



Does exercise-induced muscle damage impair subsequent motor skill learning?



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ARTICLE INFO

Keywords:

Motor learning
Internal models
Proprioception
Muscle damage
Exercise-induced muscle damage

ABSTRACT

Motor skill learning is a fundamental aspect of human behavior based on the calibration of internal models via sensory information such as proprioception. Some conditions, as exercise-induced muscle damage (EIMD), disrupt proprioceptive information, and may cause learning impairment. Such possible relation between EIMD and motor skill learning has not yet been investigated and it is the aim of this study. For this purpose, thirty male university students (19.3 ± 1.8 years) were equally assigned to two groups: EIMD and CON group. The EIMD group received a treatment to induce muscle damage consisting of a weight lifting protocol directed to the agonist muscles related to the task prior to the pretest and to the learning sessions. EIMD was verified and compared between groups and along the process (0–168 h) by means of the degree of delayed onset muscle soreness (DOMS), perceived total quality recovery and maximal isometric strength (MIS). To investigate motor skill learning, both groups practiced a dart throwing task for four sessions with 150 trials in each session. Recovery status and DOMS were recovered at 96 h in the EIMD group, and MIS was not recovered throughout 168 h. In contrast, muscle damage parameters were not altered across 168 h in the CON group. Accuracy and consistency were compared within and between groups in a pretest posttest design. The EIMD group showed less accurate and consistent results on the long term (delayed posttest). Results confirmed our hypothesis that EIMD, a common condition in sports and in rehab practices, may hinder motor skill learning, possibly due to neurological aspects such as proprioceptive information, its relation to central nervous system reorganization and internal model consolidation.

1. Introduction

Motor learning is a fundamental aspect of human behavior involving the calibration of internal models, which are neural representations of the environment and the individuals own musculoskeletal dynamics to control movements (Wolpert & Kawato, 1998; Wolpert, Diedrichsen, & Flanagan, 2011). Internal models may be calibrated on an error-feedback-learning basis, that is: at the beginning of the practice of a new task or in a new motor condition, movements result in high error rates and variability. Such error information and its related body coordinates are sent back to the central nervous system (CNS) via sensory feedback channels such as

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proprioception, and then the CNS proceeds with a series of movement adjustments within a trial or between trials in order to reduce movement error and performance variability (Wolpert & Kawato, 1998; Wolpert et al., 2011).

Proprioceptive sensors (i.e., muscle spindles) play a relevant role in the learning process by refining sensory information (Dimitriou, 2016; Dimitriou & Edin, 2010), which feeds back the CNS with performance related information. Such feedback information will calibrate internal models related to the dynamics of a muscle group responsible to adequately adjusting movement in order to achieve the specified goal (Hwang & Shadmehr, 2005). Complementarily, feedback will also participate in cortical reorganization (Lotze, Braun, Birbaumer, Anders, & Cohen, 2003), which is important for the consolidation of internal models (Shadmehr & Brashers-krug, 1997; Shadmehr & Holcomb, 1997). Proprioception seems to provide unique information about the temporal characteristics of unconstrained movements (joint integration and reversals), which is necessary to produce spatially accurate movements (Sainburg, Poizner, & Ghez, 2017). During a basketball free throw, for example, it seems that the quality of proprioceptive information directly influences performance (Sevrez & Bourdin, 2015) and that consistent and accurate performance in throwing tasks is achieved by learning to couple hand trajectory and end point position – release timing (Cohen & Sternad, 2011; Nasu, Matsuo, & Kadota, 2014).

