



**HAL**  
open science

## **Enhancing endurance performance with combined imagined and actual physical practice**

Robin Souron, Benjamin Pageaux, Nathan Grosboillot, Aymeric Guillot, Mathieu Gruet, Mathilde F Bertrand, Guillaume Y Millet, Thomas Lapole

### ► **To cite this version:**

Robin Souron, Benjamin Pageaux, Nathan Grosboillot, Aymeric Guillot, Mathieu Gruet, et al.. Enhancing endurance performance with combined imagined and actual physical practice. *European Journal of Applied Physiology*, 2024, <10.1007/s00421-024-05510-6>. <hal-04586980>

**HAL Id: hal-04586980**

**<https://nantes-universite.hal.science/hal-04586980v1>**

Submitted on 24 May 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

# Enhancing endurance performance with combined imagined and actual physical practice

Robin Souron<sup>1,2</sup>  · Benjamin Pageaux<sup>3,4,5</sup>  · Nathan Grosboillot<sup>6,7</sup>  · Aymeric Guillot<sup>8,9</sup>  · Mathieu Gruet<sup>1</sup>  · Mathilde F. Bertrand<sup>6</sup> · Guillaume Y. Millet<sup>6,9</sup>  · Thomas Lapole<sup>6</sup> 

## Abstract

**Purpose** The perception of effort exerts influence in determining task failure during endurance performance. Training interventions blending physical and cognitive tasks yielded promising results in enhancing performance. Motor imagery can decrease the perception of effort. Whether combining motor imagery and physical training improves endurance remains to be understood, and this was the aim of this study.

**Methods** Participants ( $24 \pm 3$  year) were assigned to a motor imagery ( $n = 16$ ) or a control ( $n = 17$ ) group. Both groups engaged in physical exercises targeting the knee extensors (i.e., wall squat, 12 training sessions, 14-days), with participants from the motor imagery group also performing motor imagery. Each participant visited the laboratory Pre and Post-training, during which we assessed endurance performance through a sustained submaximal isometric knee extension contraction until task failure, at either 20% or 40% of the maximal voluntary contraction peak torque. Perceptions of effort and muscle pain were measured during the exercise.

**Results** We reported no changes in endurance performance for the control group. Endurance performance in the motor imagery group exhibited significant improvements when the intensity of the sustained isometric exercise closely matched that used in training. These enhancements were less pronounced when considering the higher exercise intensity. No reduction in perception of effort was observed in both groups. There was a noticeable decrease in muscle pain perception within the motor imagery group Post training.

**Conclusion** Combining motor imagery and physical training may offer a promising avenue for enhancing endurance performance and managing pain in various contexts.

**Keywords** Motor imagery · Physical training · Perception of effort · Perception of muscle pain · Endurance performance

## Abbreviations

MIQ-3      Movement Imagery Questionnaire 3  
MVC        Maximal voluntary contraction

NASA-TLX    National Aeronautics and Space Administration's Task Load Index  
TTF         Time to task failure

---

Communicated by Nicolas Place.

---

✉ Robin Souron  
robin.souron@univ-nantes.fr

<sup>1</sup> J-AP2S, Université de Toulon, Toulon, France

<sup>2</sup> Nantes Université, Movement, Interactions, Performance (MIP), UR 4334, 44000 Nantes, France

<sup>3</sup> École de Kinésiologie et des Sciences de l'activité physique (EKSAP), Faculté de Médecine, Université de Montréal, Montréal, Canada

<sup>4</sup> Centre de Recherche de l'Institut universitaire de gériatrie de Montréal (CRIUGM), Montreal, Canada

<sup>5</sup> Centre Interdisciplinaire de Recherche sur le Cerveau et l'Apprentissage (CIRCA), Montreal, Canada

<sup>6</sup> Laboratoire Interuniversitaire de Biologie de la Motricité, Université Jean Monnet Saint-Etienne, Lyon 1, Université Savoie Mont-Blanc, Saint-Etienne, France

<sup>7</sup> Université de Limoges, HAVAE, EA 6310, 87000 Limoges, France

<sup>8</sup> LIBM, Laboratoire Interuniversitaire de Biologie de la Motricité, Université Lyon 1, F-69622 Villeurbanne, France

<sup>9</sup> Institut Universitaire de France, Paris, France

## Introduction

The ability to perform in endurance activities primarily relies on consistently maintaining the highest possible workload throughout the task. When exercising at a given workload, it is critical for athletes to postpone as much as possible the moment when they voluntarily disengage from the task, i.e., the moment when they stop exercising or decrease their level of engagement in the exercise. This upper limit of endurance is commonly referred to as “exhaustion” or “task failure”.

Traditional theories in exercise sciences state that task failure is determined by physiological interactions between muscle and nervous mechanisms (Hunter et al. 2004), and that the mechanisms related to task failure vary depending on the nature of the task, e.g., low-intensity versus high-intensity (Place et al. 2009), local versus global (Kayser 2003). Recent evidences published in the last 15 years strongly challenge this assumption [e.g. Marcora and Staiano (2010); Marcora et al. (2008); Souron et al. (2020)], and support the idea that physiological changes during endurance performance interact with psychological factors, which ultimately trigger task failure. In this context, task failure is a conscious decision to disengage from the exercise (Marcora and Staiano 2010; Marcora 2019). Inspired by the motivational intensity theory (Brehm and Self 1989), this perspective is developed in the psychobiological model of endurance performance (Marcora 2019; Marcora and Staiano 2010). According to this model, task failure occurs (1) when the individual perceives the effort required to perform the task as equal to or beyond her/his motivation to succeed in the task, or (2) when the individual believes having exerted maximal effort so that exercise continuation is perceived as impossible or not worth it (Marcora et al. 2008; Marcora 2019). In this model, endurance performance is proposed to be influenced by two key factors: the motivation to succeed in the task and the perception of effort (Pageaux 2014; Marcora 2019). Specifically, any manipulation of the intensity of the perception of effort is supposed to alter endurance performance. An increased perception of effort should be associated with decreased endurance performance [e.g., effect of fatigue; Pageaux and Lepers (2016)], while a decreased perception of effort should be associated with increased endurance performance [e.g., effect of self-talk intervention; Blanchfield et al. (2014)].

Training interventions that combine physical and cognitive tasks demonstrated greater effectiveness in improving endurance performance compared to physical training alone. While this may be achieved by performing physical and cognitive activities simultaneously, i.e., dual-task (Staiano et al. 2015), implementing such an approach in

field settings may pose significant challenges. Alternative approaches to dual tasks have been explored, such as performing cognitive tasks immediately after physical training (Staiano et al. 2023; Dallaway et al. 2023, 2021). Notably, some of these interventions were reported to reduce the perception of effort (Staiano et al. 2015; Marcora et al. 2013). Motor imagery is one intervention that can acutely reduce the perception of effort (Razon et al. 2010, 2014), hence improving subsequent endurance performance. Motor imagery is a dynamic mental state that involves mentally representing an action without physically executing it. It can be performed through various sensory modes, including internal (i.e., first-person) or external (i.e., third-person) visual imagery, kinesthetic, tactile, auditory or olfactory imagery. It is widely accepted that motor imagery and actual movement execution activate overlapping neural networks across all stages of the motor pathway (Hardwick et al. 2018). This unique characteristic of motor imagery allows athletes or patients to maintain a certain level of training load or increase their training intensity by activating corticomotor pathways without producing any movement. When motor imagery is used up to ~20 min per training session (Jacquet et al. 2021), it has the potential to substantially enhance physical performance; e.g., muscle strength (Piveteau et al. 2023), movement efficacy (Guillot et al. 2013), or endurance performance (Razon et al. 2010, 2014). Despite these promising findings, the extent to which combining motor imagery and physical training can contribute to increase endurance performance remains largely unknown.

In this context, the primary aim of this study was to investigate the effect of combining motor imagery and physical training, as opposed to physical training alone, on local endurance performance. According to the proposed positive effect of motor imagery on performance, we hypothesized a greater improvement in endurance performance in participants performing the combined training. In line with the psychobiological model of endurance performance (Marcora 2019; Marcora and Staiano 2010), the secondary aim of this study was to test if the improved endurance performance would be associated with a reduction in the intensity of the perception of effort. We hypothesized that participants showing an improved endurance performance would report lower intensity of effort perception during the Post-training endurance exercise compared to the Pre-training endurance exercise.

## Methods

### Participants

Thirty-four participants (11 female; age:  $24 \pm 3$  year; height:  $173 \pm 8$  cm; weight:  $68 \pm 9$  kg) were recruited for this study.

Participants reported engaging in 2–6 h of moderate physical activity per week, and could be characterized as *recreationally active*. One participant was excluded after reporting concurrent involvement in another experimental study that required repeated sessions of intense physical training. To the best of our knowledge, no previous study investigated the effect of combining motor imagery and physical training on endurance performance. We decided to *a-priori* determine our sample size based on published studies demonstrating a positive effect of psychological interventions on endurance performance (Lakens 2022). As self-talk interventions have been shown to enhance endurance performance (our primary outcome of interest) via a reduction in perception of effort (our secondary outcome of interest), we based our sample size on these studies (Basset et al. 2022; Blanchfield et al. 2014). These studies have sample size ranging from 24 (Blanchfield et al. 2014) to 29 (Basset et al. 2022). Considering potential attrition, we recruited 34 participants, and one was excluded as previously described. Our reached sample size, according to GPower 3.1 software calculation, allows detecting a moderate effect size of  $f = 0.30$  (i.e.  $\eta_p^2 \sim 0.085$ ), with a power of 0.9, for the within-between interaction of a repeated-measures ANOVA and with correlations among measures being equal to 0.5.

