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Is reaction time altered by mental or physical exertion?

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Abstract

Purpose Reaction time, classically divided into premotor time and electromechanical delay (EMD), can be determinant in daily life or sport situations. While some previous studies reported a negative impact of both muscle and mental fatigue on reaction time, the respective contributions of premotor time and EMD to the changes of reaction time remains unclear. The aim of the study was, therefore, to assess the effects of both muscle and mental effort on reaction time and its components.
Methods Thirteen subjects performed three conditions (mental effort condition, i.e., 14 min of a mathematical cognitive task; muscle effort condition, i.e., intermittent contractions of the *biceps brachii*; control condition, i.e., watching a documentary). Before and after each condition, reaction time, premotor time and EMD were measured during voluntary contractions of the *biceps brachii*. EMD was also measured during evoked contractions of the *biceps brachii* to separate the parts due to the onset of muscle fascicle motion and the onset of force production.
Results Reaction time and premotor time remained stable regardless of the condition considered (all P values > 0.05). EMD increased only after the muscle effort condition ($+ 25\%$ during voluntary contractions, no significant; $+ 17\%$ during evoked contractions, $P = 0.001$), mainly due to an increase in the passive part of the series elastic component.
Conclusion Our study showed that neither mental nor muscle effort has a negative effect on simple reaction time during voluntary contractions.

Keywords Mental effort · Muscle effort · Premotor time · Electromechanical delay

Abbreviations

ANOVA	Analysis of variance
EMD_{stim}	Electromechanical delay during electrical stimulation
EMD_{vol}	Electromechanical delay during voluntary contraction
MVC	Maximal voluntary contraction
RFD	Rate of force development

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Introduction

Reaction time, defined as the time interval between the onset of a stimulus and the time to initiate a response (Pachella 1974), can be influenced by several factors such as age (Der and Deary 2006), gender (Der and Deary 2006), or stimulus intensity (Davranche et al. 2006). Based on the work of Weiss (1965), reaction time is classically fractionated into two components, i.e., premotor time and motor time or electromechanical delay (EMD), in which premotor time reflects cognitive function, i.e., central components, while EMD reflects motor function, i.e., peripheral components (Schmidt and Alan Stull 1970). In addition, EMD can be reliably evaluated either during voluntary (EMD_{vol}) (Minshull et al. 2009) or stimulated (EMD_{stim}) (Nordez et al. 2009; Esposito et al. 2016) contractions.

Fatigue is a complex phenomenon involving muscular (Gandevia 2001) and mental (Marcora et al. 2009) components. Muscle fatigue can be defined as any exercise-induced reduction in the ability to generate a required level of force or power (Gandevia 2001). Mental fatigue can be defined as a psychobiological state characterized by subjective feelings

of "tiredness" and "lack of energy" (Marcora et al. 2009). Some studies previously investigated the effects of muscle fatigue on reaction time but produced different results. A low level of exercise intensity (heart rate around 115 beats per min, Sjöberg 1975) can improve reaction time during both running (Collardeau et al. 2001) and cycling (Davranche et al. 2006) as a result of an increase in attentional focus, i.e., arousal or state of attention (Chmura et al. 1998). Beyond a given exercise duration and/or intensity, muscle fatigue induces an increase in reaction time that can be due to a decrease in cognitive performance (Chmura et al. 1994). Thus, the relation between the level of arousal and reaction time response looks U-shaped, i.e., fastest reaction time with an intermediate level of arousal and slower reaction time when the subject is either too relaxed or too tense (Welford 1980). In addition, a significant increase in EMD_{vol} following muscle fatigue was reported while premotor time remained relatively stable (Klimovitch 1977; Stull and Kearney 1978). Klimovitch (1977) showed that the increase in EMD_{vol} led to a significant increase in reaction time while in the study of Stull and Kearney (1978), this parameter did not change. The discrepancy between these two studies may be attributed to the large role of EMD_{vol} in total reaction time for Klimovitch (~45%) when compared to Stull and Kearney (~15%). More recently, Pääsuke et al. (1999) found similar results, i.e., unchanged premotor time and longer EMD_{vol} due to muscle fatigue. Many studies have assessed the effects of muscle fatigue on EMD (and not total reaction time) and reported an increase of this parameter measured during voluntary (Conchola et al. 2015) and stimulated (Rampichini et al. 2014) contractions, supporting the results cited above. Considering the contributions to the EMD of both muscle force transmission and excitation–contraction coupling, either can explain the changes due to fatigue (Rampichini et al. 2014). It is also possible that mental characteristics of the participants, for example people who suffer from attentional difficulties in every-day life (Steinborn et al. 2016), which were not controlled in the previous studies (Klimovitch 1977; Stull and Kearney 1978; Pääsuke et al. 1999), may explain the differences observed. In the same way, the presence or absence of written or oral instructions, i.e., motivation, given to the participants, may influence RT (Steinborn et al. 2017). Finally, it is not clear if muscle fatigue impairs the central (premotor) or the peripheral (EMD) component (or both) of reaction time and if this elongation leads to a significant elongation of the total measure.

While the topic of mental fatigue seems to be of interest in the field of sport sciences (Pageaux and Lepers 2018), the effects of mental fatigue on physical performance and on reaction time has been less documented. Mental fatigue is generally induced by prolonged engagement in demanding cognitive task (Rozand and Lepers 2017; Pageaux and Lepers 2018) such as incongruent Stroop task or AX-continuous

performance task (AX-CPT) and involves various executive functions, such as sustained attention, response-inhibition and updating, depending on the characteristics of the cognitive task performed (Diamond 2013). According to a recent review (Pageaux and Lepers 2018), mental fatigue impairs the performance during many activities such as endurance performance (Marcora et al. 2009; Pageaux et al. 2013, 2014), goal-directed movement involving the speed-accuracy trade-off (Smith et al. 2016a; Le Mansec et al. 2018) and decision-making performance (Laborde and Raab 2013; Smith et al. 2016b). Interestingly, it appears that the decline of performance during mental fatigue is generally mediated by higher perceived exertion when compared to a control condition (Pageaux and Lepers 2018).

In addition, it seems that mental fatigue impairs complex tasks, i.e., tasks requiring high cognitive levels, while automated tasks are not altered (Lorist et al. 2000, 2005; Langner et al. 2010a). Considering the effects of mental fatigue on reaction time, Langner et al. (2010a) reported a significant increase in reaction time after 17 min of a simple reaction time task. These authors suggested that mental fatigue affects the attentional aspect, i.e., processing stimulus information and initiation of the motor response.