Generally, sensory information is well-integrated and learning occurs normally; performance accuracy increases whereas variability decreases. Hence, if sensory information is disrupted, one may also expect motor learning to be compromised. That might be the case of exercise-induced muscle damage (EIMD), which is a rather common phenomenon found in sports training or rehabilitation sessions that may compromise proprioception (Torres, Vasques, Duarte, & Cabri, 2010). EIMD is characterized by morphological alterations on muscle tissue induced by mechanical or metabolic stimuli during exercise (Ferreira-Junior et al., 2014; Paulsen, Mikkelsen, Raastad, & Peake, 2012). In brief, during muscle contraction, weaker sarcomeres absorb most of the muscular tension, resulting in their disruption following numerous contractions. This damage may extend to the surrounding structures, including other sarcomeres, sarcolemma, and muscle spindles. Such alterations cause long-term impairment of muscle performance including those related to proprioceptive information, such as joint position sense and force production (Brockett, Warren, Gregory, Morgan, & Proske, 1997; Torres et al., 2010) and may last from 48 h to more than seven days for full recovery (Paulsen et al., 2012). Due to the importance of proprioception on motor learning and because EIMD seems to disrupt proprioceptive information, one might suppose that EIMD results in motor learning impairment. To our knowledge, a possible interaction between EIMD and motor learning has yet to be investigated. Investigating this interaction can help to understand the factors underlying motor learning and also provide useful knowledge to sports training and rehabilitation professionals. Therefore, the purpose of the present study was to evaluate whether a session of exercise that induces muscle damage impairs subsequent motor skill learning.

2. Methods

2.1. Participants

Thirty male college students (age 19.3 ± 1.8 years, weight 76.8 ± 16.2 kg, and height 182.1 ± 6.9 cm) participated in this study. This sample size was determined by using GPower (version 3.1.2; Franz Faul, Universitat Kiel, Germany) (Faul, Erdfelder, Lang, & Buchner, 2007) assuming the following design specifications: $\alpha = 0.05$, $(1 - \beta) = 0.8$, effect size $f = 0.25$, test family = F test, and statistical test = ANOVA repeated measures: within-between interaction (Beck, 2013). Participants were physically active individuals engaged in moderate physical activity around three days a week, but they had not performed resistance training for at least six months before the study and were naïve at the experimental task. Prior to signing the written informed consent form, approved by the Institutional Research Review Board, all participants were informed of the procedures, possible discomforts, risks and benefits of the study, and answered to the Physical Activity Readiness questionnaire – PAR-q (Thomas, Reading, & Shephard, 1992). Additionally, the present study was approved by the Institutional Review Board of Federal Institute of Sudeste of Minas Gerais (Protocol 56710716.5.0000.5588) and the study procedures were performed in accordance with the ethical standards of the Helsinki Declaration.

2.2. Experimental design

Fig. 1 illustrates the experimental design. The participants attended the laboratory on eight occasions. The first visit involved anthropometric assessment, familiarization to experimental procedures, and 10 repetition maximum (RM) test. On the second visit, 48–72 h later, participants performed 10 RM re-test. At the end of the second session, participants were randomly assigned in two groups: 1) Control group (CON group, $n = 15$), or 2) Exercise-induced muscle damage group (EIMD group, $n = 15$). On visit three, one week after the first visit, the participants of the EIMD group performed a damaging muscle protocol (detailed below), while the CON group remained seated for 20 min (control condition). From visit four to visit seven both groups practiced a dart-throwing task, which corresponded to 24, 48, 72, and 96 h post damaging exercise/control condition. Motor skill learning was assessed by measuring performance accuracy and consistency on dart throws in a pretest-posttest design. The pretest was on the third visit, just before the damaging exercise/control condition. An immediate posttest was carried out on visit seven, which corresponded to 96 h after damaging exercise/control condition, and a delayed posttest were carried out on visit eight, which corresponded to 168 h after damaging exercise/control condition. Additionally, indirect markers of muscle damage were evaluated before (pre), 24, 48, 72, 96, and 168 h following the damaging exercise/control condition by measuring perceived recovery status, maximal isometric strength (MIS) for shoulder flexors, and delayed onset muscle soreness (DOMS) for shoulder flexors. Measurements were carried out always in the same order. Participants were asked to visit the laboratory always at the same time of day in order to avoid circadian influences.

