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**Research article**

# The Combination of Motor Imagery and Post-Activation Performance Enhancement is Efficient to Emphasize the Effects of Warm-Up on Sport-Specific Performance

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## Abstract
Motor imagery (MI) or post-activation performance enhancement (PAPE) have shown acute benefits for sports performance. The aim of the present study was to investigate the cumulative effects of MI and PAPE when combined within a warm-up routine. Ten men boxers participated in this study. They underwent four experimental sessions composed of a standardized warm-up followed by 1) maximal leg press extensions (CONTROL-PAPE), 2) mental imagery of force and sprint tasks (CONTROL-MI), 3) maximal leg press extensions followed by mental imagery of force and sprint tasks (PAPE-MI) and 4) mental imagery of force and sprint tasks followed by then maximal leg press extensions (MI-PAPE). Post-tests consisted of boxing reaction time, average and maximal boxing force, maximal handgrip strength, repeated sprint ability and the NASA-TLX fatigue questionnaire. No difference was obtained between PAPE-MI and MI-PAPE for the different measurements. Compared to CONTROL-PAPE and CONTROL-MI, both the PAPE-MI and MI-PAPE significantly enhanced boxing average force ($P < 0.05$) and repeated sprint ability ($P < 0.01$). Compared to CONTROL-PAPE, both the PAPE-MI and MI-PAPE increased boxing reaction time ($P < 0.05$), PAPE-MI increased the handgrip strength ($P < 0.05$) and MI-PAPE increased boxing maximal force ($P < 0.01$). Compared to CONTROL-MI, both the PAPE-MI and MI-PAPE increased boxing maximal force ($P < 0.001$), handgrip strength ($0 < 0.01$) and MI-PAPE increased boxing reaction time ($P < 0.05$). The NASA-TLX questionnaire was not affected by the warm-up modalities ($P = 0.442$). Combining PAPE-MI and MI-PAPE protocols within the warm-up produced cumulative positive effects on acute muscular performance without increasing subjective fatigue. PAPE-MI and MI-PAPE are both interesting modalities for optimizing warm-up routines.

**Key words:** Agility, repeated sprint ability, reaction time, subjective fatigue, boxing.

## Introduction

It is generally accepted that warm-up, the primary routine prior to any training session or competition, improves the performance of athletes and reduces the risk of injury (Ghasemi et al., 2013). Whether thermo-dependent or -independent (Bishop, 2003), warm-up mechanisms generally modulate the cardiovascular, neuromuscular and cognitive systems (González-Fernández et al., 2022; Babault et al., 2022) and have an impact on subsequent physical, psychological, cognitive as well as technical performance.

Athletes have the option of performing active or passive warm-up exercises, depending on the presence or absence of physical activity, respectively (Bishop, 2003). Active warm-up strategies are generally the most widely used (Schilling and Stone, 2000). They include a variety of low to high intensities activities such as running, stretching or activity-specific exercises (Schilling and Stone, 2000). Many studies have recommended using high-intensity contractions at the very end of warm-up routines to emphasize warm-up and focusing on the muscular system (Kilduff et al., 2008; Zois et al., 2015; Rumeau et al., 2023). Frequently named post-activation potentiation, this mechanism is now referred to as post-activation performance enhancement (PAPE) without any direct evidence for the specific post-activation potentiation effect (Blazevich and Babault, 2019). Particularly, PAPE describes the phenomenon by which a high intensity conditioning contraction lead to an enhancement of maximal performance (Blazevich and Babault, 2019). Today, these high-intensity conditioning contractions have become very popular and time-efficient for acutely enhancing the neuromuscular system for power- or even explosive-type actions it (Dos Anjos et al., 2022).

In contrast, passive warm-up does not require any voluntary contractions. It is achieved, for example, by using hot conditions such as clothes or warm rooms and has been shown to be very effective in optimizing the neuromuscular function (Bishop, 2003). Among passive warm-up modalities, motor imagery (MI) may be of interest for its central effect. MI is defined as the process by which an individual mentally represents an action, without physically performing it (Dos Anjos et al., 2022). This technique is one of the most widely used simulation tools in sports psychology interventions (Slimani et al., 2016). Acute MI associated effects include an increase in motivation, a decrease in anxiety or even an increase in motor performance while enhancing strength and coordination (Guillot and Collet, 2008; Dos Anjos et al., 2022). MI has also been shown to acutely increase the excitability of motor brain regions and circuits of the spinal cord that are normally activated during real movements (Grosprêtre et al., 2016; 2019). In a previous study (Rumeau et al., 2023), MI, when applied within a comprehensive warm-up, was shown to increase repeated sprinting and agility performance without increasing the subjective load of the warm-up. Interest-

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ingly, the gains after MI were only observed during the imagined tasks and were of similar amplitude to those obtained after a PAPE procedure. However, because MI has only central origins, the subsequent effects cover a smaller range of the neuromuscular performance as compared to PAPE.