Mental fatigue is known to negatively affect several execution functions, i.e., impaired action monitoring and response preparation (Boksem et al. 2006), reduction in goal-directed attention (Boksem et al. 2005) and a decrease in the ability to generate or test new hypotheses (van der Linden et al. 2003). Alteration at the anterior cingulate cortex is classically put forward as a main mechanism (Boksem et al. 2006; Pageaux et al. 2014), due to high activation of this brain area during cognitive tasks involving response inhibition (Pageaux and Lepers 2018). Considering the mechanisms involved in the decrease in performance during or after a mental effort task, it would be likely that they negatively affect premotor time rather than EMD.

Thus, this study aimed to assess the effects of both muscle and mental effort on reaction time and its components, i.e., premotor time and electromechanical delay, during a simple reaction time task involving the upper limbs. For a better understanding of the underlying mechanisms involved at a peripheral level, we also aimed to fractionate the motor component during electrical stimulations (EMD_{stim}) by using ultrafast ultrasound, as depicted by Nordez et al. (2009). We hypothesized that (1) mental effort would impair premotor time and consequently reaction time, and (2) muscle effort would impair EMD and consequently reaction time.

## Materials and methods

Participants

Based on a previous study (Le Mansec et al. 2017) and on an a priori sample size calculation for a target power of 80% (α err prob = 0.05), it was compulsory that 12 participants were necessary for the present study. Only men were recruited in the present study, because it is generally thought that men have a faster reaction time than women (Der and Deary 2006) although this disadvantage is diminishing for visual reaction time (Silverman 2006). As Hopkins (2006) recommended using only subjects of one sex, we decided to test only men to avoid a possible sex effect. Thus, 13 healthy and active men (mean ± SD; age 25.2 ± 3.7 years, height 180.1 ± 6.5 cm, weight 71.6 ± 9.4 kg, physical activity 6.0 ± 3.5 h/week) volunteered to participate in this study after receiving a full explanation of the experimental procedures. None of them had any known mental disorder or muscular/tendon upper limb injury in the past year. Each participant gave his written and informed consent prior to the study. The local ethics committee, in accordance with the Declaration of Helsinki, approved all procedures. All participants were given instructions to sleep for at least 7 h and not to practice vigorous physical activity the day before each session (checked by completion of a pre-test checklist).

Experimental design

Four sessions were performed to assess the effects of both mental and muscle effort on reaction time and its components. A familiarization was performed in the first session to accustom the participants to all procedures. During this session, participants performed neuromuscular tests, consisting of superimposed maximal voluntary contractions (MVC) and potentiated twitch, resting twitch (EMD$_{stim}$) and performed 50 reaction time trials (visual stimulus). Participants also learned to quickly fill out the psychological test to minimize the time lag between the end of the fatiguing protocol and the reaction time trials (< 1-min).

Thereafter, all participants achieved the three actual testing sessions in a randomized order (control condition, mental effort condition, muscle effort condition) at the same time of day (± 1 h), with a minimum of 1-week recovery between sessions. During each session (between 50 and 60 min duration), participants completed the fatigue protocol (mental effort, muscle effort) or the control task (watching a movie). MVC, EMD and reaction time were measured before (pre) and after (post) both mental and muscle protocols and the control task. Subjective workload imposed by the protocols
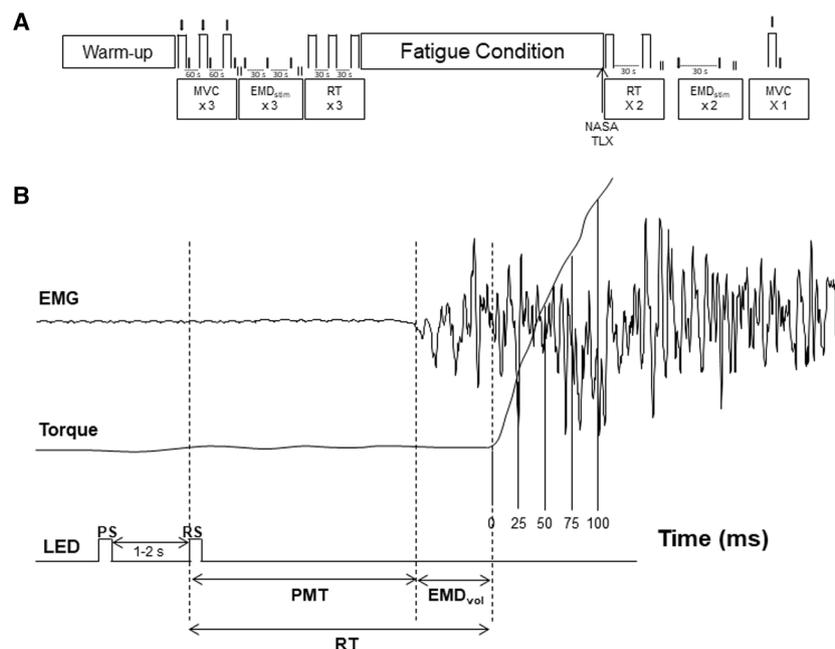
Fig. 1 **a** Overview of the experimental protocol. MVC: maximal voluntary contraction of the biceps brachii; EMD$_{stim}$: electromechanical delay assessed during evoked contraction; RT: reaction time. Arrow = single stimulation during (superimposed) or after (potentiated resting twitch) MVC. **b** Diagram showing raw electromyography (EMG), non filtered torque and visual stimuli (preparatory signal, PS and response signal, RS). Reaction time (RT) was determined as the time (ms) between RS and torque onset. Pre-motor time (PMT) was determined as the time (ms) between RS and EMG onset. Voluntary electromechanical delay (EMD$_{vol}$) was determined as the time (ms) between EMG and torque onsets. To improve the visibility of the diagram, the calibration of the time scale has not been followed

was assessed after each protocol. An overall view of the protocol can be found in Fig. 1.