All participants engaged in physical activity at least once per week. They were provided with written instructions detailing all study procedures but were unaware of its objectives and hypotheses. They were not informed that motor imagery was used to enhance endurance performance. Participants were instructed not to consume caffeine and nicotine for at least 3 h before testing and were asked to declare if they had taken any medication or had any acute illness, injury, or infection. Written informed consent was obtained from each participant. This study adhered to the standards outlined in the latest revision of the Declaration of Helsinki (with the exception of registration in a database) and was approved by the Nantes University ethics committee (n° IRB: IORG0011023).

## Study design

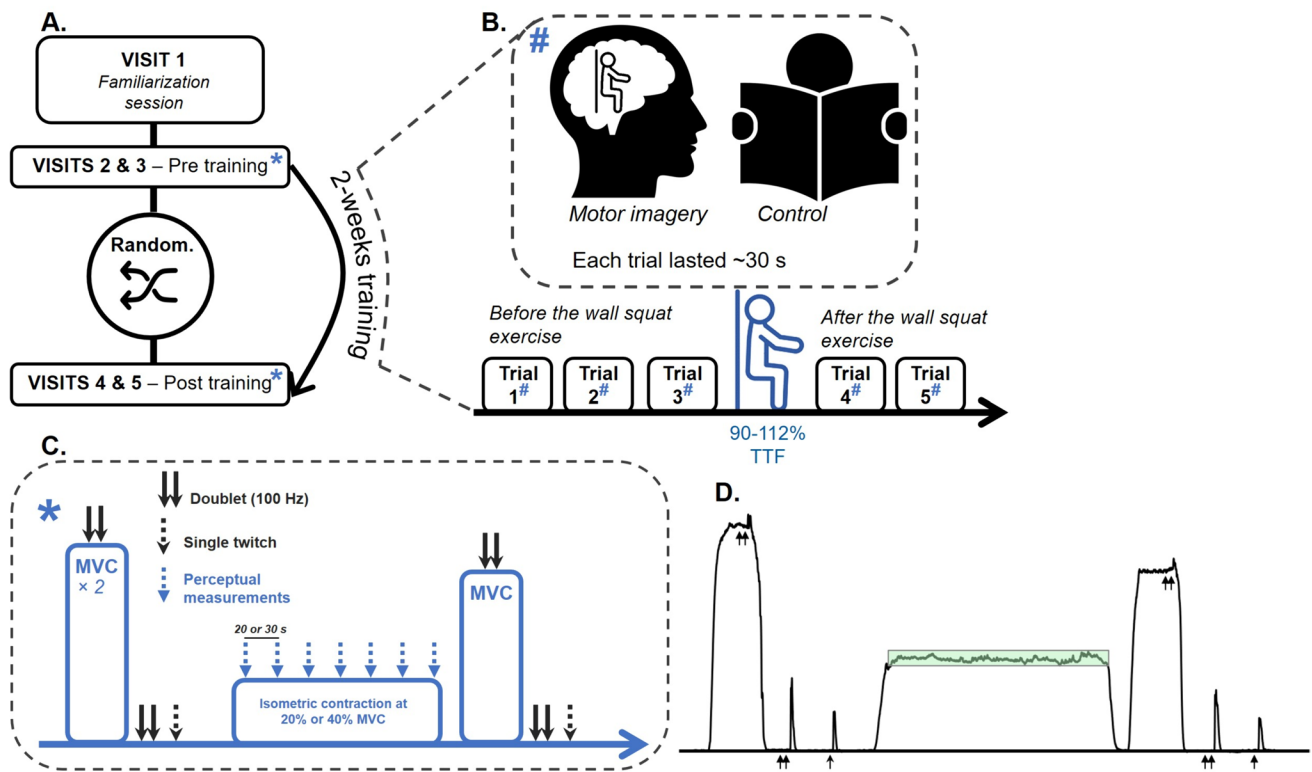
Participants were randomly assigned to either an active control ( $n = 17$ , 12 males and 5 females) or a motor imagery ( $n = 16$ , 10 males and 6 females) group. The motor imagery group involved combining physical training with motor imagery, whereas the active control group involved physical training paired with a time-matched neutral cognitive task (see below). The study was a controlled Pre–Post training design in which participants visited the laboratory on five separate occasions (Fig. 1). Each experimental session was performed at the same time of the day for a given participant.

The first laboratory visit involved a familiarization with the procedures, completion of questionnaires, and

determination of the initial performance at the isometric wall squat exercise used during the 2-week training period. After a minimum of 2 days, participants returned to the laboratory for two Pre-training (Pre) sessions, interspaced with at least 48 h in-between. During these sessions, endurance performance was measured with a sustained submaximal isometric contraction of the right knee extensors performed until task failure (time to task failure, TTF). All participants were right-handed, except one left-handed participant in each group. We used an isometric modality of exercise for its transferability to home-based physical training sessions and its relative simplicity in assessing neuromuscular function (see below for more details). Two contraction intensities, namely 20% and 40% of the maximal voluntary contraction (MVC) peak torque, were randomly tested during two Pre-training visits (i.e., one for 20% and one 40% MVC, respectively). The TTF at 20% MVC peak torque (TTF<sub>20%</sub>) was chosen based on pilot experiments, as it had a comparable exercise duration to the wall squat posture used during training sessions (mean  $\pm$  SD durations of the wall squat exercise and the TTF<sub>20%</sub>:  $276 \pm 239$  and  $267 \pm 109$  s, respectively). The TTF at 40% MVC peak torque (TTF<sub>40%</sub>) was chosen to investigate a potential transfer to exercise performed at a greater intensity for a shorter duration. During the two TTF tests, perceptions of effort and muscle pain were measured. The neuromuscular function of the knee extensors was assessed both before the sustained isometric exercise (i.e., Pre-TTF) and immediately upon task failure (TF). This assessment involved examining the exercise-induced changes in (1) MVC, (2) voluntary activation level using the twitch interpolated technique, and (3) amplitudes of both doublet and single twitches. Two days after the second Pre-training session, participants completed a 2-week training period. We opted for this specific training duration for two primary reasons: firstly, due to time constraints, as it is relatively short, and secondly, because such a brief period of motor imagery training has proven to be adequate for enhancing motor performance (Grosprêtre et al. 2018). The training program involved daily wall squat exercises combined (motor imagery group) or not (control group) with motor imagery (see section *Training modalities* for more details). Two days after the completion of the training period, participants were retested in two Post-training (Post) visits (i.e., one for 20% and one 40% MVC, respectively). The order for the Pre–Post training sessions (i.e., TTF<sub>20%</sub> and TTF<sub>40%</sub>) was randomized between participant and kept the same for each participant.

## Familiarization

After a warm-up including submaximal isometric contractions, participants performed three shorts ( $\sim 3$  s) isometric MVCs with the right knee extensors. Following a 3-min



**Fig. 1** **A** Overview of the experimental protocol. Each participant underwent a familiarization session (visit 1) followed by four experimental sessions (visits 2 to 5). **B** Home-based training. A two-week physical training regimen (wall squat exercises) was conducted between the third (end of Pre) and fourth (beginning of Post) visits. Participants were divided into two groups: one utilizing motor imagery (motor imagery group) and the other without (control group). **C** Experimental session details. Each experimental session involved the performance of a sustained isometric task with the knee extensors, set at either 20% or 40% of maximal voluntary contraction (MVC) peak torque measured Pre-training, until task failure. Perceptions of effort and muscle pain were recorded at regular inter-

vals during the exercise. Assessment of MVC peak torque, as well as peripheral and central components of the knee extensor neuromuscular function, was conducted both before and at task failure. **D** Original torque trace record. A representative torque trace recorded during an experimental session performed at 40% MVC is displayed. Black arrows indicate the timing of peripheral nerve stimulation, with double arrows representing doublet stimulation and single arrows indicating single twitch. The green zone denotes the target torque feedback for the sustained isometric exercise. For the sake of clarity, the scale has been adjusted and does not accurately reflect the actual duration of the isometric exercise performed by the participant nor the actual range of the feedback given to the participant

resting period, participants were instructed to perform an isometric wall squat exercise. They were asked to maintain the wall squat position with the knee at  $\sim 90^\circ$  until task failure, defined as the moment when (1) the participant voluntarily stopped the task or (2) the experimenter stopped the task because the participant was unable to maintain the  $\sim 90^\circ$  sitting position for more than 3 s. The experimenter noted the total exercise duration, which was subsequently used for the training program (see below). Then a 15-min resting period was given, during which participants were accustomed with all questionnaires and scale instructions. They also completed the French version of the Movement Imagery Questionnaire 3 (Robin et al. 2020). Following this resting period, participants were familiarized with the TTF tests. First, participants performed the  $TTF_{40\%}$ . Following a second 15-min break, participants performed the  $TTF_{20\%}$ . Before and immediately after the TTF tests, participants

were further familiarized with neuromuscular function assessment procedures.

### Experimental sessions

Each experimental session started with a neuromuscular evaluation of the right knee extensors (i.e., Pre-TTF), which included determining the baseline MVC peak torque. During and after the MVC, peripheral nerve stimulation was used to elicit superimposed and resting twitches. Participants then performed the TTF test, which involved sustaining a sub-maximal isometric contraction at either 20 or 40% of the MVC peak torque until reaching task failure. Task failure was defined as the point at which participants were unable to maintain the target torque for three consecutive seconds. For the Post-training sessions, the MVC peak torque measured during the Pre-training session was used to set the

target torque for the  $TTF_{20\%}$  and  $TTF_{40\%}$ . This ensured the investigation of endurance performance at the same absolute torque before and after the training program (control or motor imagery). Perceptions of effort and muscle pain were recorded every 20 and 30 s during the  $TTF_{40\%}$  and  $TTF_{20\%}$  tests, respectively. Immediately after reaching task failure, the same neuromuscular evaluation completed Pre-TTF was performed to assess the exercise-induced decline in torque capacities (i.e., knee extensors' fatigability) and its etiology. Standardized encouragements (e.g., "you are doing good, keep going", "do not give up", "keep going, you are doing a good job") were provided during the exercise after asking for perceptions of effort and muscle pain, in a neutral tone. If participants deviated from the target torque feedback, the experimenter calmly requested them to "return to the zone". If participants were unable to return to the target torque within 3 s, despite the experimenter's request, we considered it a task failure.