MI and PAPE therefore appeared to be two interesting modalities for optimizing a warm-up (Rumeau et al., 2023). Because of their characteristics (very brief high-intensity contractions for PAPE or no contractions for MI), and because they are diametrically opposed in terms of peripheral or central contributions, both PAPE and MI could be combined to emphasize their isolated effects. This could further enhance the neuromuscular performance without increasing the physical and mental demands of warm-up. For example, it has been shown that an MI session comprising 80 imagined contractions did not induce neuromuscular fatigue, even when these contractions were combined with 80 real contractions (Rozand et al., 2014). However, the effect of a such combination and the effective order of application of these techniques (PAPE then MI or vice versa), remains to be determined. Accordingly, the aim of the present study was to compare the effects of PAPE and MI in isolation or in combination on some sport-specific tasks. We hypothesized that the combination of MI and PAPE would be more effective than either PAPE or MI alone. Because PAPE has a beneficial effect for a duration of less than 15 minutes (Blazevich and Babault, 2019), we further hypothesized MI followed by PAPE would be more effective than PAPE followed by MI. This study was carried out on elite boxers from the French men's team. As both the PAPE and MI are applicable in the field, this study will provide useful information for the practitioner to optimize warm-up routines.

## Methods

### Experimental approach to the problem

This study was a cross-over, randomized, controlled trial. All participants came to the laboratory on five separate occasions (familiarization and four experimental conditions) with at least 24h between sessions. During the four randomized experimental sessions, participants started with a 10-minutes standardized warm-up followed by baseline tests. Participants then completed one of the four experimental conditions, according to randomization and finally took part in post-tests.

### Subjects

Ten men from the French national boxing team were included in this study. Participants characteristics are presented in Table 1. Throughout the study, the physical load was standardized for all participants. None reported any injuries within the last three months. Prior to participation, they were fully informed of the purpose of the study and the experimental procedure. However, participants were blinded to our *a priori* hypothesis. All signed an informed consent form. This study was conducted according to the declaration of Helsinki. Approval was obtained from the CERSTAPS (ethics committee for research in sports sciences; IRB00012476-2022-15-03-165).

### Procedures

All participants came to the laboratory on five separate occasions (one familiarization and four experimental conditions) with a minimum of 24h between sessions (Figure 1). All experimental sessions were performed at the same hour of the day (in the morning, 2h after a standardized breakfast).

**Table 1. Characteristics of the volunteers.**

| Characteristics | Mean ± SD (Range) |
|---|---|
| **Age (year)** | 22.7 ± 2.8 (18; 27) |
| **Height (cm)** | 181.8 ± 8.0 (171.0; 201.0) |
| **Body mass (kg)** | 77.4 ± 12.4 (63.5; 105.2) |
| **Percent fat mass (%)** | 9.8 ± 3.2 (4.5; 14.2) |
| **Weekly training volume (hours per week)** | 13.2 ± 3.2 (10.0; 19.0) |
| **Weekly strength training volume (hours per week)** | 4.9 ± 2.4 (8.0; 2.0) |
| **Weekly boxing training volume (hours per week)** | 8.3 ± 1.7 (11.0; 7.0) |

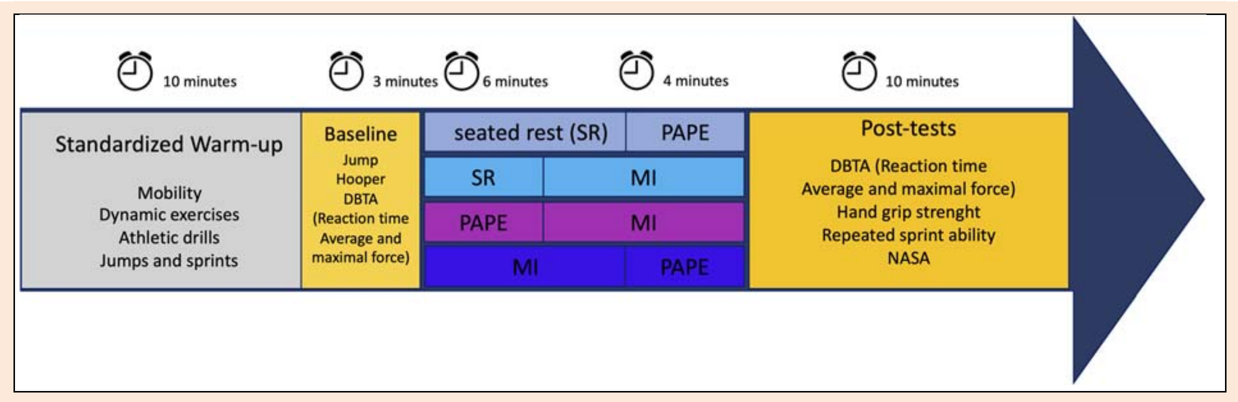


**Figure 1. Overview of the study design.** CONTROL-PAPE: control condition including a standardized warm-up, sitting rest (SR) and then standardized maximal contraction named PAPE (post-activation performance enhancement). CONTROL-MI: control condition including standardized warm-up, SR followed by standardized motor imagery (MI). PAPE-MI: standardized warm-up followed by SR, PAPE and then MI. MI-PAPE: standardized warm-up followed by SR, MI and then PAPE. DBTA; digital boxing trainer assistant. NASA-TLX (NASA-task load index): subjective fatigue questionnaire.

The familiarization session aimed to (i) explain the experimental procedure, (ii) determine anthropometrics (age, height, body mass and percentage of fat mass), leg press one-RM (repetition maximum) and MI ability, and (iii) familiarize the participants with the different tests and warm-up exercises. Body mass and percentage of fat mass were measured using Dual-energy X-ray Absorptiometry (DEXA) scan (Hologic Discovery A, WA, USA). During this session, participants completed the 3rd version of the Movement Imagery Questionnaire (MIQ-3) (Robin et al., 2020) to determine volunteers' self-estimation of MI ability. The initial mean MIQ-3 score was 14.3 ± 2.1 out of 21, indicating a good imagery ability in all participants. The one-RM leg press was assessed using five different loads and individually adjusted increments. Participants were requested to lift each load only once. Three minutes rest was allowed between trials.