Prior to the pre-effort MVC, participants completed a warm-up of 8 submaximal contractions (~8-s) ranging from 20 to 80% of the estimated isometric MVC torque, followed by a 3-min rest. Before completion of the effort protocol/control task, participants performed three isometric maximal voluntary contractions of 4-s duration interspersed by 60-s rest in between of the elbow flexors. Thereafter (~5 min later), three evoked contractions were applied to assess the stimulated electromechanical delay, followed (~10 min later) by three reaction time trials (see below for further details). After completion of the effort protocol/control task, participants performed, in the same order, two reaction time trials, two evoked contractions and only one MVC. To ensure that only a minimum of recovery occurred (see Froyd et al. 2013 and below for further details), all the post tests were performed without rest, except the time required to adjust the device (e.g. cables, electrode array).

Measured variables

Subjective workload

The National Aeronautics and Space Administration Task Load Index (NASA-TLX; Hart and Staveland 1988) was used to assess the subjective workload of the effort protocols. The NASA-TLX is composed of six subscales (i.e., mental demand, physical demand, temporal demand, performance, effort and frustration) in which the participants had to put a mark on a scale divided into 20 equal intervals anchored by a bipolar descriptor (very low/very high). This score was multiplied by 5, giving a final score between 0 and 100 for each subscale. Participants completed the NASA-TLX immediately after completion of the effort protocol/control task (Fig. 1).

Maximal voluntary contraction

During MVCs, participants sat in a chair in a dimly lit room, and their dominant arm was fixed in a home-made dynamometer equipped with a strain gauge (F2712, MEIRI, Spherel Systèmes, France). Both shoulder and arm were set at 90° in the transverse plane, and the hand was in supination, with the wrist firmly attached to the dynamometer with a strap. During completion of the MVCs, strong verbal encouragements were provided (Gandevia 2001) and the best trial was retained for further analysis (pre-effort) while one MVC was performed post-effort to avoid any recovery effect (Froyd et al. 2013). Prior to the completion of MVCs, participants were instructed to perform 'as hard as possible' (Maffiuletti et al. 2016).

Voluntary activation and contractile properties

Electrical stimulations (200 µs duration, 400 V) were delivered using an electrical stimulator (Digitimer, DS7A, Hertfordshire, UK) at supra maximal-intensity (120% of the stimulation intensity inducing maximal mechanical response) through two electrodes placed 1 cm apart on the anterior face below the motor point (10-mm diameter, Ag-AgCl, Kendall, Covidien, Dublin, UK) and the distal portion of the biceps brachii muscle (9 cm × 5 cm; Stimex®, Rouffach, France). Single electrical stimulation was delivered in relaxed muscle to assess electromechanical delay (EMD$_{stim}$). A superimposed stimulation was delivered over the isometric plateau during each MVC as well as 2 s after the MVCs in the relaxed muscle. The superimposed and potentiated twitches were used to assess voluntary activation and biceps brachii contractile properties. The following formula was used to assess voluntary activation:

$$\text{Voluntary activation (\%)} = \left(1 - \left[\frac{\text{superimposed twitch}}{\text{potentiated resting twitch}}\right]\right) \times 100.$$

Reaction time, pre-motor time and motor time (EMD$_{vol}$)

Participants sat as for the neuromuscular tests (see above). One LED (red light, imperative stimulus) was presented at a distance of 1 m in front of the participants. Participants were asked to react as fast and explosive as possible to the visual stimulus by contracting their elbow flexor muscles. A warning signal (identical to the imperative stimulus) from an electronic box, simultaneously connected to electromyographic (EMG) and torque data acquisition, was presented with a time lag between 1 and 2 s before the imperative stimulus in order to (1) ensure that participants remained uncertain about the exact moment of stimulus occurrence and to avoid anticipation (Langner et al. 2010a) and (2) to avoid any effect of foreperiod length (Langner et al. 2010a). As it has been previously shown that punctual instructions (e.g. written, oral) could have a significant influence on RT (i.e., spare capacity model, Steinborn et al. 2017), we chose not to nudge the participants during the RT trials to avoid any exogenous influence. To prevent unwanted movement, such as pre-tension or countermovement that could alter the shape of the rising force–time curve during the reaction time trials (Maffiuletti et al. 2016), participants were accustomed to maximally relax their arm during the foreperiod, i.e., delay between the warning and the imperative stimulus (Langner et al. 2010a). Prior to the completion of reaction time trials, participants were instructed to perform 'as fast and explosive as possible' (Maffiuletti et al. 2016).

It has been previously demonstrated that skeletal muscle function recovery occurs very early after exercise (~ 1 min, Froyd et al. 2013), which can bias the results if the test is performed too late after the end of the exercise. To attenuate this drawback, we recently reported a satisfying reliability of reaction time, premotor time and EMD_{vol} when limiting the number of trials, i.e., two trials (Le Mansec et al. 2017). Thus, participants performed three trials before the fatigue protocol and two trials after the fatigue protocol. For each series, the best trial, measured as faster reaction time, was retained for further analysis.

To accurately determine premotor time, we recorded EMG signals with an electrode array, as previously described by Le Mansec et al. (2017). EMG was amplified (× 500) and sampled at a 2048-Hz frequency (EMG-USB, LISIN Ottino, Bioelettronica, Italy). After careful preparation of the skin, by abrading and cleaning with alcohol, a 64-channel electrode array was positioned on the muscle belly of the biceps brachii. For each fastest reaction time trial, the fastest channel was considered as the onset of EMG and was retained for analysis. Lastly, EMD_{vol} was calculated as follow: EMD_{vol} (ms) = reaction time − premotor time.

EMD (EMD_{stim}) during electrical stimulation

EMD_{stim} was defined as the time lag between the stimulation artifact and the onset of force production (Nordez et al. 2009) and was assessed during electrical stimulation. To fractionate EMD_{stim}, we used a very high frame rate (4 kHz) ultrasound device (Supersonic Imagine, Aix-en-Provence, France). During the electrical stimulations, an ultrasound probe was maintained over the biceps brachii muscle belly, parallel to the bone. As described by Nordez et al. (2009), muscle stimulations were started using a trigger delivered by the ultrafast ultrasound device with a 50 ms delay. By using this device, we determined the delay between the onset of electrical stimulation and the onset of muscle fascicules motion, i.e., part of the EMD_{stim} due to the synaptic transmission, excitation–contraction coupling and force transmission along the active part of the series elastic component (Nordez et al. 2009), i.e., EMD_{stim} part 1. To avoid any desynchronization, the trigger of the stimulation, force, and stream generator (DG 2A, Digitimer, Hertfordshire, UK) were recorded using the same device (see below).