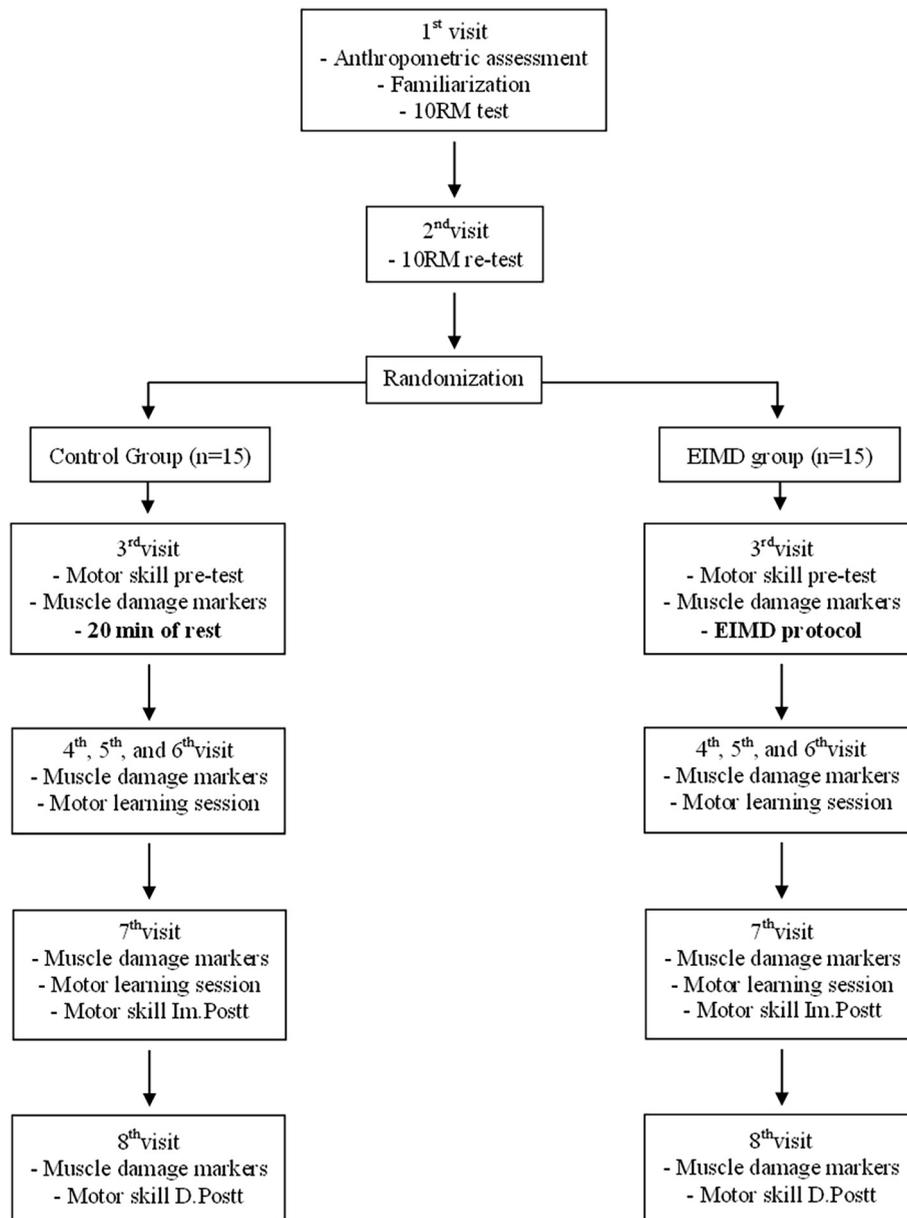


Fig. 1. Experimental design. EIMD, exercise-induced muscle damage. Im.Postt, Immediate posttest. D.Postt, delayed posttest.

Participants were instructed and recommended not to perform any vigorous physical activities or unaccustomed exercise, and not to intake medications or supplements during the experiment period.

2.3. 10 Repetition maximum test and re-test

To determine the training load of the damaging exercise protocol, 10 RMs were assessed in a bilateral shoulder flexion exercise (Fig. 2). Exercise consisted of participants flexing (extending) their shoulders with elbows almost fully extended and hands in supine position while standing upright with their back resting against a wall for support and avoiding compensatory movements. Motion ranged from 5–10° (0° neutral) to 90–100°. The load was implemented by dumbbells, one in each hand, and was adjusted starting at 1 kg. On the testing day, participants performed a warm-up set, which consisted of 30 s of shoulder circular movements, followed by 10 repetitions of shoulder flexion using dumbbells of 1 kg. Two minutes later, they performed 10 repetitions with 40% of their MIS.

