110})}{TotalForce(\text{Best maximal isometric strength during warm} - \text{up})}\right) \times 100$$

The total force was used as the behavioral performance variable quantifying strength.

Physiological recordings. For each trial, we recorded the surface electromyograms (EMG) of the main agonists. After shaving and cleaning the skin with alcohol, we recorded EMG from the *biceps brachii* using pairs of surface electrodes (1 cm EMG Triode, nickel-plated brass, inter-electrode distance 2 cm, Thought Technology, Montreal, Canada). We also recorded EMG from the *anterior deltoideus*, a synergist muscle of the experimental task (Di Rienzo et al., 2015). Electrodes positioning was determined according to the recommendations of the "*Surface Electromyography for the Non-Invasive Assessment of Muscles*" (SENIAM) project (Hermens et al., 2000). Electrodes location was marked with a pen and photographed to ensure reproducible positioning across experimental sessions. We continuously recorded and synchronized EMG data by LabChart ProV8© (ADInstruments Pty Ltd., 2014). We processed the raw signal using the TrignoTM Wireless EMG© system (2014, Delsys Incorporated). We then rectified and smoothed the raw EMG signal with a 20–500-Hz pass-band filter (Butterworth fourth). For each trial, we calculated the integrated EMG (iEMG) with respect to the 12 s of each voluntary contraction (Fig. 1B). We considered iEMG a global measurement of motor units activation related to isometric strength output (Moritani and deVries, 1978). We finally normalized iEMG data in percentage of the maximal iEMG value recorded during the maximal isometric force trial of the warm-up:

$$iEMG_{(Normalized)} = \left(\frac{iEMG(\text{Maximal isometric strength trial 110})}{iEMG(\text{Best maximal isometric strength during warm} - \text{up})}\right) \times 100$$

We continuously recorded electrodermal activity through skin conductance measures (micro Siemens, µS, i.e. $1{\cdot}10^{-6}\,\text{m}^{-2}{\cdot}\text{kg}^{-1}{\cdot}\text{s}^{3}{\cdot}\text{A}^{2}$), using two 50- mm^2 unpolarizable bipolar electrodes placed on the second phalanx of the second and third digits of the non-dominant hand (Fig. 1; MLT116f GSR Finger Electrodes, ADInstruments, New Zealand). Electrodermal activity reflects the activity of eccrine sweats glands, which are under the unique control of the sympathetic branch of the autonomic nervous system (Shields et al., 1987). Increased skin conductance attests increased sympathetic activity, and inversely. After checking that electrodermal activity exhibited a similar pattern across experimental sessions, we collected the electrodermal response (EDR) for each maximal isometric strength trial. We then calculated the EDR amplitude as the delta separating the sudden increase and the onset of the prolonged and regular return to the pre-stimulus baseline (for further development and experimental illustration, see Vernet-Maury et al., 1995; Kanthack et al., 2017). EDR amplitude is typically associated with the mental workload elicited by cognitive processing during both physical and mental tasks (Collet et al., 2013). Accordingly, we used EDR amplitudes as an objective measure of participants' commitment to a maximal effort during the isometric strength trials.

Statistical analysis

Linear mixed effects analysis. We used R (2018) and *nlme* (Pinheiro et al., 2014) to run a linear mixed-effects analysis with a by-subject random intercept of the psychometric, behavioral and physiological dependent variables. For FOLQ scores, we entered DIMENSION (i.e. Skill, Strategy and Performance) as fixed effect. We investigated self-reports of motivation and perceived performance, as well as self-reports of perceived difficulty to complete the cognitive tasks administered during the inter-trial recovery periods (i.e. AO, AO + MI), using CONDITION (i.e. Control, AO, AO + MI) as fixed effect. For EDR amplitude, we built a linear mixed effect model with the fixed effect of CONDITION and TRIAL (with interaction term). For total force, we entered the interaction between CONDITION and TRIAL, $\text{iEMG}_{\text{BICEPS BRACHII}}$, $\text{iEMG}_{\text{ANTERIOR DELTOIDEUS}}$ as fixed effects. For all analyses, we included TRIAL as numeric regressor (i.e. ranging from 1 to 10). This procedure enabled qualitative investigation of linear trends (Di Rienzo et al., 2015, 2019; Kanthack et al., 2017 for comparable statistical analysis frameworks). We implemented a backward stepwise procedure to fit the random-coefficient regression model formulae (Hocking, 1976; Draper and Smith, 2014). Inspection of the residual plots did not reveal any obvious deviation from the hypotheses of homoscedasticity or normality. We set up the statistical significance threshold for a type 1 error rate of $\alpha = 5\%$. As effect sizes, we reported partial coefficients of determination (Rp^2), using the procedure for linear mixed effects models implemented in the *r2glmm* package (Edwards et al., 2008; Jaeger et al., 2017). We finally investigated main effects and interactions using general linear hypotheses testing of planned contrasts from the *multcomp* package (Hothorn et al., 2008; Bretz et al., 2016). We applied Holm's sequential corrections to control the false discovery rate (Holm, 1979).