During the four randomized experimental sessions, participants completed a 10-minutes standardized warm-up. This was immediately followed by baseline tests that served to control for baseline fitness. Then, the participants did one of four experimental conditions according to randomization: PAPE (CONTROL-PAPE), MI (CONTROL-MI), PAPE immediately followed by MI (PAPE-MI), MI immediately followed by PAPE (MI-PAPE) (Figure 1). Immediately after these experimental conditions, participants took part in post-tests.

### Standardized warm-up

During the standardized warm-up (Rumeau et al., 2023), participants performed two minutes of joint mobility (~10 rotations for shoulder, hip exterior/interior, hip flexion/extension, hip abduction/adduction, pelvis, knee and ankle joints). Once this was completed, they performed three minutes of dynamic exercises including: 1) three sets of 20 bodyweight lunges (alternating the left and right side) interspersed with 30 seconds of rest, 2) three sets of 10 bodyweight front squats and, 3) 12 repetitions of rubber band chest pulls (15 kg rubber band resistance). For this last exercise, the starting position was arms parallel to each other and to the floor, holding each end of the rubber band. Then, arms move to the side, remaining parallel to the floor, until the rubber band touched the chest. The participants then performed three minutes of athletic drills (two sets of 28 meters for each exercise) including: heel to toe, tipping, bouncing strides. Finally, participants did two minutes of high-intensity exercises including: three jumping squats and three sets of 28 meters of running at 75%, 85% and 95% of the self-esteemed maximal sprinting velocity with 30 seconds between each exercise.

### Baseline

Baseline tests served to control the fitness level and to ensure a daily reproducibility between the different experimental sessions. They immediately followed the standardized warm-up and included measurements of the vertical jump height, boxing performance and subjective rating. Participants first performed two counter movement jumps (CMJ), separated by a 2-minutes recovery period. The volunteers had to bend their knees to a 90° knee joint angle and jump as high as possible while maintaining their arms akimbo. Volunteers were instructed to have the same positioning during landing as during take-off. To make it easier, volunteers were requested to have 2 - 3 bouncing with straight legs immediately after landing. Jump height was measured in cm using optometric cells placed on the ground and was associated with a camera to control joint angle (Optojump Next, Microgate Italy, Bolzano, Italia). The best trial was retained for analyses. Participants then performed the digital boxing trainer assistant test (DBTA) (Nikko Sports, Eindhoven, Nederland). The DBTA test consisted of reacting as quickly and as hard as possible to the appearance of a light on a punching area and hitting the correct area. Three sets of 10 seconds (four to six strikes, depending on boxer's performance in reaction) were performed with 20 seconds of recovery in-between. The program used was "reac-V", a personalized program (DBTA - Nikko Sports, Eindhoven, Nederland). The average reaction time (A-RT), average force (A-F) and maximal force (M-F) were measured. The intraclass correlation coefficients (ICC(3,1)) for these three variables were 0.880, 0.911 and 0.895 for A-RT, A-F and M-F, respectively. Coefficients of variation were 10.3, 7.4 and 9.1 for A-RT, A-F and M-F, respectively. These values revealed good reliability for these different measurements. Finally, the HOOPER questionnaire was completed. It was composed of eight items (fatigue, psychological stress, sleep, muscle pain, enthusiasm for training, irritability, health, recovery), each of which was scored from 1 to 7 (Hooper and Mackinnon, 1995). The sum of the individual scores was calculated and used as the Hooper index in the statistics.

### PAPE

PAPE protocol was performed with maximal contractions on a leg press machine (Pure Leg Press, Technogym, Technogym France Sas, Issy les Moulineaux). Participants were first asked to perform a 15-s bilateral isometric contraction with a 120 ° joint angle at 85% of their subjective maximum. After 3 minutes of recovery, participants then performed five bilateral concentric contractions at 90% of their one-RM with 5 seconds rest between repetitions. The range of motion was from 110 ° knee flexion until the maximal knee extension. This procedure took a total of 4 minutes.

### MI

MI protocol consisted of mentally performing four exercises in a row, two DBTA tests, then a grip test, followed by a repeated sprint ability test (RSA). The exercises were interspaced by 30 seconds recovery. Participants were instructed to imagine doing their maximal performances. Each exercise was preceded by a verbal signal from the experimenter. Participants were asked to verbally indicate when they had finished imagining the movement. MI condition lasted a total of 6 minutes.

During the CONTROL-PAPE, volunteers first remained seated for 6 minutes and then performed the 4-minutes PAPE procedure. During the CONTROL-MI, volunteers remained seated for 4 minutes and then performed the 6-minutes MI procedure. For PAPE-MI and MI-PAPE, the two procedures followed each other with no rest (Figure 1).