After warm up, 10 RM load for the participants was determined within five attempts and 5 min recovery between attempts. Each repetition took 4 s and was controlled by an electronic metronome: 1 s for the concentric action and 3 s for the eccentric action. Finally, verbal encouragement was provided across the test and 10 RM values presented a test-retest reliability coefficient (ICC) of



Fig. 2. 10 repetition maximum (10 RM) test.

0.93.

2.4. Damaging exercise protocol

Damaging exercise protocol consisted of 10 sets of 10 RM bilateral shoulder flexion and 2 min of rest intervals between sets. In the second, fifth, and eighth sets the exercise load was reduced by 1 kg to avoid a severe reduction in the number of repetitions. Participants' position, movement range, and duration of repetitions were the same as in the 10 RM test.

2.5. Indirect markers of muscle damage

Muscle damage was assessed by three indirect markers: perceived recovery status, MIS, and DOMS measured in this same order, as described above in the *experimental design*. The total quality recovery scale assessed perceived recovery status – TQR (Kenttä & Hassmén, 1998), in which participants answered to the question “how do you feel about your recovery now?” in a scale ranging from “6” (no recovery) to “20” (full recovery).

MIS of the shoulder flexors was assessed bilaterally using a load cell (Capacity of 5000 N, EMG System, São José dos Campos, Brazil) connected to a signal acquisition system (SAS1000V4, EMG System, São José dos Campos, Brazil) (Fig. 3). One extremity of the load cell was fixed to the floor and the other extremity was fixed to a hand bar. Before the test, participants performed a warm-up set, which consisted of 30 s of shoulder circular movements, followed by 10 repetitions of shoulder flexion using dumbbells of 1 kg. One minute later, the test began. Participants were positioned upright with their back resting against a wall for support and to avoid compensatory movements while holding the hand bar attached to the load cell. Their shoulder was flexed at 60° (0° neutral), elbows almost fully extended, and hands in supine position. Then, they were asked to perform two maximal contractions (flexion) for 4 s with 60 s of rest between them. The maximum isometric contraction was recorded and the highest value was used for statistical analysis. Participants received verbal encouragement throughout the test and all testing procedures were performed by the same investigator. Test/retest ICC, typical error and CV values for MIS, assessed with 48 h between test sessions, was 0.91, 1.2 and 10.7%, respectively.

DOMS was assessed by asking the participants to rate their shoulder flexors soreness during the bilateral isometric strength test. A 100-mm visual analog scale was used, with 0 mm corresponding to “no soreness” and 100 mm corresponding to “severe soreness” (Ferreira-Junior et al., 2015).



Fig. 3. Maximal isometric strength (MIS) test.

2.6. Motor learning sessions

Motor learning sessions consisted of throwing a saloon dart (Fig. 4) similar to Campos, Lage, Andrade, Couto, Santos, Profeta, and Ugrinowitsch (2019). Participants were instructed to throw the saloon dart with a posterior-anterior swing of the dominant arm at the shoulder joint to a graded target fixed on a rubber carpet and placed on the floor 3.0 m away from the participant. The target was a 20 cm width \times 40 cm length rectangle with 40 scoring stripes with 5 mm each placed posterior and anterior to the central stripe (the bull's eye of 10 mm wide/0 error). Each posterior stripe counted 1 point-error (maximum 40 at the last stripe) and indicated the strength applied to the dart surpassed the necessary strength. Likewise, each anterior stripe counted -1 point-error (maximum -40 at the last stripe) and indicated the strength applied to the dart was not enough to hit the central stripe. Darts that landed either before or beyond the target counted -41 and 41 point-error respectively. All participants watched a video demonstration before each learning session. The demonstration consisted of nine executions of the dart throwing task: three in normal speed, three in slow motion, followed by three with normal speed. Both groups performed 150 trials per day, with 1 min rest after every 30 trials.