Power analysis. We carried out power calculations using the *pwr* package implemented in R (Champely et al., 2018). Due to the nature of the experimental hypotheses, sample size should afford a reliable statistical power to detect a main effect of the EXPERIMENTAL CONDITION on total force. Considering the repeated measures nature of the design, a sample size of $n = 21$ yielded a statistical power of $p_{(1-\beta)} = 0.80$ to detect small effect sizes, i.e. corresponding to 1–5% of explained variance with a type 1 error rate of 5%. The statistical power was superior to 0.90 for medium and large effect sizes, i.e. corresponding to 10% of explained variation and higher.

RESULTS

Monitoring compliance to the experimental design

Psychometric data. FOLQ scores. The linear mixed effects analysis revealed a statistically significant effect of the DIMENSION ($\chi^2(2) = 85.66$, $p < 0.001$, $R_p^2 = 0.47$). FOLQ for performance scores (M ± SE; 2.85 ± 0.25) were lower than those recorded for both strategy (4.33 ± 0.33) and skills (5.41 ± 0.31) dimensions (fitted difference: 1.46 ± 0.28, $p < 0.001$; 2.57 ± 0.28, $p < 0.001$; respectively). FOLQ scores for skill were also higher than those for strategy (fitted difference: 1.08 ± 0.28, $p < 0.001$).

Self-reports on Likert-type scales. The linear mixed effects analysis on motivation and perceived performance yielded no CONDITION effect ($\chi^2(2) = 0.53$, $p = 0.77$; $\chi^2(2) = 1.35$, $p = 0.51$, respectively), as shown by Fig. 2. The COGNTIVE TASK affected Likert ratings of perceived difficulty ($\chi^2(1) = 3.90$, $p = 0.04$, $\text{Rp}^2 = 0.06$ - Fig. 2). Participants rated that it was more difficult to complete AO + MI (4.38 ± 0.51) than AO alone (3.23 ± 0.65, fitted difference: 1.14 ± 0.59, $p = 0.04$). Finally, vividness ratings after AO + MI were 6.66 ± 1.83 on the 10-point Likert scale, i.e. corresponding to the "*Quite good (…)*" vividness item (Fig. 2).

Skin conductance data. The analysis of EDR amplitude revealed that the CONDITION × TRIAL interaction approached the statistical significance threshold ($\chi^2(2)$: 4.56, $p = 0.10$, $\text{Rp}^2 = 0.01$). As shown in Fig. 3, there was a marginally negative TRIAL effect on EDR amplitudes during AO + MI (fitted estimate: -0.05 µS ± 0.06, $p = 0.09$). By contrast, there was no TRIAL effect on EDR amplitudes recorded during both AO ($p = 0.74$) and Control conditions ($p = 0.73$). The linear mixed effects analysis revealed no main effect of CONDITION ($\chi^2(2) = 3.79$, $p = 0.15$) or TRIAL ($\chi^2(1) = 1.36$, $p = 0.24$) (Fig. 3).