### Post-tests

They were administered immediately after the four experimental conditions, always in the same order: DBTA test, grip test, RSA test and NASA-TLX questionnaire. One minute rest was allowed between tests. The DBTA test followed the same procedure as previously described. The grip test was performed using a digital handgrip dynamometer (CAMRY, model: SCACAM-EH101, South El Monte, USA). The participant had to sit in an upright position and place the forearm of the dominant hand on a standard table in full supination. Prior to the start of the measurement, all participants had the opportunity to pull the handle twice to familiarize themselves with the device. The handle was pulled with maximum force for three seconds followed by five seconds of relaxation under supervision of the experimenter. This procedure was repeated three times with the dominant hand. Participants were verbally motivated during the measurement to continue using their maximum strength and to complete all repetitions. The dynamometer measured the highest value achieved within the three seconds (force measurement in kg). The attempt with the highest measurement out of the three repetitions was considered as the maximal strength. RSA consisted of six consecutive straight sprints over 10 seconds on Assault Bike classic model (Assault Fitness Products; Carlsbad, CA, USA) (Ponce-García et al., 2021), with 20 seconds of passive recovery between sprints. The bike is an air-resisted bike with the peculiarity of using both upper and lower extremities simultaneously. Performance in this test was measured as the total distance (metres) covered during the test. The result in meters was directly calculated and displayed by the bike computer dial. Participants started each sprint in a standardized position (forefoot in the pedals, hand on the top of the handlebars, in a stationary position). Finally, the NASA-TLX questionnaire was a subjective questionnaire assessing internal workload with six items (Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, Frustration). Increments of high, medium and low estimates for each item result in 21 gradations. Participants were asked to answer questions by ticking feeling boxes. The scores were then summed, and the total was retained (Hart and Staveland, 1988).

### Statistical analyses

The normality and sphericity of the data were tested and confirmed by the Shapiro-Wilk and Mauchly's tests. All variables were analysed using a one-way repeated-measures analysis of variance (ANOVA) with warm-up as the main factor (CONTROL-PAPE vs. CONTROL-MI vs. PAPE-MI vs. MI-PAPE). In case of a significant effect, a post-hoc test with Bonferroni correction was performed. In addition, effect sizes were quantified. Partial-eta-squared ($\eta_p^2$) was calculated from ANOVA results, with values of 0.01, 0.06, and above 0.14 representing small, medium, and large differences, respectively (Cohen, 1969). Subsequently, qualitative descriptors of standardized effects were used for pairwise comparisons with Cohen's d, <0.5, 0.5 - 1.2 and 1.2 representing small, medium, and large magnitudes of change, respectively (Cohen, 1969). $P < 0.05$ was taken as the level of statistical significance for all comparisons. Absolute values are expressed as mean ± SD or mean difference with 95% confidence intervals (95%CI). Statistics were preformed using the JASP Software (version 0.13, JASP Team (2020), University of Amsterdam).

## Results

Baseline values are shown in Figure 2. No difference was obtained between the different conditions for the CMJ (P = 0.134, $\eta_p^2$ = 0.153, large), A-F (P = 0.964, $\eta_p^2$ = 0.008, small), A-RT (P = 0.919, $\eta_p^2$ = 0.015, medium), M-F force (P = 0.929, $\eta_p^2$ = 0.014, medium) and Hooper questionnaire (P = 0.924, $\eta_p^2$ = 0.014, medium).

For the post-tests, the one-way ANOVA showed significant warm-up effects for A-RT (P < 0.001, $\eta_p^2$ = 0.482, large), A-F (P < 0.001, $\eta_p^2$ = 0.599, large), M-F (P < 0.001, $\eta_p^2$ = 0.489, large), handgrip strength (P = 0.001, $\eta_p^2$ = 0.434, large) and RSA (P < 0.001, $\eta_p^2$ = 0.682, large). In contrast, no significant difference was observed for the NASA-TLX questionnaire (P = 0.442, $\eta_p^2$ = 0.093, medium).

Post-hoc analyses revealed that A-RT during the boxing test was significantly lower for PAPE-MI (mean difference (95%CI): -0.029 (-0.003; -0.055), d = -0.348, small, P = 0.022) and MI-PAPE (mean difference (95%CI): 0.042 (-0.016; -0.068), d = -0.502, medium, P < 0.001) as compared to CONTROL-PAPE (Figure 3A). In addition, MI-PAPE was significantly lower than CONTROL-MI (mean difference (95%CI): -0.032 (-0.005; -0.058), d = -0.375, small, P = 0.012). No difference was observed between PAPE-MI and CONTROL-MI (mean difference (95%CI): 0.019 (-0.008; 0.045), d = 0.222, small, P = 0.319), PAPE-MI and MI-PAPE (mean difference (95%CI): 0.013 (-0.013; 0.039), d = 0.154, small, P = 1.000) and between CONTROL-PAPE and CONTROL-MI (mean difference (95%CI): 0.011 (-0.016; 0.037), d = 0.126, small, P = 1.000).

Post-hoc analyses revealed that A-F during the boxing test was significantly greater for PAPE-MI (mean difference (95%CI): 8.78 (14.42; 3.13), d = 0.685, small, P < 0.001) and MI-PAPE (mean difference (95%CI): 9.37 (15.01; 3.72), d = 0.732, small, P < 0.001) as compared to CONTROL-PAPE (Figure 3B). A-F was also significantly greater for PAPE-MI (mean difference (95%CI): 8.42 (14.06; 2.78), d = 0.658, small, P = 0.001) and MI-PAPE (mean difference (95%CI): 9.01 (14.65; 3.37), d = 0.704, small, P < 0.001) as compared to CONTROL-MI (Figure 3B). No difference was observed between PAPE-MI and MI-PAPE (mean difference (95%CI): -0.59 (-6.23; 5.05), d = -0.046, small, P = 1.000) and between CONTROL-PAPE and CONTROL-MI (mean difference (95%CI): -0.35 (-5.99; 5.28), d = -0.028, small, P = 1.000).