### Training modalities

Both the control and motor imagery groups engaged in physical exercises as part of their training regimen. While the motor imagery group incorporated motor imagery alongside physical exercises, the control group completed a time-matched neutral cognitive task in addition to physical exercises (see below). Participants in the control group were not supervised throughout the entire training period. In contrast, participants in the motor imagery group received semi-supervision solely for the motor imagery task, not the physical aspect. Specifically, the motor imagery bouts during sessions #4, #8, and #12 were supervised via videoconferencing. This was primarily done to accurately time the duration of the imagery bouts (see below). All participants were instructed to maintain a training log, recording details of each training session, such as the precise duration of the wall sit exercise, levels of fatigue, and perceived workload. Despite this information being collected retrospectively, the adherence rate to the training protocol was 100%, with all participants from both groups participating in the 12 training sessions over the 2 weeks.

### Physical exercise

Six times a week for 2 weeks (for a total of 12 training sessions over a period of 14 days), participants in both the control and motor imagery groups engaged in the same physical training routine at home. The training sessions consisted of performing a wall squat isometric exercise (Fig. 1). During the first training session, the exercise duration was set to 90% of the total exercise duration performed during the familiarization session. The exercise duration was gradually increased throughout the training period. Each subsequent

training session incremented the duration by 2% compared to the previous session, i.e., the exercise duration for the second session was set to 92%, the third session to 94%, and so on, until reaching 112% of the initial total exercise duration. This progression scheme was chosen to strike a balance between progression within the training period and feasibility. If a participant discontinued the exercise before reaching the target duration, they were instructed not to resume the exercise, and the session was concluded. At the end of each training session, participants from both groups provided feedback on their perceived workload with the National Aeronautics and Space Administration's Task Load Index (NASA-TLX) (Hart and Staveland 1988).

### Motor imagery

Participants in the motor imagery group received specific instructions from a sport psychology and motor imagery training specialist (AG). They were given standardized instructions to perform five 30-s imagined isometric contractions of the wall squat exercise during each training session. The first three imagined isometric contractions were performed just before the wall squat exercise, while the last two imagined contractions were performed immediately after the wall squat exercise, with ~30 s recovery between trials (Fig. 1). We chose to perform the cognitive task separately from the physical one, for practical reasons and to enhance the transferability of our findings to real-world scenarios. Participants were instructed to combine visual and kinesthetic imagery modalities using a first-person perspective. Their task involved imagining themselves performing the final 30 s of the isometric wall squat exercise previously performed either on the preceding training day (for the three first imagined contractions) or on the current training day (for the final two imagined contractions). The focus of their imagery was on appropriately maintaining muscle contractions and body position during the wall squat exercise, disregarding any perceived fatigue. Utilizing first-person visual imagery provided participants with the flexibility to concentrate either on a fixed point within their environment, akin to what might be beneficial during physical exercise, or on the positioning of the lower limbs involved in the movement. Moreover, this approach facilitated precise visual control of their position during the exercise and aided in directing focus to the relevant body part where sensations were mentally evoked. Additionally, participants were encouraged to manage and cope with discomfort and pain that might arise during the exercise. Accordingly, they were instructed to pay attention to their ability to successfully complete the wall squat exercise despite intense muscle contractions, maintaining proper body posture, and managing their effort throughout the motor sequence. Participants remained seated on a chair during the whole motor imagery procedures.

## Control cognitive task

In the control group, the imagined contractions were substituted with reading from a collection of articles covering neutral topics such as sport, history, ecology and economy. If a participant did not complete reading a sentence by the end of the 30-s period, she/he was allowed to finish it to prevent any potential frustration associated with the control task.

## Psychological measures

To ensure clarity regarding the specific timing of psychological measures, note that (1) perceptions of effort and muscle pain were recorded continuously throughout the sustained exercise, (2) subjective workload (NASA-TLX) was assessed at the end of each of the 12 training sessions, (3) motor imagery abilities of each participant were evaluated during the familiarization session, and (4) motor imagery ease and vividness were recorded for participants in the motor imagery group at the conclusion of each training session.

### Perception of effort

Participants were instructed to report the intensity of their perceived effort using the CR100 scale (Borg and Kaijser 2006) every 20 s during the TTF<sub>40%</sub> test and every 30 s during the TTF<sub>20%</sub> test (which coincided with the time point for assessing muscle pain perception, as detailed below). Detailed and standardized instructions on how to use the scale and dissociate between effort and muscle pain perceptions were provided during the familiarization session (Pageaux et al. 2020). Briefly, participants were asked to rate how hard and intense it was for them to drive their leg and breathe. The CR100 scale ranges from 0 (nothing at all effort at all) to 100 (maximal effort). The maximal effort was anchored as the greatest intensity of effort ever experienced by one participant during a physical task. Modifications on the scale were made on the anchoring 0 and 100 to explicitly incorporate the term “effort” in the description (Jacquet et al. 2021). The scale included verbal anchors that correspond to different levels of intensity, such as weak/light (13), moderate (23), strong/heavy (50) or very strong (score of 70). If participants perceived an intensity of effort stronger than 100, “Maximal” (i.e., higher than the greatest effort ever experience), they were instructed that they may use numbers on the scale above 100, such as 110, 120, or even higher. Verbal examples illustrating “no effort” and “maximal effort” were provided to each participant as a reference.

### Perception of muscle pain

A separated modified CR100 scale was used to measure muscle pain. The word “pain” was added in the description

of the anchors 0 (no pain at all) and 100 (maximal pain). As for effort, memory anchoring was used to anchor the 100. Participants were instructed to rate “the intensity of pain they felt during the exercise, with this perception depending on localized sensations in the quadriceps (knee extensor) muscle”. These sensations were described as potentially including feelings of burning, intense or sharp pain (O’Connor and Cook 1999). It was emphasized to participants that they should not confuse or equate the rating of effort with the perception of pain (Pageaux 2016; Bergevin et al. 2023). Each participant received verbal examples illustrating “no muscle pain” and “maximal muscle pain” as reference points for using the scale.

To compare perceptions of effort and muscle pain before and after the training period, we used an “individual isotime” method (Nicolò et al. 2019). This is an efficient method to analyze the effects of an experimental manipulation and performance ranking on physiological and psychological variables measured during a TTF exercise (Nicolò et al. 2019). For each participant, we identified the shortest TTF<sub>20%</sub> and TTF<sub>40%</sub> recorded between the Pre and Post sessions. The effort and pain perception intensities reported at the last recorded time point before task failure were considered the isotime point and were compared between the Pre and Post-training assessments. For example, if a participant had a TTF of 303 s during the Pre-training session and 357 s during the Post-training session, the effort and pain perception measurements at the 300-s mark were used for analysis.

### Subjective workload

Participants reported their perceived workload for each training session using the NASA-TLX scale (Hart and Staveland 1988). The NASA-TLX scale consists of six items, i.e., (1) mental demand, (2) physical demand, (3) temporal demand, (4) performance, (5) effort, and (6) frustration. Participants rated each item on a scale divided into twenty equal intervals anchored by a bipolar descriptor (i.e., high/low). This score was multiplied by five, resulting in a final score between 0 and 100 for each item.

### Motor imagery ability

Participants from both groups completed the French version of the Movement Imagery Questionnaire 3 [MIQ-3f; Robin et al. (2020)] during the familiarization session. The MIQ-3 is a self-report questionnaire composed of 12 items that evaluate the ability to imagine four specific movements (arm abduction and adduction, standing hip flexion, knee lift and jump) after actual physical performance, using external visual imagery, internal visual imagery, as well as kinaesthetic imagery (Robin et al. 2020). Participants rated the difficulty of forming external and internal visual imagery as

well as kinesthetic imagery using two 7-point scales ranging from 1 (very hard to see/feel) to 7 (very easy to see/feel). A mean score ranging from 1 to 7 was calculated for each imagery modality, with higher scores representing higher motor imagery abilities.

### Motor imagery ease and vividness

Participants in the motor imagery group rated the vividness of the imagined contractions and the ease of imagining these contractions using a Likert-type scale at the end of each training session. The scale ranged from 1 (“absence of visual/kinesthetic information during imagination”) to 10 (“comparable visual/kinesthetic information as during physical practice”). The actual time of each motor imagery trial (that was supposed to be 30 s) was timed for the fourth, eighth and twelfth training sessions during which the experimenter was connected in videoconference with the participant and timed the exact duration of each imagined contraction. The participant announced a “go” for the beginning and a “stop” for the end of each imagined contraction to help the experimenter to correctly time the duration.

### Neuromuscular function

Neuromuscular function was assessed to ensure that any observed changes in local endurance performance were not attributed to changes in neuromuscular function/fatigue induced by our intervention.

### Torque recording

Participants sat upright on an isometric ergometer chair (S2P Ltd, Ljubljana, Slovenia) with knee and hip at 90° of flexion. The knee axis was aligned with the axis of the dynamometer’s lever arm. The minimally padded shank support was adjusted for each participant approximately 2 cm above the lateral malleolus. Hip and knee fixation was ensured with rigid straps over the pelvis and knee. Participants were instructed to push against the strain gauge (i.e., knee extension) with their right leg. The torque signal was acquired using a PowerLab data acquisition system (16/30-ML880/P, ADInstruments, Bella Vista, Australia) at a sampling rate of 2 kHz.