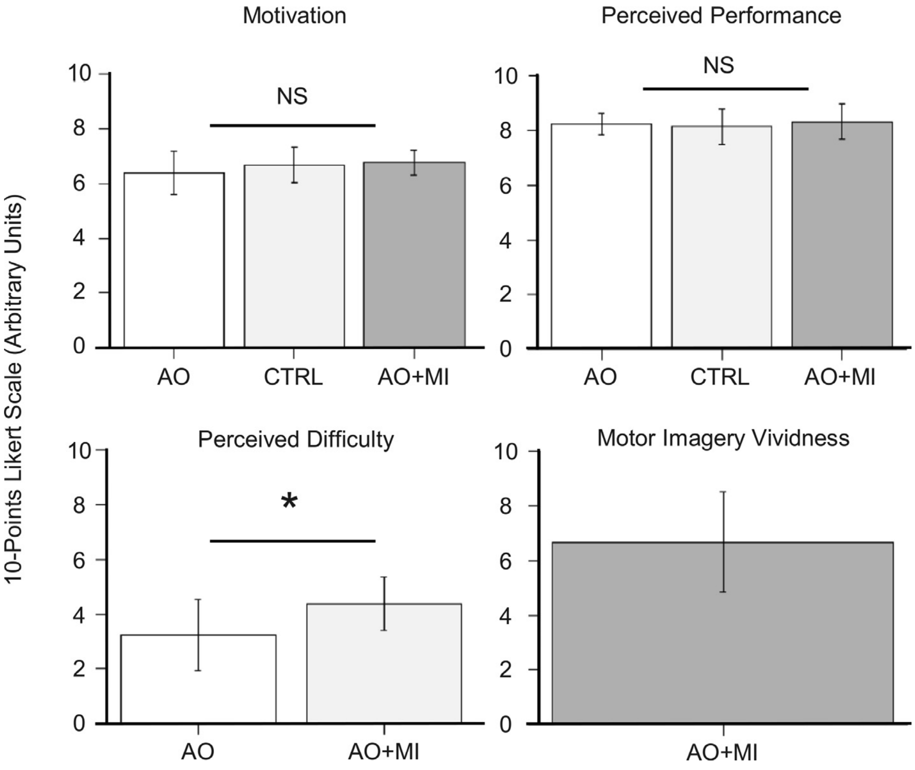

Fig. 2. Barplots with 95% confidence intervals (error bars) of self-reports data on the 10-point Likert scale used for psychometric measures. (A) Perceived motivation across experimental session. (B) Perceived strength during the experimental session. (C) Perceived difficulty during AO and AO + MI. (D) Perceived vividness during AO + MI. NS: Not statistically significant. *: $p < 0.05$.

Analysis of the maximal isometric strength

Raw group values used for normalization (see Materials and methods) of the total force, $\text{iEMG}_{\text{BICEPS BRACHII}}$ and $\text{iEMG}_{\text{ANTERIOR DELTOIDEUS}}$, are provided in Table 1.

The CONDITION × TRIAL and CONDITION × $\text{iEMG}_{\text{BICEPS BRACHII}}$ interactions were removed during the backward stepwise model selection ($\chi^2(2) = 1.91$, $p = 0.38$; $\chi^2(2) = 3.85$, $p = 0.15$, respectively). However, the total force was affected by the TRIAL × $\text{iEMG}_{\text{DELTOIDEUS}}$ interaction ($\chi^2(2) = 7.90$, $p = 0.02$, $\text{Rp}^2 = 0.01$). As shown in Fig. 4, there was a positive relationship between $\text{iEMG}_{\text{DELTOIDEUS}}$ and strength during AO (fitted estimate: 0.09% ± 0.02, $p < 0.01$), but not during Control (fitted estimate: 0.02% ± 0.02, $p = 0.66$) nor AO + MI (fitted estimate: 0.00% ± 0.02, $p = 0.99$).

The total force analysis revealed a main effect of TRIAL ($\chi^2(1) = 90.42$, $p < 0.001$, $R^2_p = 0.10$), $\text{iEMG}_{\text{BICEPS BRACHII}}$ and $\text{iEMG}_{\text{ANTERIOR DELTOIDEUS}}$ ($\chi^2(1) = 53.39$, $p < 0.001$, $R^2_p = 0.12$; $\chi^2(1) = 3.66$, $p = 0.05$, $R^2_p = 0.001$; respectively). As shown in Fig. 4, there was a negative relationship between TRIAL and strength (fitted estimate: −0.94% ± 0.01, $p < 0.001$). Conversely, the relationship between $\text{iEMG}_{\text{BICEPS BRACHII}}$, $\text{iEMG}_{\text{ANTERIOR DELTOIDEUS}}$ and the total force was positive (fitted estimate: 0.17% ± 0.02, $p < 0.001$; fitted estimate: 0.04% ± 0.01, $p = 0.03$, respectively). There was also a main CONDITION effect ($\chi^2(2) = 32.43$, $p < 0.001$, $\text{Rp}^2 = 0.02$). Total force recorded during AO + MI (79.07% ± 19.58) outperformed that recorded during Control (76.47% ± 20.59; fitted difference: 3.68% ± 0.69, $p < 0.001$). Likewise, the total force recorded during AO (78.72% ± 23.17) outperformed that recorded during Control (2.79% ± 0.75 of fitted difference, $p < 0.001$). There was no difference between AO + MI and AO ($p = 0.44$, see Fig. 4).