Post-hoc analyses revealed that M-F during the boxing test was significantly greater for MI-PAPE (mean difference (95%CI): 19.20 (34.35; 4.04), d = 0.625, small, P = 0.007) as compared to CONTROL-PAPE (Figure 3C). M-F was also significantly greater for MI-PAPE (mean difference (95%CI): 23.20 (38.35; 8.04), d = 0.755, small, P = 0.001) and for PAPE-MI (mean difference (95%CI): 17.90 (33.05; 2.74), d = 0.583, small, P = 0.009) as compared to CONTROL-MI (Figure 3C). In addition, no difference was observed between PAPE-MI and CONTROL-PAPE (mean difference (95%CI): -13.90 (-29.05; 1.25), d = -0.453, small, P = 0.087), between PAPE-MI and MI-PAPE (mean difference (95%CI): -5.30 (-20.45; 9.85), d = -0.173, small, P = 1.000) and between CONTROL-PAPE and CONTROL-MI (mean difference (95%CI): 4.00 (-11.15; 19.15), d = 0.130, small, P = 1.000) (Figure 3C).

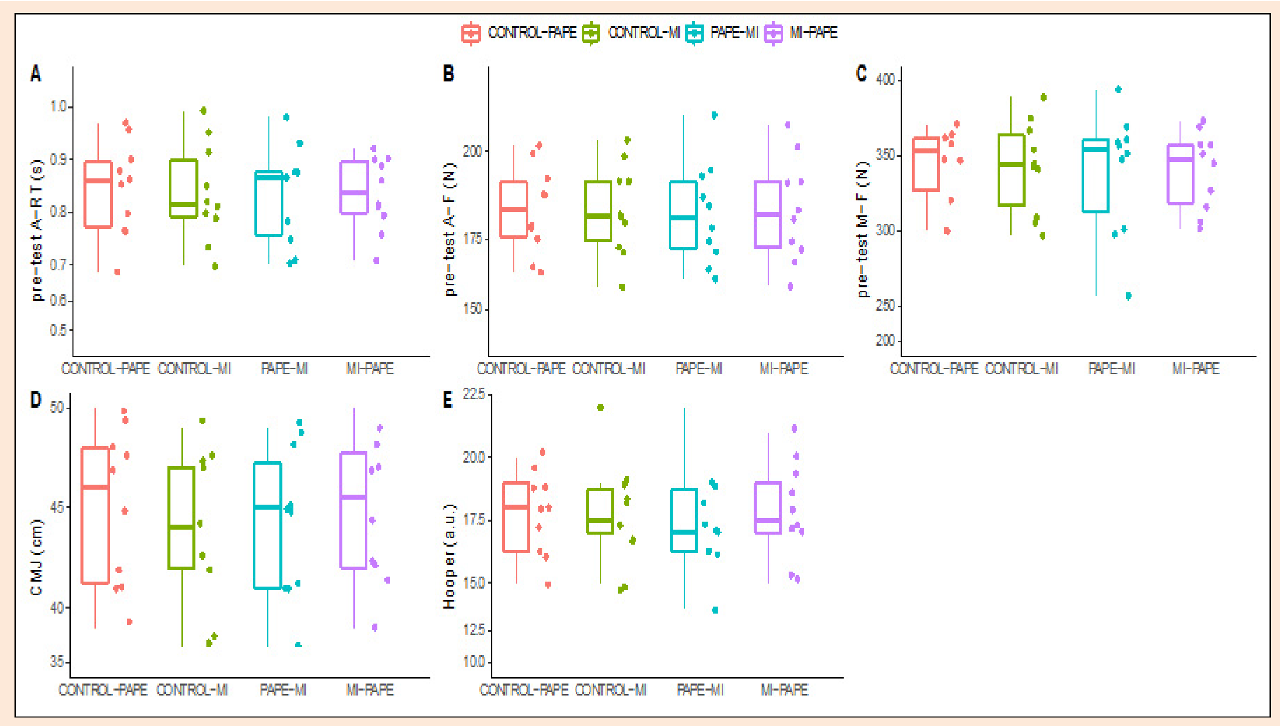


**Figure 2. Whisker plots during baseline tests of the boxing average reaction time (A-RT) (A), boxing average force (A-F) (B), boxing maximal force (M-F) (C), counter movement jump performance (CMJ) (D), Hooper-Mackinnon questionary (Hooper) (E).** CONTROL-PAPE and CONTOL-MI: control conditions including PAPE and MI alone, respectively. PAPE-MI and MI-PAPE: experimental conditions including PAPE followed by MI and MI followed by PAPE, respectively.