Mechanical data (superimposed MVC, potentiated twitch, EMD_{stim} and reaction time) and the electronic box used for the light signals (reaction time trials) were recorded and stored (PowerLab 16/35, ADInstruments Ltd) at a sampling frequency of 4 kHz for off-line analysis (LabChart 8, ADInstruments Ltd).

Effort protocols

Biceps effort

To induce muscle fatigue of the elbow flexor muscles, the incremental test previously validated by Bachasson et al. (2013) for the quadriceps muscle was used. Briefly, participants performed sets of 10 intermittent contractions (5-s on/5-s off) at a submaximal target force starting at 10% MVC for the first set, 20% MVC for the second and so on until task failure. The test ended when two consecutive contractions were visually under the target force required for at least 2.5 s (Bachasson et al. 2013). Participants had a visual force feedback providing the target level and an auditory feedback indicating the contraction–relaxation rhythm. To ensure maximal engagement, participants were strongly encouraged during the contractions (from 40% MVC intensity).

Mental effort

To induce mental fatigue, a mathematical cognitive task similar to that used by Keller-Ross et al. (2014) and Noteboom et al. (2001) was used. Participants performed serial subtraction of a four digit number during 14 min. In the first 7 min, participants counted backward by 7, starting from 1022. Participants were instructed to count as fast as possible. When participants made a mistake (wrong answer, without time constraints), the experimenter stopped him and gave the last good answer given by the participant. After 7 min, the participant was told to stop counting and to restart the task (same number), counting backward by 13 during a second bout of 7 min. To ensure engagement and vigilance during the cognitive task, a money prize was given for the three best performances (50, 30 and 20 euros), but no further financial benefit was granted in this study. To minimize the time lag between the end of the protocol and the reaction time trials (time to fill out questionnaires), a pilot study ($n = 21$) was previously conducted to assess the ability of this cognitive task to induce a mental fatigue. In this pilot study, participants were asked to rate their feelings of fatigue on a visual analogue scale (Marcora et al. 2009) and their mood (both vigor and fatigue) using the Brunel Mood Scale (BRUMS, Terry et al. 2003) before and after completion of the mathematical task (14 min duration). A significant effect of the cognitive task was found for feelings of fatigue, i.e., increase of the VAS ($P = 0.002$, $d_z = 0.94$) and for the mood, i.e., decrease of vigor ($P = 0.003$, $d_z = 0.73$), indicating a state of mental fatigue. Thus, although mental fatigue has not been directly measured in the current study, the term 'mental fatigue' is used in the manuscript.

Control task

The control protocol consisted of watching a movie ("Home"; Y. Arthus Bertrand, 2009) for 20 min. Subjects were sat as they were during the fatigue protocols and the film was projected onto a wall (80 cm length/50 cm width). This movie does not induce subjective feelings of fatigue (Rozand et al. 2015).

Data processing

Mechanical data

As a visual approach was defined as the Gold standard method to detect the contraction onset (Maffiuletti et al. 2016), mechanical signals were not filtered and the onset of torque production was visually determined for both reaction time and EMD_{stim}. Total reaction time was fractionated into two components, i.e., premotor time and motor time (EMD_{vol}). Premotor time was defined as the delay between the imperative stimulus and the onset of the EMG activity of the biceps brachii. EMD_{vol} was defined as the delay between the onset of EMG and the onset of torque production. The part of the delay attributed to the muscle force propagation along the passive part of the series elastic component (EMD_{stim} part 2) was EMD_{stim} minus EMD_{stim} part 1. The rate of force development (RFD) was measured during the reaction time trials as the slope of the torque–time curve in the time intervals 0–25 ms (RFD_{0-25}), 0–50 ms (RFD_{0-50}), 0–75 ms (RFD_{0-75}) and 0–100 ms (RFD_{0-100}) before (pre) and after (post) completion of the fatigue protocol/control task (Tillin et al. 2012).

EMG data

EMG data were processed using Matlab scripts (R2008b, USA). EMG signals were filtered (10–400 Hz, 2nd order Butterworth filter), then the Teager-Kaiser energy operator (TKEO) was applied to improve signal-to-noise ratio and minimize erroneous EMG onset detection (Solnik et al. 2010). The baseline noise was not systematically small enough to easily detect the onset of EMG (Begovic et al. 2014). Therefore, all EMG signals were smoothed (5 s moving average) and all 64 channels were visually inspected for the fastest reaction time of each series.

Statistical analysis

Statistical tests were performed with Statistica V6 software (Statsoft, Tulsa, OK, USA) and G*Power software (version 3.1.6 Universität Düsseldorf, Germany). All data are expressed as the mean ± SD. Assumption of normality was checked as appropriate by using a Kolmogorov–Smirnov

test. Assumption of sphericity was also checked using the Mauchly's test. When appropriate, the Greenhouse–Geisser Epsilon correction was applied to the degrees of freedom. One-way factorial analysis of variance (main effect ANOVA, three groups: control vs mental effort vs muscle effort) was used to test the effects of the three protocols on the NASA-TLX subscales. Two-way repeated measures ANOVAs (condition: control, mental effort and muscle effort, time: pre and post effort protocols/control task) were used to test the effect of the protocols on neuromuscular parameters (MVC, voluntary activation, contractile properties), EMD_{stim} components (EMD_{stim}, onset of muscle fascicles motion and passive part of the series elastic component) and reaction time components (reaction time, premotor time and EMD_{vol}). Three-way repeated measures ANOVA (time intervals: RFD_{0-25}, RFD_{0-50}, RFD_{0-75} and RFD_{0-100}, condition: control, mental effort and muscle effort, time: pre and post) was used to test the effect of the protocols on different torque-time curve RFD. When a significant interaction was revealed, an honestly significant difference Tukey test for multiple comparisons was performed. For the main effects of the ANOVAs, partial eta squared (η_p^2) are reported, with small, moderate and large effects considered for $\eta_p^2 \geq 0.01$, ≥ 0.06 and ≥ 0.14. For the follow up tests, Cohen's effect sizes d_z are reported, with small, moderate and large effects considered for $d_z \geq 0.2$, ≥ 0.5 and ≥ 0.8, respectively. Pearson's product moment correlation coefficient (r) was calculated to determine the association between reaction time components and EMD_{stim} components. The significance was set at $P < 0.05$ (two-tailed) for all analyses.