DISCUSSION

The present experiment investigated the short-term effects of AO and AO + MI on maximal isometric strength. In a previous study, we demonstrated the efficacy of MI practice during the inter-trial recovery periods (Di Rienzo et al., 2015). The performance analysis first revealed a positive relationship between the maximal isometric strength and the activation of primary and secondary agonists of the elbow flexion. This corroborates the well-established relationship between isometric strength and the integrated surface electromyogram (e.g. Moritani and deVries, 1978). The *biceps brachii* activation accounted for 12% of the variance of the maximal isometric strength. This was expected considering the nature of the strength task (Serrau et al., 2012). We also found a positive relationship between the *anterior deltoideus* activation and strength, which also confirmed its assistance function in the present elbow flexion force task (Di Rienzo et al., 2015). Repeated maximal isometric strength efforts lead to a corollary increase in the difficulty to recruit motor units (Kroll, 1968; Babault et al., 2006; Camic et al., 2013). A decrease in strength occurred along with trials repetition, yielding to a 9.46% decrease in maximal isometric strength at the session level. This measure is congruent with the 10% of maximal isometric strength decrease reported by Di Rienzo et al. (2015) in a similar paradigm, and attests participant's commitment to a maximal isometric effort. The nature of the experimental condition did not impact the decrease in strength across trials. Performing AO and AO + MI during inter-trial recovery periods did not attenuate the performance decrease across trials compared to Control. This argues for the relative independence between the mental load associated with mental training and the accumulation of muscle fatigue (Rozand et al., 2014a, 2014b). However, both AO and AO + MI outperformed Control in terms of maximal isometric strength output across all trials of the session. These results confirm a previous report from Di Rienzo et al. (2015), where MI practice yielded no effect on the

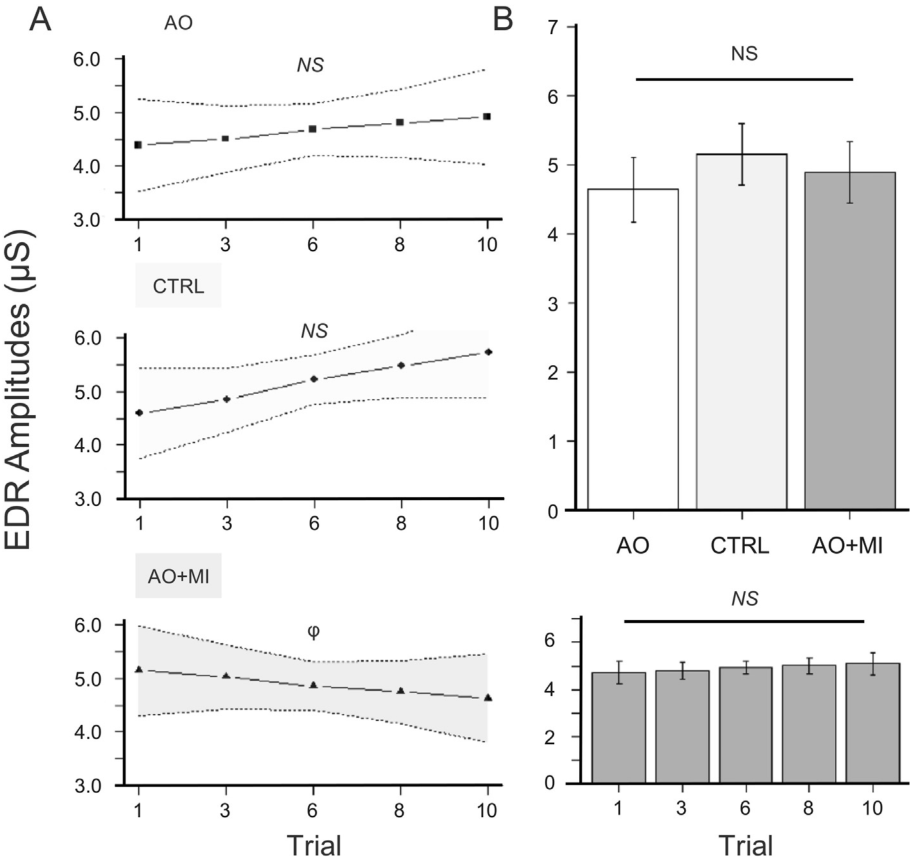

Fig. 3. Linear mixed effects analysis of EDR amplitude. (A) EDR amplitude by TRIAL regression slopes during AO, CONTROL and AO + MI. Regression slopes are represented with 95% confidence interval (dotted lines). (B) Barplot of the main CONDITION (upper panel) and TRIAL (lower panel) effects. Estimates are represented with 95% confidence intervals (error bars). NS: Not statistically significant. φ: $p < 0.10$.