In each experimental session, and after a standardized isometric warm-up, participants performed two ~3 s MVCs with the right knee extensors before the sustained TTF isometric test (i.e., Pre-TTF), with the best MVC peak torque kept for statistical analysis, and one MVC immediately at task failure. The Pre-TTF versus TF difference in peak torques was considered as an index of knee extensors fatigability. During the MVCs and the TTF tests, the torque produced was displayed

in live on a monitor position from of the participant. Strong verbal encouragements were given during MVCs.

### Peripheral nerve stimulation

We used a constant-current stimulator (DS7AH, Digitimer, Hertfordshire, UK) for administering electrical stimulation to the right femoral nerve. Single rectangular electrical pulses with 0.2-ms duration and 400 V maximal output voltage were delivered via a 30-mm diameter surface cathode (Meditrace 100) taped to the skin into the femoral triangle and a 50×90 mm anode (Durastick Plus; DJO Global Vista, CA) in the gluteal fold. At the beginning of each experimental session, single stimuli were delivered incrementally by steps of 10 mA until resting M-wave and twitch amplitudes plateaued to determine the optimal intensity of stimulation. The optimal intensity was then increased by 20% for the electrical stimulation to be supramaximal.

Electrical stimulations were delivered in the following order: (1) a 100 Hz-doublet during the MVC, (2) a 100 Hz-doublet on the relaxed muscle 2 s after the MVC, (3) a single stimulation on the relaxed muscle 5 s after the MVC (Fig. 1). Potentiated peak doublet and twitch amplitudes were measured via doublet and single electrical stimulations performed on the relaxed knee extensors (i.e., after the MVC), respectively, and were used as markers of muscle contractility. The ratio of the amplitude of the superimposed doublet over the amplitude of the control doublet was calculated to obtain the percentage of voluntary activation (i.e., indicative of the strength of the neural drive) as follows:

$$\text{Voluntary activation} = (1 - \text{SIT}_{\text{MVC}}/\text{peak doublet}) \times 100$$

where  $\text{SIT}_{\text{MVC}}$  is the superimposed twitch evoked during MVC.

### Statistics

Statistical analyses were conducted with Jamovi 1.2.27.

### Questionnaires

Independent t-tests were used to assess differences in baseline MIQ-3f global and sub scores between control and motor imagery groups. For NASA-TLX interpretation, the mean score of each item of the 12 training sessions was inputted in the statistical analysis (i.e., one general score for each item). Independent t-tests were then used to compare each item separately between groups.

## Time to task failure

Independent t-tests were performed to compare TTF values of the two groups before the training intervention. Within each group, paired t-tests were performed to evaluate the effect of the 2-week training period, comparing TTF values (in s) between Pre- and Post-training sessions. To answer our main research question as to whether participants from the motor imagery group improved more at Post-training (i.e., longer Post-training TTF value after adjusting for Pre-training value) than participants from the control group, we used analysis of covariance (ANCOVA) with Post-TTF as the dependent variable, Pre-TTF as the covariate and group (motor imagery vs control) as the fixed factor. ANCOVA is the method of choice for analyzing the results of trials with baseline and post treatment measurements.

## Perceptual measurements

Independent t-tests were performed (1) on the first perceptual measurements that were recorded during the exercise (i.e., 3 s after the beginning of the isometric task) to confirm that both groups reported identical perceptions at the beginning of the exercise, and (2) on the perceptual measurements recorded at task failure to confirm that both groups reported similar perceptions at exercise termination. Within each group, paired t-tests were performed to evaluate the effect of the 2-week training period, comparing perceptual isotime measurement (in CR100 units) between Pre- and Post-training sessions. ANCOVA were performed with isotime perceptions of effort and muscle pain recorded Post-training as the dependent variable, isotime perceptual measurements recorded Pre-training as the covariate, and group as the fixed factor.

We used Pearson's correlation coefficient to assess the strength of the association between Pre-Post changes in both perceptual measurements at isotime and TTF performance.

## Neuromuscular function and fatigability

When referring to MVC Pre-exercise (i.e., Pre-TTF), we considered the maximal value of the two MVCs performed for the associated exercise. Subsequently, when assessing the amplitude of force loss (in Nm) after the fatiguing exercise, we compared the highest MVC performed Pre-TTF with the MVC performed at task failure. For the manipulation checks (i.e., comparing the two experimental groups at baseline), we calculated the mean of the two best MVCs performed in each of the two Pre-training sessions. Independent t-tests were performed to compare MVC peak torque of the two groups before the training. To detect potential between-group differences in the amplitude of knee extensors fatigability after the training period, we used ANCOVA with

Post-training MVC delta as the dependent variable, Pre-training MVC delta as the covariate, and group as the fixed factor. Similar analyses were performed resting twitch and doublet amplitude, as well as voluntary activation.

The normality of the data was verified using the Shapiro–Wilk test and visual inspection of the QQ plots on. In cases where the data deviated from normal distribution (i.e., for TTF<sub>20%</sub>, perceptions of effort and muscle pain related to TTF<sub>20%</sub>), we employed the Wilcoxon signed-rank test. For these parameters, we present the results of both the Student t-test and the Wilcoxon rank test. The alpha level for statistical significance was set at  $\alpha \leq 0.05$ . Partial eta squared ( $\eta_p^2$ ) are reported, and thresholds for small, moderate, and large effects were set at 0.01, 0.07, and 0.14, respectively (Cohen 1988). Cohen's d were calculated when t-tests were performed and thresholds for small, moderate and large effects were set at 0.2, 0.5, and 0.8 respectively (Cohen 1988). Greenhouse–Geisser correction to the degrees of freedom was applied when violations of sphericity were present. All data are presented as means  $\pm$  standard deviation unless stated.

## Results

### Manipulation checks

Pre-training MVC did not differ between groups (motor imagery:  $251 \pm 75$  Nm; control:  $252 \pm 73$  Nm;  $P = 0.973$ ,  $d = 0.011$ ). Pre-TTF<sub>20%</sub> did not differ between groups (motor imagery:  $250 \pm 125$  s; control:  $285 \pm 92$  s;  $P = 0.351$ ,  $d = 0.330$ ). No baseline differences were found in TTF<sub>40%</sub> between groups (motor imagery:  $104 \pm 36$  s; control:  $100 \pm 29$  s;  $P = 0.724$ ,  $d = 0.123$ ) either. Raw perceptual data are presented in Table 1.

The perception of effort recorded at the beginning of exercise (i.e., 3 s in) did not differ between participants in both groups for Pre- (TTF<sub>20%</sub>:  $P = 0.621$ ,  $d = 0.179$ ; TTF<sub>40%</sub>:  $P = 0.600$ ,  $d = 0.184$ ) and Post-training (TTF<sub>20%</sub>:  $P = 0.800$ ,  $d = 0.081$ ; TTF<sub>40%</sub>:  $P = 0.456$ ,  $d = 0.273$ ) sessions. No between-group difference was observed at task failure for both Pre- (TTF<sub>20%</sub>:  $P = 0.183$ ,  $d = 0.472$ ; TTF<sub>40%</sub>:  $P = 0.975$ ,  $d = 0.311$ ) and Post-training (TTF<sub>20%</sub>:  $P = 0.161$ ,  $d = 0.500$ ; TTF<sub>40%</sub>:  $P = 0.277$ ,  $d = 0.390$ ) sessions.

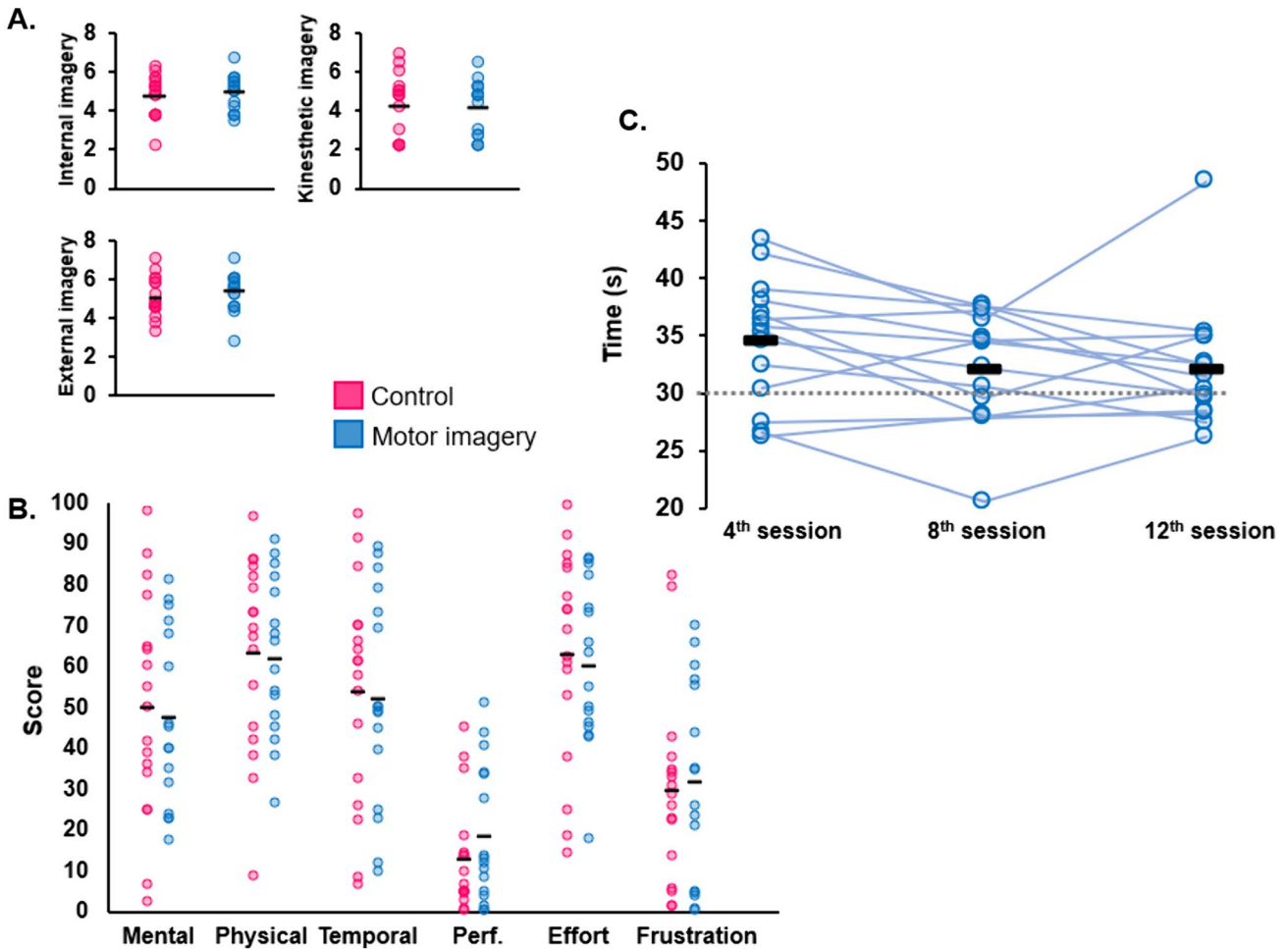
The perception of muscle pain did not differ between groups at the beginning of exercise for Pre- (TTF<sub>20%</sub>:  $P = 0.421$ ,  $d = 0.286$  and TTF<sub>40%</sub>:  $P = 0.740$ ,  $d = 0.110$ ) and Post-training (TTF<sub>20%</sub>:  $P = 0.500$ ,  $d = 0.230$  and TTF<sub>40%</sub>:  $P = 0.613$ ,  $d = 0.184$ ) sessions. No between-group difference was observed at task failure for both Pre- (TTF<sub>20%</sub>:  $P = 0.060$ ,  $d = 0.700$ ; TTF<sub>40%</sub>:  $P = 0.554$ ,  $d = 0.214$ ) and Post-training (TTF<sub>20%</sub>:  $P = 0.358$ ,  $d = 0.328$ ; TTF<sub>40%</sub>:  $P = 0.108$ ,  $d = 0.596$ ) sessions.