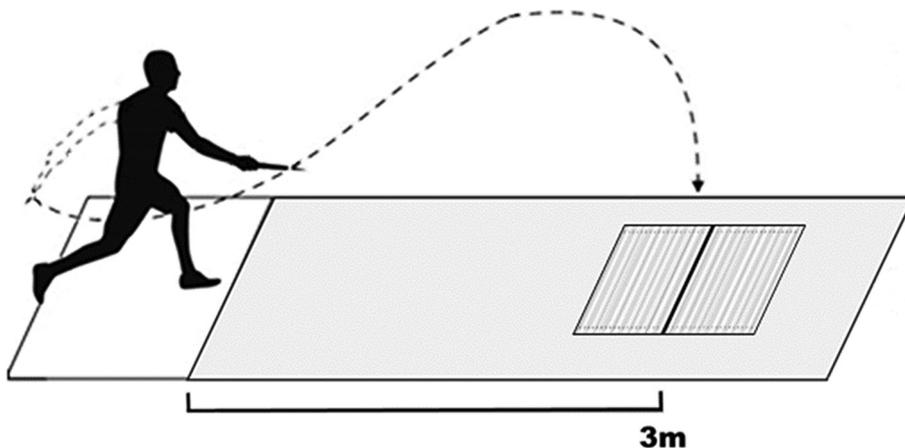


Fig. 4. Illustration of the dart throwing task used on learning sessions and on the pre- and posttests. Adapted from Campos et al. (2019).

2.7. Learning assessment

For motor skill learning assessment, participants performed 10 trials of a saloon dart throwing task specially designed for this study before (pretest), 96 h (immediate posttest) and 168 h (72 h delayed posttest) following the damaging exercise/control condition. Task and apparatus were the same used in the motor learning sessions. Two variables were used to indicate performance: absolute error and variable error. The absolute error was the score registered in each trial and indicated performance accuracy. The variable error was the population standard deviation of the raw score errors within each block of 10 trials and indicated performance variability. All learning data was registered manually and transposed to software for posterior analysis.

2.8. Statistical analyses

Data is expressed as mean \pm standard deviation, unless otherwise stated. The Shapiro-Wilk test was used to check data for normal distribution. Absolute error, variable error, and MIS data were normally distributed. MIS data was analyzed via a group (EIMD and CON) \times time (pre, 24, 48, 72, 96, and 168 h) ANOVA with repeated measures on factor time. Absolute error and variable error were analyzed by a group (EIMD and CON) \times blocks of 10 trials (pretest, immediate posttest, and delayed posttest) ANOVA with repeated measures on the factor blocks. In the case of significant differences, the Least Significant Difference *post hoc* test was used. The physical characteristics and baseline MIS values were evaluated by using an independent *t*-test. Total quality recovery and DOMS data did not present a normal distribution, therefore the Mann-Whitney (between groups) and Friedman (within group) tests were used to analyze these variables. The significance level was set a priori at $p < 0.05$. Additionally, in order to examine the magnitude of each condition effect, Cohen's *f* effect size was obtained from GPower (version 3.1.2; Franz Faul, Universitat Kiel, Germany) (Faul et al., 2007) by providing the partial eta-squared value. Cohen's ranges of 0.10, 0.25, and 0.40 were used to define small, medium, and large *f* values, respectively (Cohen, 1988).

3. Results

3.1. Physical characteristics and muscle damage markers

Age, weight, height, MIS, total quality recovery, and DOMS were not significantly different between groups at baseline ($p > 0.05$, Table 1). However, the muscle damage markers differed between groups and throughout 168 h for the EIMD group, as expected (Table 2). There was a significant group by time interaction for MIS ($F = 9.9$, $p < 0.001$, power = 1.0), which dropped $23 \pm 9\%$ 24 h post-resistance exercise in EIMD group ($p < 0.001$) and was not recovered throughout the 168 h post testing period ($p < 0.001$). On the other hand, MIS was not altered in the CON group throughout 168 h ($p = 0.72$). Total quality recovery was impaired 24 h post-resistance exercise in the EIMD group ($\chi^2 = 47.1$, $p < 0.001$) but it was recovered at 96 h post testing period ($p = 0.52$). The CON group did not alter total quality recovery throughout the entire 168 h ($\chi^2 = 6.5$, $p = 0.26$). Additionally, total quality recovery was lower in the EIMD group at 24, 48, and 72 h after damaging exercise when compared to the CON group ($p < 0.001$). The EIMD group recovered from DOMS at 96 h after damaging exercise ($\chi^2 = 22.8$, $p < 0.001$), while DOMS was not altered in the CON group throughout the entire 168 h ($\chi^2 = 1.6$, $p = 0.89$). Moreover, DOMS was higher in EIMD group at 24 ($p < 0.001$), 48 ($p < 0.001$), and 72 h ($p = 0.03$) after damaging exercise when compared to the CON group.