trial-to-trial decrease in strength but enhanced the overall strength output by 2.1–3.5% at the session level (i.e. irrespective of the trial number). Here, short-term improvements during AO and AO + MI ranged from 2.8 to 3.7% compared to Control. Albeit modest, these gains are of practical relevance considering ceiling effects associated with the voluntary repetition of maximal isometric contractions. The literature reported 10–30% improvements in strength after training programs scheduled within a span of several weeks including mental training (Ranganathan et al., 2004; Porro et al., 2007; Lebon et al., 2010; Yao et al., 2013). The levels of perceived performance and motivation to engage in the strength paradigm were similar across experimental conditions. Hence, the superiority of AO and AO + MI compared to Control may not account for psychological factors. We also ruled out the effects of increased attentional focus on the dominant upper limb during inter-trial recovery periods. Indeed, the Control condition also involved a visual exposure to upper limb movements. Skin conductance measures confirmed that the sympathetic activity during maximal isometric strength trials was comparable across conditions. We therefore postulate that there is neurophysiological origin to the short-term beneficial effects of AO and AO + MI on maximal isometric strength.

The psycho-neuromuscular theory hypothesizes that mental training improves muscle function by prompting neural excitability within the neural pathways mediating the forthcoming physical performance. This was advanced as a primary underlying mechanism to the beneficial effects of training with AO and MI on strength (Porro et al., 2007; Di Rienzo et al., 2015; Grosprêtre et al., 2018). Indeed, AO and AO + MI both involve low-threshold facilitation of the corticospinal pathways controlling the corresponding physical performance (Naish et al., 2014; Wright et al., 2014, 2016, 2018). We predicted corticospinal facilitation during the inter-trial recovery periods during AO and AO + MI, but not during Control. In light of the psycho-neuromuscular theory, we suggest that the preliminary activation of the corticospinal pathways controlling the elbow flexion task during AO and AO + MI facilitated the forthcoming maximal voluntary isometric contractions. We thus posit that a priming effect would explain the short-term impact of AO and AO + MI on strength (for illustrations in AO experiments, see Obhi and Hogeveen, 2010; Salama et al., 2011). Priming refers to "*[a] change in behaviour based on previous stimuli*" (Stoykov and Madhavan, 2015, p. 33). At a neurophysiological level, priming originates from short-term plasticity yielding increased cortical gain over motor units (Stoykov and Madhavan, 2015; Stoykov et al., 2017). Priming-related plasticity may first facilitate *intramuscular* coordination, i.e. the capacity of the central nervous system to recruit motor units targeting agonist muscles (Fallentin et al., 1993; Farina et al., 2002; Taylor et al., 2003). Priming-related plasticity can also facilitate *intermuscular* coordination. It involves muscle synergies, e.g. between the *biceps brachii* and *anterior deltoideus*. Reciprocal inhibition represents another central component of intermuscular coordination (Baratta et al., 1988; Hautier et al., 2000; Simoneau et al., 2006). Although necessary for joint stabilization, residual activity in antagonist muscles can affect the development of strength (Hautier et al., 2000).

The strength task involved a primarily quantitative effort. There was thus a potentially confounding factor with regard to participants' uses of AO, which rarely involved achieving physiological arousal goals, as reflected by the low FOLQ performance scores. AO of a bodybuilder could have placed too low demand on the motor system to elicit priming effects. The performance

Table 1. Group averages and 95% confidence intervals for raw total force, $iEMG_{BICEPS\ BRACHII}$ and $iEMG_{ANTERIOR\ DELTOIDEUS}$ corresponding to the best warm-up trial. iEMG: Integrated electromyogram. 95% CI: 95% confidence interval.

Total force		$iEMG_{Biceps\ brachii}$		$iEMG_{Anterior\ deltoideus}$	
Mean	95% CI	Mean	95% CI	Mean	95% CI
2617.34 $mV.s^{-1}$	2276.83–2957.85	7803.91 $mV.s^{-1}$	6063.21–9544.61	2548.14 $mV.s^{-1}$	1546.65–3549.62

analysis did not confirm this statement since AO outperformed CONTROL. It can be objected that characterizing an effect of AO alone would require a control condition without upper-limb movements, e.g. watching a bodybuilder sitting passively in a chair. Such control condition would be relevant although it would not discriminate the reallocation of attentional resources to the upper-limb, which is in itself sufficient to elicit a facilitation of corticospinal pathways (Hiraoka et al., 2013), from task-specific motor simulation. Also, since we did not independently evaluate the effect of AO and MI it may be objected that the experimental design does not make possible to identify what was driving the effects on performance during AO + MI. Considering the recent evidence demonstrating the beneficial effect of MI alone in a comparable design (Di Rienzo et al., 2015), the absence of difference between AO and AO + MI could indicate that MI has in fact no effect on performance. Rigorously disentangling this issue would require including a MI alone condition in the design. Albeit valid, this limitation