Results

Effects of the protocols on psychological parameters

Subjective workload related to the protocols

There was a significant difference between conditions for the following subscales: mental demand ($P < 0.001$, $\eta_p^2 = 0.835$), physical demand ($P < 0.001$, $\eta_p^2 = 0.923$), temporal demand ($P < 0.001$, $\eta_p^2 = 0.690$), performance ($P = 0.001$, $\eta_p^2 = 0.548$), effort ($P < 0.001$, $\eta_p^2 = 0.859$) and frustration ($P < 0.001$, $\eta_p^2 = 0.648$). Follow-up tests are presented in Fig. 2. Mental demand was significantly higher after completion of the mental effort protocol when compared to the control task ($P < 0.001$, $d_z = 3.323$) and the muscle effort protocol ($P < 0.001$, $d_z = 1.760$). Physical demand was significantly higher after completion of the muscle effort when compared to the control task ($P < 0.001$, $d_z = 5.884$) and the mental effort protocol ($P < 0.001$, $d_z = 2.889$).

Fig. 2 Subjective workload related to the fatigue protocols. $^{\$,\$\$,\$\$\$}$Significant difference between conditions ($P < 0.05$, $P < 0.01$ and $P < 0.001$ respectively). †Trend difference between conditions ($0.05 < P < 0.1$). Data are presented as mean $\pm$ SD
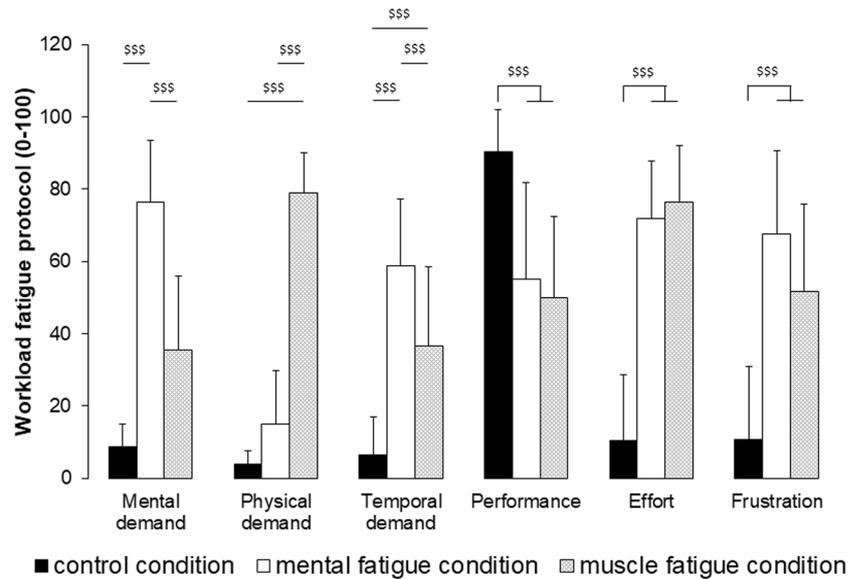
Effects of the protocols on neuromuscular function

Maximal voluntary contraction

There was a significant interaction time × condition for the MVC torque ($P < 0.001$, $\eta_p^2 = 0.671$). MVC torque significantly decreased solely after the muscle effort protocol (100.4 ± 16.6 N m to 82.5 ± 15.9 N m, i.e., $-17.7 \pm 8.3\%$, $P < 0.001$, $d_z = 1.851$) and not after both mental effort protocol and control task (99.0 ± 16.8 N m to 96.7 ± 18.0 N m, i.e., $-2.3 \pm 6.3\%$, $P = 0.851$, $d_z = 0.347$ and 100.9 ± 12.9 N m to 100.4 ± 15.2 N m, i.e., $-0.7 \pm 4.5\%$, $P = 0.999$, $d_z = 0.107$ for mental effort and control task, respectively). The biceps fatigue task lasted 10 min 55 s (± 1 min 24 s) on average.

Voluntary activation

There was no significant main effect of time ($P = 0.277$, $\eta_p^2 = 0.097$), condition ($P = 0.173$, $\eta_p^2 = 0.135$) or interaction ($P < 0.477$, $\eta_p^2 = 0.059$) on voluntary activation level.

Contractile properties

There was a main effect of time ($P < 0.0001$, $\eta_p^2 = 0.870$), condition ($P = 0.047$, $\eta_p^2 = 0.224$) and interaction ($P = 0.006$, $\eta_p^2 = 0.429$) for the potentiated twitches. Follow-up tests revealed a significant decrease in the contractile properties after both control and muscle effort sessions (21.8 ± 4.8 Nm to 18.3 ± 4.8 Nm, i.e., $-16.1 \pm 10.0\%$, $P = 0.004$, $d_z = 1.625$ and 21.2 ± 5.0 Nm to 14.3 ± 4.9 Nm, i.e., $-33.0 \pm 16.6\%$, $P < 0.0001$, $d_z = 1.740$ for control session and muscle effort session, respectively). Moreover, there was a significant difference for the contractile properties assessed after completion of the fatiguing protocol between the control session

and the muscle effort session ($P < 0.001$, $d_z = 1.099$). Contractile properties assessed after the mental effort session did not decrease significantly (20.9 ± 4.5 Nm to 18.8 ± 4.7 Nm, i.e., $-9.8 \pm 12.7\%$, $P = 0.180$, $d_z = 0.827$).

Effects of the protocols on reaction time and its components

All results are presented in Table 1. There was no significant interaction for total reaction time. There was no significant interaction for either premotor time or EMD_{vol}. EMD_{vol} substantially increased (not significantly) after the muscle effort session ($+25.6 \pm 35.2\%$, $d_z = 0.654$, Fig. 3). Moreover, a strong correlation was found between total reaction time and premotor time ($r = 0.98$, $P < 0.001$).

Rate of force development

Results of RFD are shown in Table 2. There was a significant conditions × time interaction ($P = 0.001$, $\eta_p^2 = 0.429$) and a significant time intervals × conditions × time interaction ($P < 0.001$, $\eta_p^2 = 0.554$). This parameter decreased only after completion of the muscle effort session for RFD_{0-50} ($-30.8 \pm 26.5\%$, $P < 0.001$, $d_z = 0.745$), RFD_{0-75} ($-41.9 \pm 16.1\%$, $P < 0.001$, $d_z = 1.744$) and RFD_{0-100} ($-42.3 \pm 15.4\%$, $P < 0.001$, $d_z = 1.966$).