**Table 1** Raw data for perceptual measurements (CR100 scale) recorded in participants from control and motor imagery groups at the beginning (i.e., 3 s) of the isometric exercise and at task failure, for Pre- and Post-training sessions

	Control group				Motor imagery group			
	Pre		Post		Pre		Post	
	Beginning	Task failure	Beginning	Task failure	Beginning	Task failure	Beginning	Task failure
20%MVC								
Perception of effort	7±5	75±29	5±4	80±30	7±4	87±21	6±5	92±18
Perception of muscle pain	9±11	88±15	5±4	94±17	6±6	97±10	6±6	99±9
40%MVC								
Perception of effort	11±12	72±26	11±11	77±24	13±10	82±24	8±7	86±21
Perception of muscle pain	10±12	80±22	9±6	83±24	11±8	85±23	11±13	94±12

No between-groups difference was reported for each item of the MIQ-3f ( $P=0.474-0.860$ ,  $d=-0.240-0.060$ ; Fig. 2A). There was no difference in the score of each

NASA-TLX items between groups ( $P=0.301-0.831$ ,  $d=-0.366-0.118$ ; Fig. 2B). Within the motor imagery group, the mean duration of the motor imagery trials of



**Fig. 2** A depicts the individual (blue and pink circles) and mean (black horizontal bar) results obtained for each of the three items of the Movement Imagery Questionnaire 3f. Mean score ranges from 1 to 7, with a higher score indicating higher motor imagery abilities. B illustrates the individual and mean results for the six items of the

NASA-TLX questionnaire. C displays the timed duration of the imagined contractions during the fourth, eighth and twelfth training sessions for participants in the motor imagery group. Blue circles represent individual data, the black horizontal bar represent the mean

the fourth ( $35 \pm 5$  s), eighth ( $32 \pm 5$  s) and twelfth ( $32 \pm 6$  s) training sessions did not differ ( $P=0.077$ ;  $F=2.840$ ;  $\eta_p^2=0.179$ ; Fig. 2C). The perceived ease of imagery for these three training sessions was reported to be  $6.2 \pm 1.9$ ,  $5.9 \pm 1.7$  and  $6.6 \pm 2.4$ , while the mean global score of the 12 training sessions was  $6.0 \pm 1.7$ .

### Effects of training on time to task failure

$TTF_{20\%}$  increased after training for the motor imagery group (Student's  $t$ :  $P=0.022$ ,  $d=0.639$ ; Wilcoxon  $W$ :  $p=0.004$ , rank biserial correlation = 0.779) but not for the control group ( $P=0.380$ ,  $d=0.221$ ) (Fig. 3A). The ANCOVA analysis revealed a difference among the group adjusted means for Post- $TTF_{20\%}$ , with longer time to task failure in the motor imagery group ( $P=0.020$ ,  $F=5.832$ ,  $\eta_p^2=0.160$ ; Fig. 3B).

$TTF_{40\%}$  increased after training for the motor imagery group ( $P=0.014$ ,  $d=-0.683$ ) but not for the control group ( $P=0.708$ ,  $d=0.009$ ) (Fig. 3C). The ANCOVA analysis revealed no difference among the group adjusted means for Post- $TTF_{40\%}$  ( $P=0.064$ ,  $F=3.753$ ,  $\eta_p^2=0.110$ ; Fig. 3D).

### Effects of combined motor imagery and physical training on perceptions of effort and muscle pain

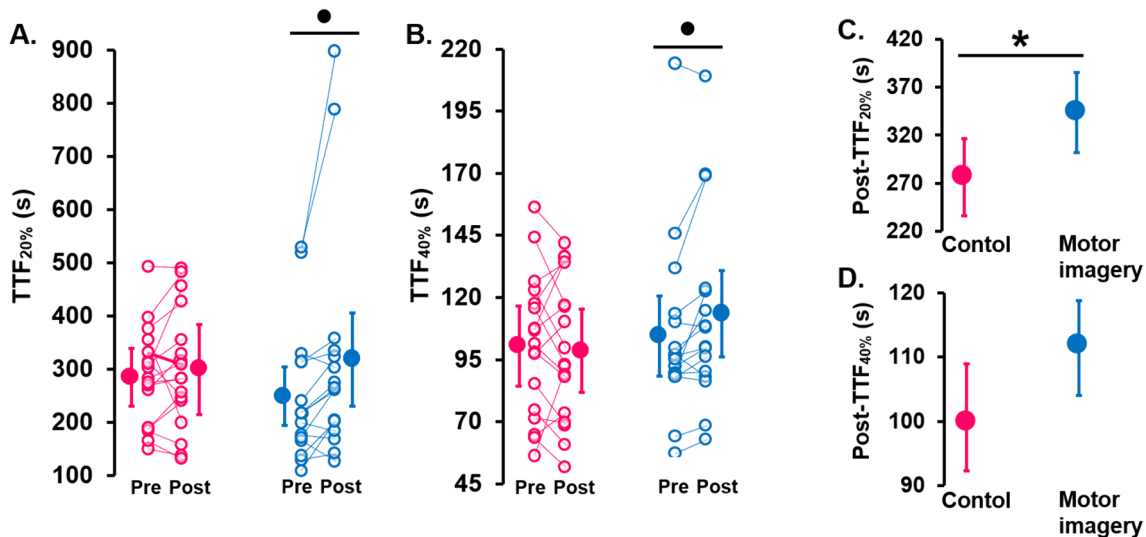
In both groups, training had no significant effect on the isotime perception of effort during the  $TTF_{20\%}$  (control group:  $P=0.910$ ,  $d=0.355$ ; motor imagery group for Student's  $t$ :  $P=0.103$ ,  $d=0.330$ ; and for Wilcoxon  $W$ :  $p=0.069$ , rank

biserial correlation = 0.545; Fig. 4A) and the  $TTF_{40\%}$  (control group:  $P=0.868$ ,  $d=0.280$ ; motor imagery group:  $P=0.573$ ,  $d=0.041$ ; Fig. 4B). The ANCOVA revealed no difference among the group adjusted means for the Post-isotime perception of effort recorded during the  $TTF_{20\%}$  ( $P=0.120$ ,  $F=2.583$ ,  $\eta_p^2=0.071$ ; Fig. 4C) and the  $TTF_{40\%}$  ( $P=0.871$ ,  $F=0.024$ ,  $\eta_p^2=0.001$ ; Fig. 4D).

For the motor imagery group, perception of muscle pain at isotime decreased from Pre- to Post-training during the  $TTF_{20\%}$  (Student's  $t$ :  $P=0.046$ ,  $d=0.45$ ; Wilcoxon  $W$ :  $P=0.034$ , rank biserial correlation = 0.636). There was no change in the control group ( $P=0.941$ ,  $d=0.404$ ; Fig. 5A). In both groups, the training had no significant effect on the perception of muscle pain during the  $TTF_{40\%}$  (control group:  $P=0.970$ ,  $d=0.554$ ; motor imagery group:  $P=0.431$ ,  $d=0.406$ ; Fig. 5B). The ANCOVA revealed that adjusted Post-isotime means were different between groups during the  $TTF_{20\%}$ , with lower values in the motor imagery group ( $P=0.051$ ,  $F=3.900$ ,  $\eta_p^2=0.110$ ; Fig. 5C). There was no difference in muscle pain during the  $TTF_{40\%}$  ( $P=0.260$ ,  $F=1.304$ ,  $\eta_p^2=0.043$ ; Fig. 5D).