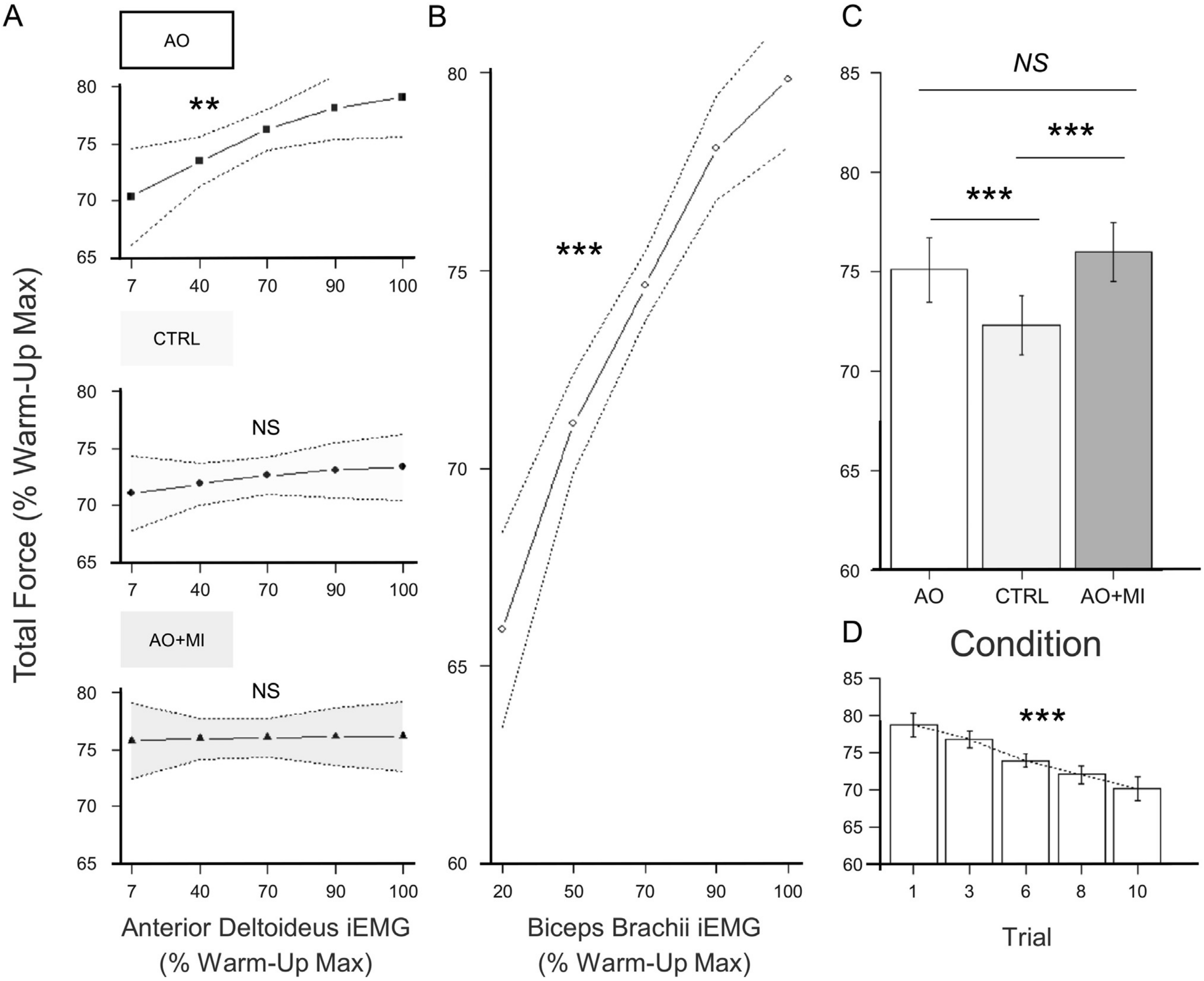

Fig. 4. Linear mixed effects analysis of the total force. (A) Total force by $iEMG_{ANTERIOR\ DELTOIDEUS}$ regression slopes (β_i ± SE) during AO (0.09 ± 0.05), CONTROL (0.02 ± 0.02) and AO + MI (0.00 ± 0.02). Regression slopes are represented with 95% confidence interval (dotted lines). (B) Regression slope (β_i ± SE) between the total force and $iEMG_{BICEPS\ BRACHII}$ (0.17 ± 0.02), irrespective of the CONDITION, represented with 95% confidence interval (dotted lines). (C) Barplot of the estimates for the main CONDITION effect represented with 95% confidence interval (error bars). (D) Barplot of main TRIAL effect (β_i ± SE) on total force (−0.94 ± 0.10), represented with 95% confidence interval (error bars). NS: Not statistically significant. ***: $p < 0.001$. **: $p < 0.01$.

is grounded in the theoretical claim that AO + MI represents a form of combination of AO and MI in the sense of summed cognitive processes. Theoretical framework rather emphasizes a theory of AO + MI where AO + MI should be considered a unitary form of motor cognition that is relatively independent from AO and MI in the sense of:

"*(...) quasi-encapsulated sensorimotor streams, which could either merge or compete depending on their contents and potential usefulness for on-going action plans*" (Eaves et al., 2016b, p. 4).

An important implication is that AO + MI might leverage distinct neurophysiological mechanisms than the practice of AO or MI alone, specifically with regard to priming effects. AO + MI required a voluntary state of attentional focus on the proprioceptive information associated with *biceps brachii* and *anterior deltoideus* contractions, while concomitantly receiving external video cues. Participants were explicitly instructed to rehearse proprioceptive information related to the targeted muscles. This is known to elicit an effector-specific facilitation of the corresponding corticospinal pathways (Wright et al., 2014). In addition, in the video of the bodybuilder, the contraction of the *biceps brachii* was prevalent (Fig. 1). This possibly placed a greater emphasis on this muscle during AO + MI (Calatayud et al., 2016; Eaves et al., 2016b). Accordingly, priming effects during AO + MI possibly favored intramuscular rather than intermuscular coordination. By contrast, AO involved an attentional focus on the whole-limb coordination (Flanagan and Johansson, 2003; Stefan et al., 2008; Richardson et al., 2009), thus suggesting that AO primarily primed intermuscular coordination, and more specifically the synergy between the *biceps brachii* and *anterior deltoideus*. This postulate is congruent with the positive relationship recorded between maximal isometric strength and the integrated electromyograms from both the *biceps brachii* and *anterior deltoideus* during AO, whereas only the integrated electromyogram from the *biceps brachii* predicted the maximal isometric strength during AO + MI.