Effects of the protocols on EMD_{stim} and its components

All results are presented in Table 3. There was a significant main effect of time ($P = 0.021$, $\eta_p^2 = 0.366$), as well as a significant interaction for EMD_{stim} ($P = 0.003$, $\eta_p^2 = 0.371$). Follow-up tests revealed a significant increase for this

Table 1 Effects of the fatigue protocols on reaction time parameters

	Control condition		Mental effort condition		Muscle effort condition		ANOVA			
	Pre	Post	Pre	Post	Pre	Post	Time effect	Condition effect	Time–condition Interaction	η_p^2
RT (ms)	180.7±29.5	177.4±37.3	169.7±22.6	175.6 21.4	172.7±26.2	176.9±16.9	P=0.632	P=0.639	P=0.516	0.053
PMT (ms)	159.0±30.0	155.7±35.0	148.5±23.0	153.4±22.1	150.9±28.6	153.5±20.2	P=0.769	P=0.612	P=0.597	0.042
EMD$_{vol}$ (ms)	21.7±4.5	21.7±4.7	21.2±4.2	22.2±5.5	21.7±7.1	26.1±7.0	P=0.096	P=0.378	P=0.169	0.137

Reaction time (RT), i.e., time gap between the imperative stimulus and the onset of torque production; premotor time (PMT), i.e., time gap between the imperative stimulus and the onset of the EMG activity; motor time (EMD$_{vol}$), i.e., time gap between the onset of EMG and the onset of torque production

Data are presented as mean±SD. η_p^2=partial eta squared
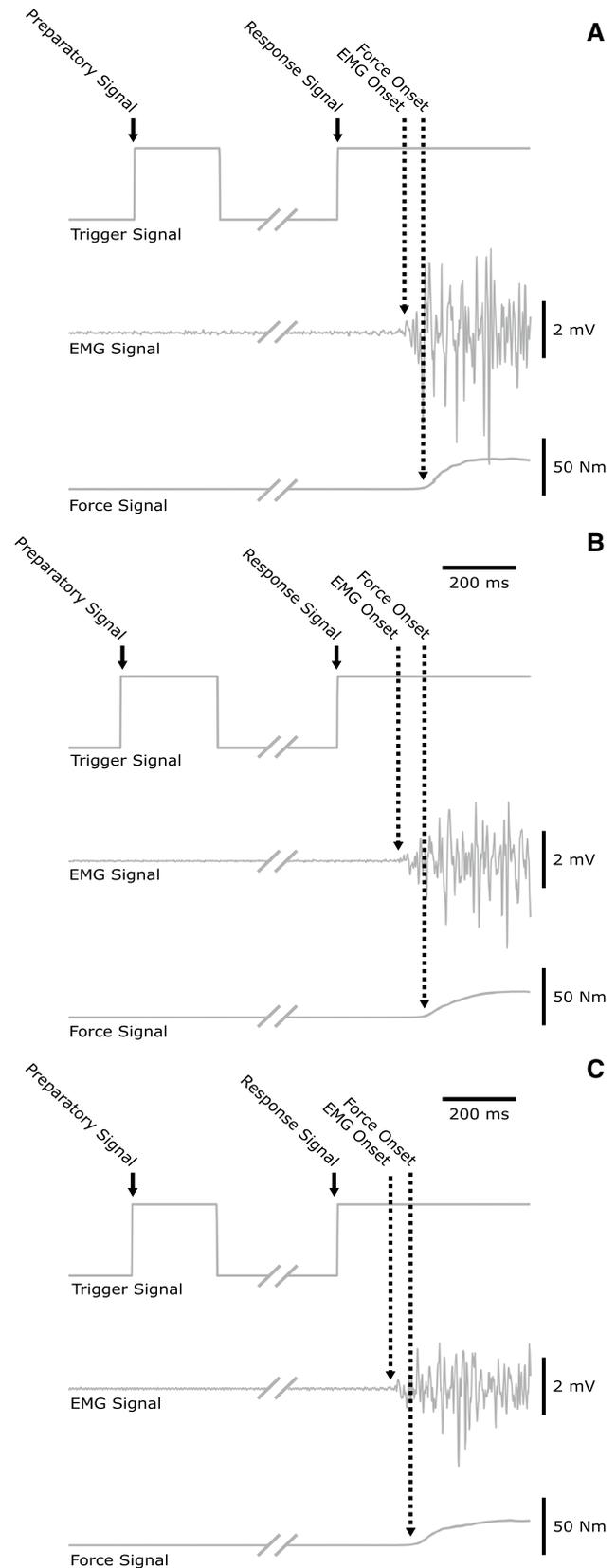
Fig. 3 Typical traces from one representative participant recorded before the effort (**a**), immediately after the muscle effort (**b**) and after the mental effort (**c**) conditions

Table 2 Effects of the fatigue protocols on the rate of force development (RFD) measured with different time intervals (0–25 ms; 0–50 ms; 0–75 ms; 0–10 ms)

RFD (Nm s^{-1})	Control condition		Mental effort condition		Muscle effort condition		ANOVA			
	Pre	Post	Pre	Post	Pre	Post	TI effect	Cond effect	Time effect	Interaction
0–25 ms	94±79	76±59	80±53	74±47	77±41	71±52	η_p^2	η_p^2	η_p^2	η_p^2
0–50 ms	226±196	184±144	245±166	250±171	268±151	170±103***	0.876	0.081	0.486	0.554
0–75 ms	391±194	348±153	356±185	386±210	412±119	233±90***	P value	P value	P value	P value
0–100 ms	429±140	399±124	394±164	426±180	449±95	255±81***	<0.001	0.36	0.055	<0.001