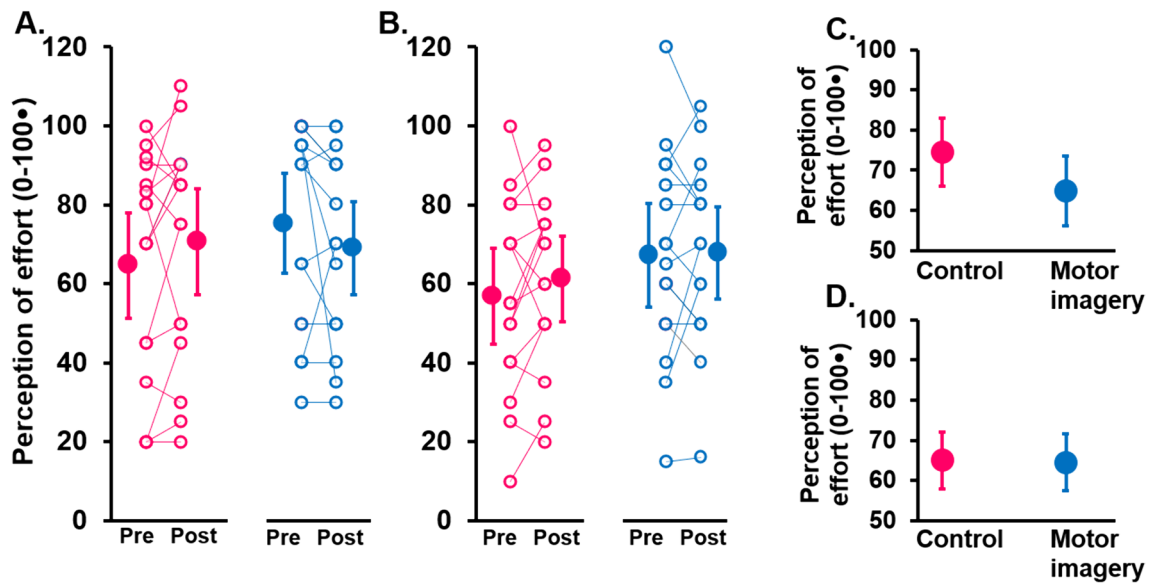
### Relationship between changes in perceptual measurements and changes in TTF

Pre-Post changes in both perceptions of effort ( $r=-0.47$ ,  $P=0.006$ ) and muscle pain ( $r=-0.45$ ,  $P=0.009$ ) recorded at isotime during the  $TTF_{20\%}$  were correlated with Pre-Post changes in  $TTF_{20\%}$  performance. The more the intensity of the



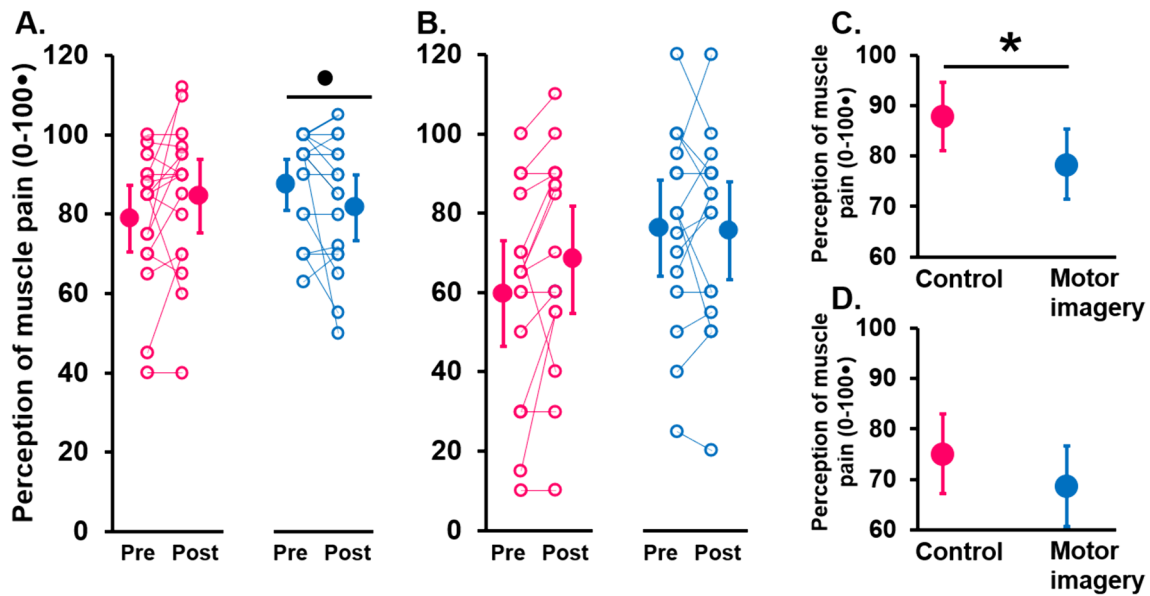
**Fig. 3** Performance in the isometric time to task failure (TTF) performed at 20% MVC ( $TTF_{20\%}$ , **A** and **C**) and 40% MVC ( $TTF_{40\%}$ , **B** and **D**). The control (i.e., physical training alone) and motor imagery (i.e., physical training + motor imagery) groups are presented in pink and blue, respectively. In **A** and **B**, data are analyzed with ANOVA, individual data are presented as empty markers and mean  $\pm$  95% con-

fidence intervals with filled markers. In **C** and **D**, data are analyzed with ANCOVA, Post training values are adjusted by Pre-training values, and presented as  $\pm$  95% confidence intervals. ● represents a significant Pre-Post difference within the same group, with  $P < 0.05$ ; \* represents a difference between the two groups, with  $P < 0.05$



**Fig. 4** Pre- vs. Post-training change in the perception of effort (Borg scale, CR100) recorded at isotime during the sustained isometric contractions at 20 (A) and 40% (B) of the MVC peak torque, for control (pink color) and motor imagery (blue color) groups. Mean Pre-Post values with 95% confidence intervals are presented by the full cir-

cles. Individual Pre-Post data are represented by the empty circles. Adjusted Post-isotime means with 95% confidence intervals obtained with the ANCOVA are displayed by C (exercise at 20% MVC) and D (exercise at 40% MVC)



**Fig. 5** Pre- vs. Post-training change in perceptions of muscle pain (Borg scale, CR100) recorded at isotime during the sustained isometric contractions at 20 (A) and 40% (B) of the MVC peak torque, for control (pink color) and motor imagery (blue color) groups. Mean Pre-Post values with 95% confidence intervals are presented by the full circles. Individual Pre-Post data are represented by the empty

circles. Adjusted Post-isotime means with 95% confidence intervals obtained with the ANCOVA are displayed by C (exercise at 20% MVC) and D (exercise at 40% MVC). ● represents a significant Pre-Post difference within the same group, with  $P < 0.05$ ; \* represents a difference between the two groups, with  $P < 0.05$

perception was reduced, the greater the gain in exercise duration after the training (supplementary material S1).

Pre–Post changes in the perception of muscle pain were associated with Pre–Post changes in  $TTF_{40\%}$  performance ( $r = -0.49$ ,  $P = 0.004$ ; supplementary material S1), but it was not the case for the perception of effort ( $r = -0.18$ ,  $P = 0.31$ ; supplementary material S1).

### **Effects of combined motor imagery and physical training on knee extensor's neuromuscular function and fatigability**

$TTF_{20\%}$ . In the control group, MVC peak torque decreased by  $42 \pm 14\%$  at Pre-training and  $48 \pm 14\%$  at Post-training following the  $TTF_{20\%}$ . In the motor imagery group, MVC peak torque decreased by  $39 \pm 15\%$  and  $42 \pm 15\%$ . The ANCOVA analysis indicated no group effect on Post-training fatigability ( $P = 0.59$ ,  $F = 0.29$ ,  $\eta_p^2 = 0.01$ ).

$TTF_{40\%}$ . In the control group, MVC peak torque decreased by  $41 \pm 17\%$  at Pre-training and  $41 \pm 12\%$  at Post-training following the  $TTF_{40\%}$ . In the motor imagery group, MVC peak torque decreased by  $36 \pm 13\%$  and  $41 \pm 12\%$ . The ANCOVA analysis indicated no group effect on Post-training fatigability ( $P = 0.34$ ,  $F = 0.94$ ,  $\eta_p^2 = 0.03$ ).

The amplitude of neuromuscular alterations was similar at Post-training between both groups for both exercise intensities. Raw neuromuscular data and associated statistics are presented in supplementary material S2.

## **Discussion**

The aim of this study was to investigate the effect of combining motor imagery with physical training, as opposed to physical training alone, on endurance performance. Contrary to the physical training alone (control) group, participants combining motor imagery with physical training improved their endurance performance. This result supports our primary hypothesis. This finding was clearly observed when the intensity of the sustained isometric time to task failure (TTF) test closely matched the one used during the 2-week training (i.e., as evidenced by similar exercise duration between tasks), but to a lesser extent when considering a greater intensity of exercise. Contrary to our secondary hypothesis, we did not observe a reduction in the perception of effort intensity following the combined training, despite the improved endurance performance. Interestingly, we observed a decrease of muscle pain perception.

### **A combined imagined and physical wall squat training, but not wall squat training alone, enhanced isometric endurance performance**

The 2-week wall squat training alone did not improve isometric endurance performance. The lack of changes in our

active control group could primarily be due to the short duration of the wall squat training sessions and to the characteristics of our participants (young and recreationally active), thus preventing from the expected physiological adaptations leading to increased endurance performance. Interestingly, adding motor imagery to the wall squat training sessions led to improvements in TTF performance, specifically in the lower intensity condition (20% of MVC peak torque). Therefore, our study extends what was previously known from acute (Razon et al. 2010, 2014) training studies about the potential for motor imagery to improve endurance performance. Our results contribute to the growing body of evidence suggesting that a training intervention combining motor imagery and movement execution can be more beneficial than physical training alone to increase performance.