Contrary to Scott et al. (2018), who emphasized the clinical relevance of AO + MI compared to MI, we did not find any superiority of AO + MI compared to the training condition involving a single method of motor simulation (here AO). The present design examined the performance outcome at the single-session level, and involved the dominant upper-limb. Both aspects represent major differences with the methodological framework adopted by Scott et al. (2018). Also, it is possible that differences between AO + MI and AO would emerge in the case of longer intervention periods targeting the lower-limbs. Another qualitative aspect that might account for differences in the pattern of results is that Scott et al. (2018) trained their participants in the mental rehearsal of a functional task involving the targeted effectors (i.e. Nordic hamstring). By contrast, the mental training intervention embedded within the inter-trial recovery periods in the present study focused on the same task from which we measured the behavioral performance. Overall, the present experimental design was closer to the methodological framework adopted by Smith et al. (2019). These authors reported comparable strength improvements on an elbow flexion task after either AO + MI or MI training (administered in a counterbalanced order across several weeks). We observed comparable results at the single-session level, particularly regarding the benefits of AO + MI (albeit we used an external visual perspective for the AO component of the AO + MI intervention). The present findings provide further original insights to Smith et al. (2019)'s conclusions with regard to equivalent gains following AO + MI and MI alone. If AO + MI represents a unitary form of motor cognition, it is plausible that the effects on strength operate through qualitatively distinct neurophysiological processes than AO or MI alone. Albeit somehow speculative, this could explain why strength gains may not be dissociable from a quantitative analysis of performance. Finally, present strength gains after AO + MI training had reduced magnitude compared to the findings by Scott et al. (2018) and Smith et al. (2019), i.e. 2.5–3.5% increase compared to the control condition versus ~6% and ~15% increase, respectively. Aside from considerations related to the cortical representation of the somatic effectors targeted by mental training (see Yue and Cole, 1992 for pioneering insights), we suggest that the magnitude of strength gains could be primarily related to mental training duration, specifically when the sessions are separately administered from physical training across a span of several weeks.