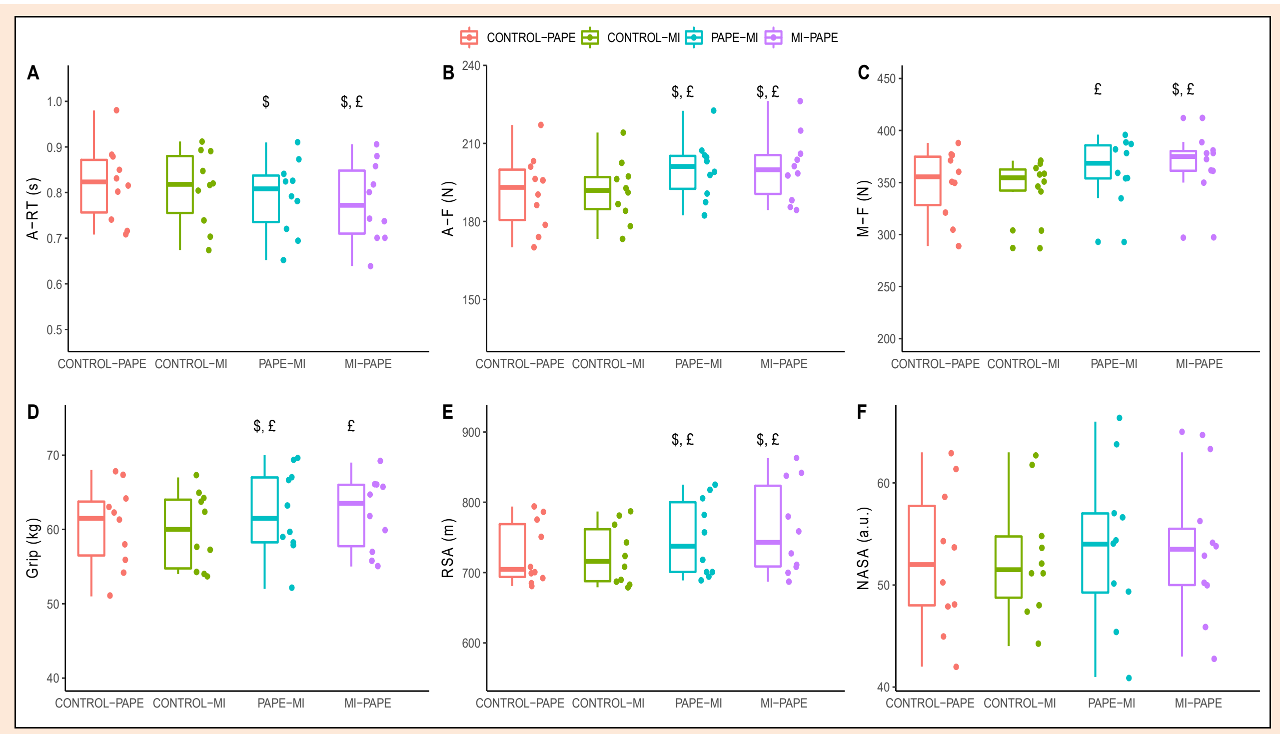


**Figure 3. Whisker plots during post-tests of the boxing average reaction time (A-RT) (A), boxing average force (A-F) (B), boxing maximal force (M-F) (C), handgrip strength (GRIP) (D), repeated sprint ability (RSA) (E), NASA-Task load index questionary (NASA) (F).** CONTROL-PAPE and CONTOL-MI: control conditions including PAPE and MI alone, respectively. PAPE-MI and MI-PAPE: experimental conditions including PAPE followed by MI and MI followed by PAPE, respectively. $: difference compared to CONTROL-PAPE with P < 0.05. £: difference compared to CONTROL-MI with P < 0.05.

For handgrip strength, post-hoc analyses revealed that it was significantly greater for PAPE-MI (mean difference (95%CI): 1.90 (3.78; 0.01), d = 0.354, small, P = 0.047) as compared to CONTROL-PAPE (Figure 3D). Handgrip was also significantly greater for PAPE-MI (mean difference (95%CI): 2.40 (4.28; 0.51), d = 0.447, small, P = 0.007) and for MI-PAPE (mean difference (95%CI): 2.30 (4.18; 0.41), d = 0.429, small, P = 0.010) as compared to CONTROL-MI (Figure 3D). No difference was observed between MI-PAPE and CONTROL-PAPE (mean difference (95%CI): -1.80 (-3.68; 0.08), d = -0.335, small, P = 0.068), between PAPE-MI and MI-PAPE (mean difference (95%CI): 0.10 (-1.78; -1.98), d = 0.019, small, P = 1.000) and between CONTROL-PAPE and CONTROL-MI (mean difference (95%CI): 0.50 (-1.38; 2.38), d = 0.093, small, P = 1.000).

Post-hoc analyses revealed that RSA performance was significantly greater for PAPE-MI (mean difference (95%CI): 21.90 (38.04; 5.75), d = 0.416, small, P = 0.004) and for MI-PAPE (mean difference (95%CI): 34.30 (50.44; 18.15), d = 0.651, small, P < 0.001) as compared to CONTROL-PAPE (Figure 3E). RSA was also significantly greater for PAPE-MI (mean difference (95%CI): 24.10 (40.24; 7.95), d = 0.458, small, P = 0.001) and for MI-PAPE (mean difference (95%CI): 36.50 (52.64; 20.35), d = 0.693, small, P < 0.001) as compared to CONTROL-MI (Figure 3E). No difference was observed between PAPE-MI and MI-PAPE (mean difference (95%CI): -12.40 (-28.54; 3.74), d = -0.235, small, P = 0.226) and between CONTROL-PAPE and CONTROL-MI (mean difference (95%CI): 2.20 (-13.94; 18.34), d = -0.042, small, P = 1.000).

## Discussion

PAPE and MI have been shown to be effective strategies during warm-up routines to increase athletic and cognitive performance (Rumeau et al., 2023). Accordingly, the present study aimed to investigate the acute effects of a warm-up combining both PAPE and MI in different orders. The main findings were as follows: 1) PAPE-MI and MI-PAPE induced significant improvements in muscular force and repeated muscular force capacities, handgrip strength, reaction time and repeated sprint capacities, as compared to either PAPE or MI alone, 2) no significant difference was obtained between PAPE-MI and MI-PAPE, 3) PAPE-MI or MI-PAPE did not alter subjective fatigue ratings (NASA-TLX) as compared to CONTROL conditions (MI and PAPE alone) after the different warm-up strategies. These results support our hypotheses that the combination of PAPE and MI was more effective than PAPE or MI alone in enhancing the effects of a traditional warm-up without causing additional subjective fatigue. Contrary to our hypothesis, the order of PAPE and MI had no effect on the subsequent performance improvement.