Data are presented as mean ± SD. η_p^2 = partial eta squared

TI time intervals, *Cond* condition

***Significantly different between pre fatigue and post fatigue during the same condition ($P < 0.001$)

Table 3 Effects of the fatigue protocols on electrically evoked electromechanical delay parameters
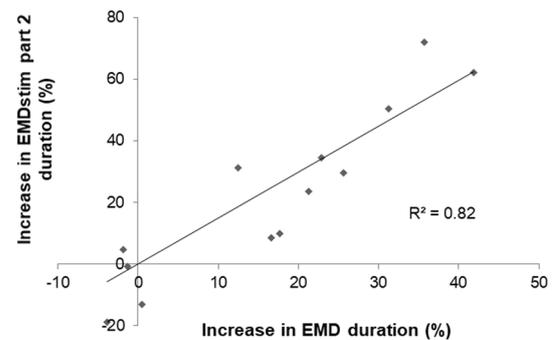
	Control condition	Mental effort condition	Muscle effort condition
EMD$_{stim}$ (ms)			
Pre	10.6±0.8	11.6±1.5	10.5±0.6
Post	11.0±1.5	11.5±1.4	12.3±1.4**
EMD$_{stim}$ part 1 (ms)			
Pre	4.8±1.3	4.7±0.9	3.7±0.4
Post	4.7±1.1	4.4±0.8	4.0±1.0
EMD$_{stim}$ part 2 (ms)			
Pre	5.9±1.3	7.0±1.6	6.8±0.7
Post	6.4±1.7	7.1±1.6	8.3±1.7

Electromechanical delay (EMD$_{stim}$), i.e., time gap between the stimulation and torque onset; EMD$_{stim}$ part 1, i.e., time gap between the stimulation and the onset of fascicle movement; EMD$_{stim}$ part 2, i.e., time gap between the onset of fascicle movement and torque onset

Data are presented as mean ± SD

**Significant difference between pre and post fatigue during the same condition ($P < 0.01$)

Fig. 4 Coefficient correlation between the increase in EMD$_{stim}$ and the increase in part attributable to the aponeurosis and tendon in the muscle effort condition

Discussion

The aim of the current study was to assess the effects of both mental and muscle efforts on reaction time components. Contrary to our first hypothesis, mental effort did not significantly impair pre-motor time. In accordance with our second hypothesis, muscle effort significantly increased electromechanical delay in stimulated condition. However, in both conditions, reaction time remained unchanged.

Markers of fatigue

We used the NASA-TLX scale to assess the subjective workload of each fatigue protocol. As expected, completion of the mathematical cognitive task and watching a movie was less physically demanding than performing a protocol of isometric contractions. Interestingly, not only performing a mental effort, but also performing isometric contractions was more mentally demanding than watching

parameter only after completion of the muscle effort session ($P = 0.001$, $d_z = 1.114$, Fig. 3). There was no significant interaction for either the onset of muscle fascicles motion ($P = 0.468$, $\eta_p^2 = 0.061$), i.e., EMD$_{stim}$ part 1, or the passive part of the series elastic component, i.e., EMD$_{stim}$ part 2 ($P = 0.256$, $\eta_p^2 = 0.107$). However, the part attributable to the passive part of the series elastic component substantially increased after completion of the muscle effort session ($+ 22.6 \pm 27.8\%$, $d_z = 0.813$). Moreover, as shown in Fig. 4, a significant correlation was found between the increase in the part attributable to the passive part of the series elastic component and the increase in EMD$_{stim}$ ($P < 0.001$).

a movie. This higher mental demand during the two fatigue protocols was associated with higher effort and higher feelings of frustration in performing the physical and mental tasks compared to watching a movie. Moreover, the self-reported fatigue assessed by both VAS and BRUMS during the pilot study showed that the participants experienced a mental fatigue state after performing the mathematical cognitive task. However, we acknowledge that the NASA-TLX does not assess motivation and/or engagement during a subsequent motor task. To assess the feeling of fatigue after completion of the mathematical cognitive task, we conducted a pilot study, which showed an increase in the feeling of fatigue (assessed by the visual analogue scale) and a decrease of vigor (assessed by the BRUMS, Terry et al. 2003). Nevertheless, further studies should assess motivation and engagement by using relevant tools, such as the Dundee Stress State Questionnaire (Matthews et al. 2002), previously used by Langner et al. (2010b) to assess the effects of time on a simple reaction time.

To measure exercise-induced muscle effort, we quantified the force production capacity of the elbow flexors following completion of the mathematical cognitive task and the muscle effort exercise. Despite inducing subjective feelings of fatigue, completion of the mental task did not alter the maximal force production capacity of the elbow flexors, as previously reported (Rozand et al. 2014a, b; Pageaux et al. 2013, 2015). As expected, muscle effort induced a significant decrease in MVC peak torque of the elbow flexor muscles, mainly due to acute impairment of peripheral mechanisms, as voluntary activation remained stable.

Considering the psychological and neuromuscular markers of fatigue all together, we can conclude that the two fatigue protocols successfully induced the required state in our subjects, while participants performed reaction time trials post control condition without any mental or physical disturbance.

Effects of mental exertion on reaction time components

In the present study, we found that mental effort did not increase reaction time performed in a limited number of trials. This result is quite surprising as mental fatigue was thought to negatively affect this parameter (Langner et al. 2010a), because cognitive processes are strongly involved in the premotor time. We also showed that both premotor time and EMD remained constant and were not impaired or enhanced by a mental fatigue state.

Considering EMD, both voluntary and evoked EMD remained unchanged after completion of the mathematical cognitive task. This result was confirmed by the absence of change for both the onset of muscle fascicles motion and the passive part of the series elastic component assessed during

the elicited EMD. This is consistent with previous studies that showed no effect of mental fatigue on contractile properties (e.g. Pageaux et al. 2015).

Due to the lack of premotor time alteration found in the present study, it is thought that after completion of a high mentally demanding task, participants were able to maintain their performance level in order to react as fast as during non-fatigued condition. Contrary to our results, Langner et al. (2010a) found a significant effect of time-on-task, i.e., mental task, on simple reaction time. The discrepancy between this result and those of the present study may be attributed to the task used for reaction time measurement. Indeed, in Langner et al. study, the same task, i.e., reaction time trials, was used to induce fatigue and to measure reaction time (600 trials) while, in the current study, two different tasks were used, i.e., mathematical cognitive task and elbow flexor muscles contraction (2 trials).

Therefore, we assume that the stability of performance level observed in the present study, despite a mental fatigue, is due mainly to the low number of trials. Indeed, it is likely that the participants were able to keep up their motivation, thus preventing from monotony. However, because in certain circumstances such as sport performance (racket sports, team sports, combat sports) or daily situations, success or failure are mainly related to the ability to reproduce repeated specific motor skills with a short reaction time, it could be of interest to evaluate the effects of mental fatigue on reaction time during an increased number of trials in diverse populations, such as athletes or elderly people.