3.2. Performance and learning variables

Fig. 5A shows mean absolute error score and the ANOVA indicated a significant group by blocks interaction ($F = 8.3$, $p < 0.001$, $f = 0.54$, power = 0.95). The EIMD group showed no significant accuracy change ($p > 0.05$), whereas the CON group increased performance along the process, as indicated by the significant absolute error reduction on the delayed posttest when compared to the pretest ($p < 0.001$) and to the immediate posttest ($p < 0.01$). Also, EIMD group was less accurate than the CON group on the delayed posttest ($p < 0.01$).

Fig. 5b depicts mean variable error score and the ANOVA indicated a significant group by blocks interaction ($F = 4.85$, $p = 0.011$, $f = 0.42$, power = 0.78). The EIMD group increased performance variability throughout the process as indicated by the difference

Table 1

Physical characteristics and baseline maximal voluntary isometric contraction, total quality recovery, and muscle soreness of each experimental Group.

| Physical characteristics | Control group (n = 15) | EIMD group (n = 15) | p-value |
|--------------------------|------------------------|---------------------|---------|
| Age (years) | 18.9 \pm 1.9 | 19.6 \pm 1.6 | 0.34 |
| Weight (kg) | 78.5 \pm 20.3 | 75.1 \pm 11.2 | 0.59 |
| Height (cm) | 182.4 \pm 7.8 | 181.8 \pm 6.2 | 0.85 |
| MIS (N) | 130.4 \pm 25.3 | 141.0 \pm 38.8 | 0.38 |
| TQR (AU) | 18 \pm 2 | 18 \pm 2 | 0.35 |
| DOMS (mm) | 7 \pm 11 | 14 \pm 15 | 0.19 |

MIS, maximal isometric strength. TQR, total quality recovery. DOMS, delayed onset muscle soreness. AU, arbitrary unity.

Table 2
Indirect markers of muscle damage of each experimental group throughout 168 h.

| Group | | Baseline | 24 h | 48 h | 72 h | 96 h | 168 h |
|-----------|------|--------------|---------------|---------------|---------------|---------------|---------------|
| MIS (N) | CON | 130.4 ± 25.3 | 130.2 ± 24.4 | 127.3 ± 25.6 | 131.8 ± 27.8 | 126.9 ± 31.7 | 127.8 ± 28.0 |
| | EIMD | 141.0 ± 38.8 | 108.2 ± 40.1* | 110.5 ± 36.3* | 115.7 ± 41.4* | 118.8 ± 38.8* | 126.4 ± 44.5* |
| TQR | CON | 18 ± 2 | 18 ± 3 | 18 ± 3 | 19 ± 2 | 18 ± 3 | 19 ± 2 |
| | EIMD | 18 ± 2 | 11 ± 3*# | 13 ± 3*# | 15 ± 3*# | 17 ± 2 | 18 ± 2 |
| DOMS (mm) | CON | 7 ± 11 | 10 ± 17 | 6 ± 15 | 7 ± 11 | 8 ± 12 | 9 ± 14 |
| | EIMD | 14 ± 15 | 35 ± 23*# | 27 ± 22*# | 23 ± 24# | 19 ± 23 | 16 ± 19 |

CON, control group. EIMD, exercise-induced muscle damage. MIS, maximal isometric strength. TQR, total quality recovery. DOMS, delayed onset muscle soreness. (*) $p < 0.05$, different from baseline. (#) $p < 0.05$, different from CON.