PAPE procedures have already been shown to be beneficial in increasing maximal muscle strength and the overall muscle function (Petisco et al., 2019; Gilmore et al., 2019; Rumeau et al., 2023). It is of particular interest in elite athletes (as in our study) who are more likely positive responders to PAPE for their specific skills (Boullosa, 2021). Whether it was with submaximal and maximal half-squats (Petisco et al., 2019), half-squats followed by vertical jumps,(Lagrange et al., 2020) maximal concentric knee extensions (Rumeau et al., 2023), conditioning activities (Petisco et al., 2019; Lagrange et al., 2020) or bodyweight plyometric exercises (Turner et al., 2015), the results are positive for the performance of the neuromuscular system. With a near-maximal muscle activation, the type of exercise does not seem to have a significant effect on the subsequent increase in muscle performance as also shown following eccentric overload or weightlifting exercises (Beato et al., 2019). PAPE is a long-lasting phenomenon with potential positive effects between 5 and 30 minutes after the conditioning exercise (Kilduff et al., 2008; Gouvêa et al., 2013). The greater effects are expected between 5 and 10 minutes after the conditioning contractions (Blazevich and Babault, 2019). Authors have often concluded that a recovery period should be programmed to alleviate the likely fatigue originating from the preceding maximal contractions (Mola et al., 2014; Turner et al., 2015). For example, Gilmore et al. observed an increased bat speed in experienced female softball players 6 minutes after a high-intensity isometric preconditioning of upper limb muscles involved in bat swing (Gilmore et al., 2019).

MI, which involves neural activity without any contractions, has also been shown to be effective in improving agility and sprint performance when used acutely (Hammoudi-Nassib et al., 2014; Rumeau et al., 2023), and muscle strength, power and endurance-type efforts when used chronically (McCormick et al., 2015; Tod et al., 2015; Slimani et al., 2016). MI primarily increases the neural circuitry normally activated during actual movement (Grosprêtre et al., 2019) and acutely increases the excitability of a large part of the cortico-spinal pathway (Grosprêtre et al., 2016). These effects can persist for at least 10 minutes after the end of MI (Grosprêtre et al., 2019). MI results in activation of motor regions of the brain (Munzert and Zentgraf, 2009), especially when participants have a high level of expertise in sports performance, i.e., when they are elite athletes (Guillot et al., 2013), as the participants under investigation here. Recently, it has been shown that MI can have acute effects on force performance, mainly by inducing a more efficient cortical drive to motor units to optimize agonist/antagonist coactivation (Dos Anjos et al., 2022). However, the activation of the motor neural system still remains weaker than during voluntary contraction (Ehrsson et al., 2003), MI being potentially an intermediate state of activation between rest and voluntary contraction (Bouguetoch et al., 2020).

According to these effects, the present study applied a combination of PAPE and MI, which could exacerbate the expected performance improvements by combining their complementary actions on the neuromuscular system. Our results showed that the combination of PAPE and MI was more effective than our control conditions applying PAPE or MI alone for repeated sprint capacities, force capacities and repeated force capacities. The effectiveness of a warm-up can be explained by several parameters, namely a difference in cellular water content, a difference in muscle temperature and a difference in muscle activation (Blazevich and Babault, 2019). The results of our study were probably due to this last parameter, greater muscle activation. In fact, whether the warm-up included PAPE or MI, some neuromuscular changes have been suggested after warm-up as evidenced by an increase in electromyographic activity (Grosprêtre et al., 2019; Babault et al., 2022), suggesting an optimised neuromuscular state for subsequent muscular contractions. Authors have suggested that warm-up exercises could exacerbate the neural adaptations (Babault et al., 2022) and would produce an additional recruitment facilitation that would improve movement quality and subsequent muscular contractions (Parr et al., 2017). Combining the two conditions, PAPE and MI, during a warm-up could exacerbate this phenomenon, leading to further improvements in maximal or repeated force production, and repeated sprint capacity. Additional neuromuscular measurements including electromyographic activity should therefore be conducted to confirm such a hypothesis.

Furthermore, the combination of the PAPE and MI was more effective to increase reaction time as compared to control conditions applying PAPE or MI alone. As a reminder, reaction time tasks were involved during mental imagery via the boxing task. Therefore, improvements in this task were expected after all MI conditions, due to the specificity of mental imagery (Grosprêtre et al., 2016). In contrast, the effects of MI alone did not differ from PAPE alone, both in a lesser extent than both combinations of PAPE and MI. Such a discrepancy could be attributed to neural activation. Indeed, as mentioned above, the warm-up produced an optimised neuromuscular state that could emphasize subsequent improvements for example during tasks with high attentional and neural activation such as during a reaction time task. Therefore, a summation effect is hypothesized after the combination of PAPE and MI, which could exacerbate the likely corticospinal adaptations. Indeed, there are several clues from fundamental previous works that the combination of actual movements and motor imagery might produce a larger activation of the neuromuscular system as compared to MI alone (Grosprêtre et al., 2016). Therefore, combining MI and voluntary contraction at a high level of force might produce an even greater activation in fine, notably by enhancing the excitability of structures along the neuromuscular system. For instance, the spinal neuronal network might particularly beneficiate from combining MI and PAPE, in which an increase of excitability lead to a better recruitment of motor units. Indeed, both MI (Grosprêtre et al., 2019) and PAPE (Blazevich and Babault, 2019) seems to acutely increase the excitability of such networks. The combination of both modalities might then lead to a cumulative effect at a neural level.