It is generally well accepted that the executive functions include several top-down mental processes, i.e., inhibition and interference control, working memory and cognitive flexibility (Diamond 2013). Considering the risk of oversimplifying the link between the cognitive task and the executive functions involved, one may consider that each cognitive control aspect is "task specific", i.e., refers to a singular type of tasks (for review, please see Diamond 2013). In the task proposed herein, i.e., mathematical subtraction, the inhibition processes were not involved, while the working memory was. It has been suggested that the anterior cingulate cortex is strongly activated during cognitive tasks involving response-inhibition processes (Pageaux and Lepers 2018). Thus, it is possible that the absence of solicitation of these specific functions during both the cognitive task and during the reaction time trials is responsible for the maintenance of premotor time (and total reaction time). In accordance with our results, Roelands et al. (2017) recently showed that when mentally fatigued, participants slowed their response only when the inhibition (for suppressing inappropriate responses, Miyake et al. 2000) was involved, and not during a simple reaction time task. It is plausible that another task to induce mental disturbance, such as a Stroop task or a Flanker task (Diamond 2013), and/or to assess reaction

time, such as multiple reaction time, would have led to a different result. Although the dissociation between inhibition and working memory is not evident (Diamond 2013), future researches must pay attention to the specificity of the task proposed to induce fatigue and/or to assess reaction time. In the present study, we intentionally decided not to provide encouragement or to gently nudge the participants during the reaction time trials. Interestingly, Steinborn et al. (2017) demonstrated that providing specific instructions during a choice reaction time sustained task allowed the participants to stabilize their performance level when compared to standard trials. The spare capacity model suggests that the capacity is never fully utilized during such a task, and that an exceptional challenging task will cause an increase in the level of arousal, thus mobilizing the spare capacity (Steinborn et al. 2017). As no specific instructions or encouragement were provided in the current study, our results seem to validate this hypothesis but also showed that there is no need for external instruction to mobilize the spare capacity during a simple reaction time task after completion of a mental effort.

Effects of physical exertion on reaction time components

We also found that reaction time was not impaired by physical exertion. This result differs from previous study reporting significant increases in reaction time (Klimovitch 1977) but is in accordance with another one reporting a non-significant effect of physical exertion on reaction time (Stull and Kearney 1978). As expected, muscle effort did not impair the central component, i.e., premotor time, of reaction time, as previously observed by Klimovitch (1977) and Stull and Kearney (1978). This result is also in accordance with previous studies that reported no significant changes in cognitive function after whole-body anaerobic exercise (for further details, please see Tomporowski 2003). Therefore, physiological fatigue does not seem to influence the cognitive function evaluated through the premotor time.

While no main effect of interaction was found for EMD_{vol} in the current study, a moderate Cohen's effect size was observed during the biceps effort protocol. In addition, impairment of peripheral function is also supported by a significant increase in EMD during elicited contractions. However, it should be kept in mind that, in the voluntary contractions, we focused on the biceps brachii to record EMG data during reaction time trials. Consequently, we cannot exclude that other elbow flexor muscles, such as brachialis anterior or brachioradialis, could be responsible for the onset of the movement. By finding a strong and significant correlation between the increase in EMD_{stim} and the increase in the passive part of the series elastic component, we provide new evidence that the major part of the increase in EMD_{stim} is due to an elongation of this component.

As previously proposed (Rampichini et al. 2014), a reduced stiffness from the muscle–tendon unit is responsible for the elongation of the time necessary to stretch the series elastic component and consequently to transmit the force to the insertion point. However, in the present study, the negative impact of muscle effort on EMD did not result in a significant increase in total reaction time. As we found no significant correlation between reaction time and EMD_{vol}, it is likely that the major reason is that EMD only represents a short part of reaction time ($12.3 \pm 3.1\%$), very close to the one reported by Stull and Kearney ($\sim 15\%$; 1978). Thus, despite a significant alteration at the peripheral level, muscle effort had no influence on reaction time. However, as RFD significantly decreased after the biceps effort protocol, it provides evidence that it will take a longer time to reach the same level of force or that the level of force will be reduced at a given moment.

Limitations

Some methodological limitations may be addressed. First, it should be kept in mind that to avoid any recovery effect, we chose to use a limited number of trials to assess reaction time performance, which decreased the reliability (Hamsher and Benton 1977) and hampered the ability to analyse the distribution of responses, i.e., time-on-task effect (Steinborn et al. 2016, 2017). As mental fatigue is known to last at least several minutes (Pageaux et al. 2015), it may be appropriate for future studies to separate the effects of both mental and physical fatigue to investigate the effects of mental fatigue only on time-on-task muscle reaction time. Secondly, we have to acknowledge that the number of participants recruited in the present study could have been insufficient to detect small changes in reaction time or its components. Thus, it is possible that a type 2 error, i.e., failing to reject H_0 while it is false, could have occurred. However, the changes in reaction time (and/or its components) was very small in our study ($+4.6 \pm 14.9\%$ and $+3.5 \pm 8.7\%$ for mental and physical effort, respectively) when compared to the reliability of these measures (Le Mansec et al. 2017) and both P values and partial eta squares were far from significant. Finally, only the effects of physical effort on voluntary electromechanical delay results could have been underestimated ($P = 0.17$; $\eta_p^2 = 0.137$). Last, as only men were recruited for methodological reasons, the results of the present study cannot be generalized to the whole population, i.e., for women.

Conclusions

By comparing the impact of mental and muscle effort on simple reaction time during an isometric contraction performed with few trials, we demonstrated that both mental and biceps effort had no impact on the ability to react

quickly. More specifically, we found that in the mental effort condition, both central (premotor time) and peripheral (electromechanical delay) parameters remained unaltered, as well as neuromuscular functions. In contrast, we found an increase of electromechanical delay in the muscle effort condition assessed in both voluntary (although there was no significant interaction) and involuntary conditions. This can be explained by an elongation of the passive part of the series elastic component. However, since the electromechanical delay represents a small relative part of the total reaction time, these changes did not induce significant change on the reaction time. We conclude that, when mentally or physically fatigued, participants are still able to perform a one-shot trial with the same level of performance.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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