Conceptually, AO might involve MI to some degree, hence making difficult to control for a strict practice of AO during the AO condition (Vogt et al., 2013; Scott et al., 2018). At this point, no method can provide objective means to control the absence of MI during AO, perhaps with the exception of fMRI. Unfortunately, fMRI is not adapted to ecological situations and revealed largely overlapping neural networks (e.g., Macuga and Frey, 2012). This limitation is inherent to any research on AO. Yet, an interesting methodological approach to address this issue in future designs would be asking participants to rate from a Likert-type scale their degree of MI experience during AO. Obviously, such scores would not represent objective proof that MI did not occur in the AO condition, but would provide some evidence of the amount of MI during AO. Here, the benefits reported for AO are unlikely to represent the concomitant effects of MI practice, for several reasons. First, participants received clear instructions not to engage MI during AO, and just focus attention on the upper limb of the bodybuilder. Therefore, if some MI occurred, it was probably not an explicit process. On the contrary, participants were explicitly instructed to engage in MI during the AO + MI condition. In other words, if some MI occurred during AO, it remains a different form of motor cognition than the deliberate MI practice instructed during AO + MI. In addition, the results advocate for distinct mechanisms underlying the benefits of AO and AO + MI condition, specifically about increased synergies under the AO condition. Eventually, the fact that participants reported that AO + MI was more difficult than AO potentially evidenced a different cognitive strategy under the two conditions. The priming effects of AO and AO + MI occurred without triggering awareness of increased efficacy compared to Control, as attested by the Likert ratings. This finding somehow challenges data by Di Rienzo et al. (2015), where the participants perceived a greater strength during MI practice. MI involves a voluntary process of mental simulation, whereas AO emulates the motor system by engaging the mirror neuron system (Shepard, 1984; Vogt et al., 2013). In AO + MI, the participant primarily engaged in top-down processing of kinesthetic information since the video alleviates for the need of top-down visual processing by providing relevant afferent visual information. Yet, AO + MI required coordinating an internal and an external state of attentional focus. In addition, AO + MI required synchronizing MI with the timing of the video. Overall, this could increase the mental load, presumably eliciting a conflict between the top-down and bottom-up processing of motor information yielding to a negative bias in performance perception. This postulate is congruent with participants' higher perceived difficulty to perform AO + MI compared to AO as well as with the marginally negative relationship between the number of trials and the EDR amplitudes present during the AO + MI condition only. EDR amplitudes are strongly linked with attentional processes, and more specifically the allocation of mental resources to face the cognitive workload of the task (Collet et al., 2011, 2013). Overall, the increased perceived difficulty of AO + MI compared to AO and Control was associated with autonomic nervous system response patterns attesting an increased mental fatigue state.

To the best of our knowledge, this is the first study investigating the short-term effectiveness of mental training including AO on maximal isometric strength. Previous research demonstrated the potential relevance of AO + MI to improve strength over the course of several weeks of training (Sun et al., 2016; Scott et al., 2018; Smith et al., 2019). The present study extends these findings and demonstrates that both AO and AO + MI increased strength at the single-session level. Increased training intensity at the session level contributes to enhance the workout load of longer training programs. Considering the importance of training intensity in strength development (Kraemer et al., 1996; Fleck and Kraemer, 2014), this may be an underlying process to the benefits of resistance training programs combining physical training with AO and AO + MI (Porro et al., 2007; Scott et al., 2018). Interestingly, AO and AO + MI facilitated strength without increasing participants' own performance perception. They even experienced a greater difficulty to perform AO + MI than AO, which was associated with decreased EDR amplitudes across trials. This result has important practical implications. Implementation of AO + MI during training might increase the mental workload for athletes while concomitantly contributing to increase their performances. While we assumed a neurophysiological origin to the beneficial effects of AO and AO + MI on maximal isometric strength through priming effects on corticospinal facilitation, this remains a working hypothesis considering the nature of the study design. Confirming this interpretation of the results would require replicating the design with direct measures of neural excitability within pathways targeting agonist and antagonist muscles. This could be implemented in future designs with transcranial magnetic stimulation and electroencephalographic measures.

ACKNOWLEDGMENTS

This work was conducted within the facilities of the sport sciences of the University Claude Bernard Lyon 1. There was no funding from organizations for this work. The authors declare no competing interests.

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(Received 7 February 2019, Accepted 12 August 2019)
(Available online 20 August 2019)