Contrary to our a priori hypothesis, there was no effect of the order in which PAPE and MI were performed. This finding is surprizing while considering that PAPE often requires a recovery to alleviate possible neuromuscular fatigue. PAPE performed first should have produced greater improvements. This apparent contradiction could first be explained by the muscle groups involved in PAPE. In fact, while PAPE was focused on the thigh muscles, the post-tests were mostly related to the upper body during the boxing and handgrip tests. It is therefore unlikely that PAPE would have caused detrimental fatigue during these tests. A second explanation could arise from the constant order of post-tests. The RSA was always conducted after the boxing and handgrip tests. The duration of these tests may have permitted partial recovery from the PAPE procedure. Finally, the volunteers involved (elite boxers) in combination with the PAPE procedure could also explain the lack of order effect. Indeed, during competition, boxers are required to maintain high impact punches despite an increased fatigue. This high muscle endurance (exacerbated by the competitive level of our participants) could have implied a reduced fatigue or accelerated recovery after the PAPE procedure. Finally, it is also possible that MI-PAPE and PAPE-MI lead to different underlying mechanisms that compensate each other and lead to similar effects. Indeed, regarding MI-PAPE order, as MI might lead to an increase in the excitability of the neuromuscular system that can last at least up to 10 minutes after the intervention (Grosprêtre et al., 2019), it might positively exacerbate the effect of the following conditioning contraction of the PAPE condition. Conversely, in the PAPE-MI, if MI is performed after the strong conditioning contraction in the time-windows of the PAPE effect, it might also beneficiate from the conditioning effects of PAPE at a neural level (Blazevich and Babault, 2019).

Finally, all four experimental procedures showed similar results in light with the NASA-TLX score. These results confirmed previous observations (Rozand et al., 2014; Rumeau et al., 2023). For example, the authors have previously shown that real contractions added to imagined contractions did not generate additional neuromuscular fatigue (Rozand et al., 2014). The practitioners could therefore propose to add these different strategies within a comprehensive warm-up routine without any mental or physiological adverse effects.

In addition, some limitations should be acknowledged. The constant order of the assessments may influence our results. Control conditions included some seated rest before PAPE or MI. This short inactivity could favour a cooling down (Kapnia et al., 2023) that could reduce our PAPE effect. One should note that MI was also conducted while volunteers were inactive, and that MI followed by PAPE produced larger effect that rest followed by PAPE. Accordingly, although we cannot exclude this potential cooling down, the effect of combining both procedures remain more beneficial than both PAPE and MI alone. In addition, a larger sample size could be of interest. However, the present study focused on elite boxer (French national team). The small size of this population makes it difficult to add other individuals. In addition, although post-hoc effect sizes were small, this could have a large impact in international competitions. Finally, although the boxing model was used here, our conclusions could be generalized to other populations of high-level athletes. Indeed, similar results for PAPE or MI alone have previously been reported in the literature for other sports (Lagrange et al., 2020; Rumeau et al., 2023). Obviously, the procedure of PAPE and MI must be adapted to the sport performed (Boullosa, 2021). For example, there are several types of MI (e.g., visual or kinaesthetic) that could specifically interfere with subsequent performance (Fontani et al., 2007).

However, the main recommendation is to use tasks related to the subsequent sporting event, as MI is task-dependent (Rumeau et al., 2023). However, exploring these different parameters in other populations requires further experiments.

## Practical applications

In a previous study (Rumeau et al., 2023), we pointed out that PAPE and MI alone, despite diametrically opposed contributions, both appeared efficient to emphasize the acute effects of a standardized warm-up. Therefore, in the present we hypothesized that combining both modalities in a single warm-up routine could lead to a better activation and therefore enlarge the effects of MI or PAPE when used alone. Results suggested that the combination of PAPE and MI, whatever the order, within a full warm-up routine is effective to increase subsequent neuromuscular performance. Additional benefits are registered as compared to PAPE or MI alone without any adverse effects. Therefore, both methods could be implemented in combination during a warm-up routine to optimise its effects and provide better results than a warm-up routine with PAPE only or MI only bringing themselves superior results than a classic warm-up (Rumeau et al., 2023). This combined method presents the advantage to be applicable in real-life situations. By the same logic, and therefore by further increasing neural activation, adding cognitive complexity to MI or PAPE could lead to better results, if it is not an overload leading to fatigue, it could be of interest and requires future experiments.

## Perspectives

This study showed that comprehensive warm-up routines including a combination of MI and PAPE, whatever the order, improved reaction time, force and repeated sprinting abilities without increasing subjective fatigue. Therefore, we recommended that the practitioner include MI and PAPE in warm-up routines. Prescribing PAPE and MI should be specific to the subsequent task performed, more particularly for MI. In addition, both strategies should be adequately programmed and organised to avoid any detrimental effects for example originating from an unexpected mental or neuromuscular fatigue.

## Conclusion

PAPE and MI are useful strategies to optimize warm-up effects. Independently of the order, combining both strategies produced cumulative positive effects on subsequent performance without increasing subjective fatigue.

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## Key points

- The combination of post-activation performance enhancement (PAPE) and motor imagery (MI) is effective to exacerbate warm-up effects.
- Combining PAPE and MI is more efficient than either isolated PAPE or MI.
- The order of application of PAPE and MI equally affects subsequent muscle performance.
- Combining PAPE and MI does not cause additional detrimental fatigue.

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