In the motor imagery group, the  $TTF_{20\%}$  increased by 25%. This increased endurance performance was confirmed by longer TTF Post training compared to control participants, with values adjusted for Pre-training  $TTF_{20\%}$ . Results are less clear for the  $TTF_{40\%}$ . The 9% Pre–Post training increases in the motor imagery group did not differ from the changes reported in the control group. By integrating these results, it seems that the greater benefits of adding motor imagery to physical training are confined to the exercise intensity closest to the one used during the combined training. As motor imagery practice induces use-dependent neural plasticity (Ruffino et al. 2019), it is plausible that the positive effect of motor imagery on endurance performance is intensity-specific. This is supported by data showing that neural configurations at both cortical (Mizuguchi et al. 2014) and spinal (Cowley et al. 2008) levels vary based on the intensity of the imagined movement. These arguments support the notion of specific adaptations occurring in response to intensity-matched training. Therefore, it is important that motor imagery interventions include the mental rehearsal of movements closely related to the actual movements performed (Guillot 2020). In our study, the intensity of the isometric wall squat exercise was similar to the one of the  $TTF_{20\%}$ . It is likely the reason why improvement in endurance performance in the motor imagery group was clearly observed only at 20%, and not at 40% of the MVC peak torque. Importantly, no changes in neuromuscular function were observed from Pre to Post training. Therefore, improvement in force production capacity of the working muscles cannot be considered as the underlying cause of the enhanced endurance performance.

### **No clear effect of the combined training on the perception of effort**

To understand how the combination of physical training and motor imagery could improve endurance performance, we decided to use the framework of the psychobiological model

of endurance performance (Marcora et al. 2008; Pageaux 2014). This model predicts that any intervention improving endurance performance should be associated with a reduction in the perception of effort reported by the participants. Contrary to our secondary hypothesis, while we observed an improved endurance performance in the motor imagery group, we did not observe a significant decrease in the intensity of the perception of effort after the 2-week training. This observation contrasts with previous studies demonstrating that psychological (Blanchfield et al. 2014) and combined (Staiano et al. 2015) training interventions improve endurance performance though a reduction in the perception of effort. Interestingly, we still observed a medium to large correlation between increased TTF in the 20% MVC condition and reduction in the perception of effort. This correlation was not present in the 40% MVC condition where the increased performance was unclear. The discrepancy in our results, as well as the difference with the existing literature, suggest that future studies should replicate our design and increase the sample size to provide clearer conclusions on the absence or presence of reduced perception of effort resulting from the combination of physical training and motor imagery interventions. Additionally, these studies may consider using the exact same exercise in the training sessions and the Pre–Post training evaluations to potentially reduce the variability of the training effect. These forthcoming studies will contribute to challenge existing models placing perception of effort as the key regulator of endurance performance, e.g. the psychobiological model of endurance performance (Marcora and Staiano 2010), the flush model (Millet 2011), and contribute to better understand the regulation of endurance performance.

Another possibility to explain the lack of significant reduction in the perception of effort is the variability in the rating of perception of effort provided by our participants. Seven out of 33 participants reported having exerted a strong effort or below (values  $\leq 55$ ) at task failure, which is far below the maximal or near maximal values reported by the other participants. These values are also much lower than values reported in the literature at task failure in isometric endurance exercises (Souron et al. 2020; Pageaux et al. 2013). These submaximal values are likely a result of the anchoring method we used for maximal effort; i.e., the greatest intensity of effort ever experienced by one participant during a physical task. It is therefore likely that these seven participants may have experienced much more intense engagement in physical tasks in their past, such as performing a marathon or an incremental running/cycling test until exhaustion. Such past experience would be associated not only with the strong muscular solicitation that our participants experienced during the knee extensor TTF, but also with strong respiratory solicitations as it is classically the case during whole-body exercise. This complements the

recent study of Malleron et al. (2023) reporting a large difference in perceived effort ratings when participants are free to select the reference for their maximal anchor compared to an imposed maximal anchor related to the performance task of interest. As effort is related to a specific goal, effort is therefore task specific (Bergevin et al. 2023; Pageaux 2016). We suggest that future studies monitoring perception of effort should impose the maximal anchor in relation to the primary task of interest. For studies interested in using self-selected maximal anchors, we propose that researchers carefully monitor for each participant (1) the self-selected reference of the maximal anchor as well as (2) the participant's physical activity and sport background to contrast with the self-selected maximal anchor. Such approach could help to better understand inter-individual differences in the perception of effort.

### **The combined training decreases the perception of muscle pain**

In line with the proposed role of muscle pain in the regulation of endurance performance [e.g. Zhang et al. (2023)], we also monitored the perception of muscle pain for exploratory analysis. The exploratory monitoring of muscle pain is also justified by previous observation suggesting a positive effect of motor imagery on pain [e.g. Volz et al. (2015)]. Interestingly, the addition of motor imagery to physical training reduced the perception of muscle pain. The instructions provided to the participants for performing motor imagery as well as the nature of the endurance exercise are likely to explain this result.

Regarding the instructions provided to the participants, the motor imagery sessions were supposed to reproduce the last 30 s of the actual exercise, when muscle pain is at its highest (e.g., “*you will only focus on the last 30 s of the wall squat exercise, when the sensations of muscle pain, discomfort, and difficulty are high*”). Therefore, participants were frequently exposed to pain-related sensory experiences during the wall squat training. It is likely that this frequent experience or rehearsal of muscle pain sensation could yield to habituation effects, leading to increased tolerance to muscle pain sensations and resulting in improved isometric endurance performance. Future neurophysiological studies are needed to unravel the potential specific neuroplastic changes induced by the combination of physical training and motor imagery (Volz et al. 2015).

Regarding the endurance exercise that we selected, its isometric nature is likely to explain the key role of muscle pain in our results. The mechanical compression during a sustained isometric contraction is unremitted, which inevitably limits the local blood flow even for contractions as low as 20% of MVC peak torque (Lind 2011). Furthermore, contrary to dynamic exercise, isometric exercise does not

activate the muscle pump, thus further contributing to the fast building of exercise metabolites (Ahlborg et al. 1972). This accumulation of metabolites within the muscle milieu, combined with the mechanical stress caused by the sustained isometric contraction, do not only contribute to the reduction in muscle force production capacity, but also to the stimulation of muscle nociceptors [afferent type III and IV fibers or A $\delta$  and C, respectively; O'Connor and Cook (1999)]. For the reasons previously mentioned, it is likely that the pain experienced during an isometric exercise is greater than during a dynamic exercise. Future studies should attempt to replicate our results with dynamic exercises, both in the context of isolated or whole-body exercise where the mechanisms explaining task failure differ. We also would like to emphasize that given the exploratory nature of our analysis on muscle pain, the reproduction of our results is of particular importance, with study focusing especially on this variable with specific *a-priori* hypothesis.

In conclusion, our study offers preliminary evidence that combining motor imagery with physical training is efficient to improve isometric endurance performance. While the effect of the combined training on the perception of effort is unclear, our results highlight a reduction in muscle pain. The combined physical plus motor imagery training appears to be equally effective as other psychological interventions [e.g., Blanchfield et al. (2014); Barwood et al. (2015)] in improving endurance performance. Of particular interest is that 12 training sessions over a span of 2 weeks was efficient in improving endurance performance in our population. Our findings also strongly suggest a specific effect of imagery training, confined within the same exercise nature and intensity (20% MVC peak torque) as the actual training performed. The positive effect of combining motor imagery with physical training beyond the intensity used in the actual training remains to be determined. The lack of transfer towards the non-specific exercise intensity (40% MVC peak torque) used in the training suggests the involvement of specific neuroplastic modulations. As our study was not designed to investigate such specific neuroplastic modulations, we encourage researchers to explore this possibility with larger sample size to optimize the possibility to detect such modulations. Even though the present observations need to be reproduced with athletes or individuals living with medical conditions, our results have potential practical implications in various domains, including sports and clinical settings. The integration of motor imagery training alongside physical training could enhance endurance performance in athletes, while also providing a means to manage and alleviate the perceived sensation of muscle pain. The combined training approach may also be particularly beneficial for individuals with pain conditions (e.g., chronic pain, critically ill patients) or those undergoing rehabilitation,

as it offers a non-pharmacological and potentially effective method for pain management and motor performance improvement.

## References

- Ahlborg B, Bergström J, Ekelund L-G, Guarnieri G, Harris R, Hultman E, Nordesjö L (1972) Muscle metabolism during isometric exercise performed at constant force. *J Appl Physiol* 33(2):224–228. <https://doi.org/10.1152/jappl.1972.33.2.224>
- Barwood MJ, Corbett J, Wagstaff CR, McVeigh D, Thelwell RC (2015) Improvement of 10-km time-trial cycling with motivational self-talk compared with neutral self-talk. *J Sports Physiol Perform* 10(2):166–171. <https://doi.org/10.1123/jsp.2014-0059>
- Basset FA, Kelly LP, Hohl R, Kaushal N (2022) Type of self-talk matters: Its effects on perceived exertion, cardiorespiratory, and cortisol responses during an iso-metabolic endurance exercise. *Psychophysiology* 59(3):e13980. <https://doi.org/10.1111/psyp.13980>
- Bergevin M, Steele J, Payen de la Garanderie M, Feral-Basin C, Marcora SM, Rainville P, Caron JG, Pageaux B (2023) Pharmacological blockade of muscle afferents and perception of effort: a systematic review with meta-analysis. *Sports Med* 53(2):415–435. <https://doi.org/10.1007/s40279-022-01762-4>
- Blanchfield AW, Hardy J, De Morree HM, Staiano W, Marcora SM (2014) Talking yourself out of exhaustion: the effects of self-talk on endurance performance. *Med Sci Sports Exerc* 46(5):998–1007. <https://doi.org/10.1249/MSS.000000000000184>
- Borg E, Kaijser L (2006) A comparison between three rating scales for perceived exertion and two different work tests. *Scand J Med Sci Sports* 16(1):57–69. <https://doi.org/10.1111/j.1600-0838.2005.00448.x>
- Brehm JW, Self EA (1989) The intensity of motivation. *Annu Rev Psychol* 40:109–131. <https://doi.org/10.1146/annurev.ps.40.020189.000545>
- Cohen J (1988) *Statistical power analysis for the behavioral sciences*. Erlbaum, Hillsdale, NJ
- Cowley PM, Clark BC, Ploutz-Snyder LL (2008) Kinesthetic motor imagery and spinal excitability: the effect of contraction intensity and spatial localization. *Clin Neurophysiol* 119(8):1849–1856. <https://doi.org/10.1016/j.clinph.2008.04.004>

- Dallaway N, Lucas SJE, Ring C (2021) Concurrent brain endurance training improves endurance exercise performance. *J Sci Med Sport* 24(4):405–411. <https://doi.org/10.1016/j.jsams.2020.10.008>
- Dallaway N, Lucas S, Marks J, Ring C (2023) Prior brain endurance training improves endurance exercise performance. *Eur J Sport Sci* 23(7):1269–1278. <https://doi.org/10.1080/17461391.2022.2153231>
- Grosprêtre S, Jacquet T, Lebon F, Papaxanthis C, Martin A (2018) Neural mechanisms of strength increase after one-week motor imagery training. *Eur J Sport Sci* 18(2):209–218. <https://doi.org/10.1080/17461391.2017.1415377>
- Guillot A (2020) 14 Neurophysiological foundations and practical applications of motor imagery. In: Abraham A (ed) *The Cambridge handbook of the imagination*. Cambridge University Press, Cambridge, pp 207–226
- Guillot A, Desliens S, Rouyer C, Rogowski I (2013) Motor imagery and tennis serve performance: the external focus efficacy. *Jsports Sci Med* 12(2):332–338
- Hardwick RM, Caspers S, Eickhoff SB, Swinnen SP (2018) Neural correlates of action: comparing meta-analyses of imagery, observation, and execution. *Neurosci Biobehav Rev* 94:31–44. <https://doi.org/10.1016/j.neubiorev.2018.08.003>
- Hart SG, Staveland LE (1988) Development of NASA-TLX (Task Load Index): results of empirical and theoretical research. *Adv Psychol* 52:139–183
- Hunter SK, Duchateau J, Enoka RM (2004) Muscle fatigue and the mechanisms of task failure. *Exerc Sport Sci Rev* 32(2):44–49. <https://doi.org/10.1097/00003677-200404000-00002>
- Jacquet T, Lepers R, Poulin-Charronnat B, Bard P, Pfister P, Pageaux B (2021) Mental fatigue induced by prolonged motor imagery increases perception of effort and the activity of motor areas. *Neuropsychologia* 150:107701. <https://doi.org/10.1016/j.neuropsychologia.2020.107701>
- Kayser B (2003) Exercise starts and ends in the brain. *Eur J Appl Physiol* 90(3–4):411–419. <https://doi.org/10.1007/s00421-003-0902-7>
- Lakens D (2022) Sample size justification. *Collabra Psychol* 8(1):33267
- Lind AR (2011) Cardiovascular adjustments to isometric contractions: static effort. *Compr Physiol* 947–966
- Malleron T, Har-Nir I, Vigotsky AD, Halperin I (2023) Rating of perceived effort but relative to what? A comparison between imposed and self-selected anchors. *Psychol Sport Exerc* 66:102396. <https://doi.org/10.1016/j.psychsport.2023>
- Marcora S (2019) Psychobiology of fatigue during endurance exercise. In: Meijen C (ed) *Endurance performance in sport*. Routledge, Abingdon, pp 15–34
- Marcora SM, Staiano W (2010) The limit to exercise tolerance in humans: mind over muscle? *Eur J Appl Physiol* 109(4):763–770. <https://doi.org/10.1007/s00421-010-1418-6>
- Marcora SM, Bosio A, de Morree HM (2008) Locomotor muscle fatigue increases cardiorespiratory responses and reduces performance during intense cycling exercise independently from metabolic stress. *Am J Physiol Regul Integr Comp Physiol* 294(3):R874–R883. <https://doi.org/10.1152/ajpregu.00678.2007>
- Marcora S, Staiano W, Merlini M (2013) Brain training improves endurance performance. *ECSS Amsterdam 2014*:1469–0691.2011
- Millet GY (2011) Can neuromuscular fatigue explain running strategies and performance in ultra-marathons? *Sports Med* 41(6):489–506. <https://doi.org/10.2165/11588760-00000-00000>
- Mizuguchi N, Nakata H, Kanosue K (2014) Activity of right pre-motor-parietal regions dependent upon imagined force level: an fMRI study. *Front Hum Neurosci* 8:810. <https://doi.org/10.3389/fnhum.2014.00810>
- Nicolò A, Sacchetti M, Girardi M, McCormick A, Angius L, Bazzucchi I, Marcora SM (2019) A comparison of different methods to analyse data collected during time-to-exhaustion tests. *Sport Sci Health* 15(3):667–679
- O'Connor PJ, Cook DB (1999) Exercise and pain: the neurobiology, measurement, and laboratory study of pain in relation to exercise in humans. *Exerc Sport Sci Rev* 27:119–166
- Pageaux B (2014) The psychobiological model of endurance performance: an effort-based decision-making theory to explain self-paced endurance performance. *Sports Med* 44(9):1319–1320. <https://doi.org/10.1007/s40279-014-0198-2>
- Pageaux B (2016) Perception of effort in exercise science: definition, measurement and perspectives. *Eur J Sport Sci* 16(8):885–894. <https://doi.org/10.1080/17461391.2016.1188992>
- Pageaux B, Lepers R (2016) Fatigue induced by physical and mental exertion increases perception of effort and impairs subsequent endurance performance. *Front Physiol* 7:587. <https://doi.org/10.3389/fphys.2016.00587>
- Pageaux B, Marcora SM, Lepers R (2013) Prolonged mental exertion does not alter neuromuscular function of the knee extensors. *Med Sci Sports Exerc* 45(12):2254–2264. <https://doi.org/10.1249/MSS.0b013e31829b504a>
- Pageaux B, Clos P, Impellizzeri F, Audiffren M, Stapley P, Grémeaux V, Perrey S, O'Connor PJ, Marcora SM, Lepers R (2020) Towards standardized instructions for measuring perception of effort and muscle pain during physical exercise. *Med Sci Sports Exerc* 52(7S):499. <https://doi.org/10.1249/01.mss.0000679556.09727.4b>
- Piveteau E, Di Rienzo F, Bolliet O, Guillot A (2023) Inter-task transfer of force gains is facilitated by motor imagery. *Front Neurosci* 17:1228062. <https://doi.org/10.3389/fnins.2023.1228062>
- Place N, Bruton JD, Westerblad H (2009) Mechanisms of fatigue induced by isometric contractions in exercising humans and in mouse isolated single muscle fibres. *Clin Exp Pharmacol Physiol* 36(3):334–339. <https://doi.org/10.1111/j.1440-1681.2008.05021.x>
- Razon S, Basevitch I, Land W, Thompson B, Biermann M, Tenenbaum G (2010) Associative and dissociative imagery effects on perceived exertion and task duration. *J Imag Res Sport Phys* 5(1). <https://doi.org/10.2202/1932-0191.1044>
- Razon S, Mandler K, Aarsal G, Tokac U, Tenenbaum G (2014) Effects of imagery on effort perception and cycling endurance. *J Imag Res Sport Phys* 9(1):23–38. <https://doi.org/10.1515/jirspa-2013-0011>
- Robin N, Coudeville GR, Guillot A, Toussaint L (2020) French translation and validation of the Movement Imagery Questionnaire-third version (MIQ-3f). *Mov Sport Sci* 2:23–31. <https://doi.org/10.1051/sm/2019035>
- Ruffino C, Gaveau J, Papaxanthis C, Lebon F (2019) An acute session of motor imagery training induces use-dependent plasticity. *Sci Rep* 9(1):1–9. <https://doi.org/10.1038/s41598-019-56628-z>
- Souron R, Voirin AC, Kennouche D, Espeit L, Millet GY, Rupp T, Lapole T (2020) Task failure during sustained low-intensity contraction is not associated with a critical amount of central fatigue. *Scand J Med Sci Sports*. <https://doi.org/10.1111/sms.13815>
- Staiano W, Marcora S, Romagnoli M, Kirk U, Ring C (2023) Brain endurance training improves endurance and cognitive performance in road cyclists. *J Sci Med Sport* 26(7):375–385. <https://doi.org/10.1016/j.jsams.2023.05.008>
- Staiano W, Merlini M, Marcora S (2015) A randomized controlled trial of brain endurance training (BET) to reduce fatigue during endurance exercise. In: *ACSM annual meeting, San Diego*

- Volz MS, Suarez-Contreras V, Portilla ALS, Fregni F (2015) Mental imagery-induced attention modulates pain perception and cortical excitability. *BMC Neurosci* 16(1):1–10. <https://doi.org/10.1186/s12868-015-0146-6>
- Zhang J, Abel S, Macphail M, Aboodarda SJ (2023) Persistent contralateral pain compromises exercise tolerance but does not alter corticomotor responses during repeated, submaximal isometric knee extensions to task failure. *Neuroscience* 526:267–276. <https://doi.org/10.1016/j.neuroscience.2023.07.005>

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.