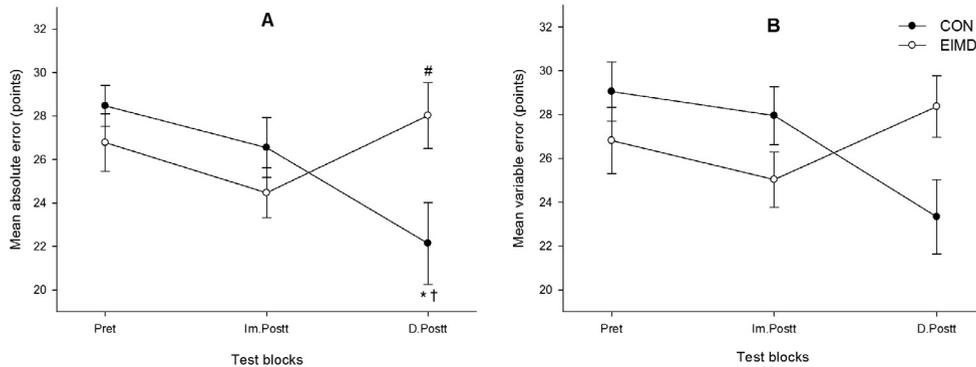


Fig. 5. (A). Mean absolute error on pretest (Pret), immediate posttest (Im.Post), and delayed posttest (D.Post). (B). Mean variable error on pretest, immediate posttest test, and delayed posttest test. CON, control group. EIMD, exercise-induced muscle damage group. (*) $p < 0.05$, different from pretest. (†) $p < 0.05$, different from Immediate posttest. (#) $p < 0.05$, different from control group. Spread bars indicate sd error.

from the delayed posttest to the immediate posttest ($p < 0.05$). The CON group reduced performance variability along the process, as indicated by the difference from the delayed posttest to the pretest ($p < 0.05$). Also, the EIMD group was more variable than the CON group on the delayed posttest ($p < 0.05$).

Due to the test results, and to further understand them, we ran additional repeated measures ANOVAs on absolute and variable errors across the initial and final trials of the four practice sessions (2 groups \times 4 blocks of 10 trials). As long as the initial trials of each session came after a 24 h interval without practice, the behavior of the groups within these trials should help to understand the delayed post test results. Similarly, the behavior within the last trials of each session could shed some light on the immediate posttest results. Results are illustrated in Fig. 6. The only significance found was a group by block interaction on absolute error for the initial trials ($F = 2.86$, $p = 0.041$, $f = 0.31$, power = 0.67), presented in Fig. 6A. The CON group reduced errors (increased accuracy) across the initial trials ($p < 0.05$) whereas the EIMD group presented no significant change ($p = 0.09$). Differences between groups reached significance in the initial block of the last session ($p < 0.01$). ANOVAs of mean absolute error for the final trials (Fig. 6B), of variable error for the initial trials (Fig. 6C), and variable error for the final trials (Fig. 6D) showed no difference between groups ($p > 0.43$), between blocks ($p > 0.30$), or significant group-blocks interaction ($p > 0.67$).

4. Discussion

The aim of the present study was to evaluate whether a session of exercise that induces muscle damage impairs subsequent motor skill learning. Our main hypothesis was that EIMD would hinder motor learning due to disruptions in proprioceptive signals/information as such information is related to the processes of motor performance (Sainburg et al., 2017; Sevrez & Bourdin, 2015) and motor learning (Dimitriou, 2016; Dimitriou & Edin, 2010; Hwang & Shadmehr, 2005). Our hypothesis was confirmed: EIMD impaired motor skill learning, with large effect sizes for performance accuracy ($f = 0.54$) and performance variability ($f = 0.42$). Absolute and variable error results indicated, respectively, that the EIMD group had no accuracy gains and increased performance variability, whereas the CON group showed both accuracy gains and variability reduction. As mentioned earlier, to our knowledge, this is the first study to investigate the effects of EIMD on motor learning; therefore, there are no similar studies with which to compare the present findings. However, our results corroborate studies that investigated the role of proprioceptive information on motor performance and learning (Dimitriou, 2016; Hwang & Shadmehr, 2005; Sevrez & Bourdin, 2015).

Differences in performance accuracy either between or within groups are evident in the long-term as shown by the delayed posttest (Fig. 5A). Delayed posttest results demonstrate that although the calibration of internal models (i.e., learning) is mainly related to practice, it is a process that continues after practices has finished (Shadmehr & Brashers-krug, 1997), and this process is underlined by changes in cortical representation (Shadmehr & Holcomb, 1997). Such aspect of the calibration process might be a key

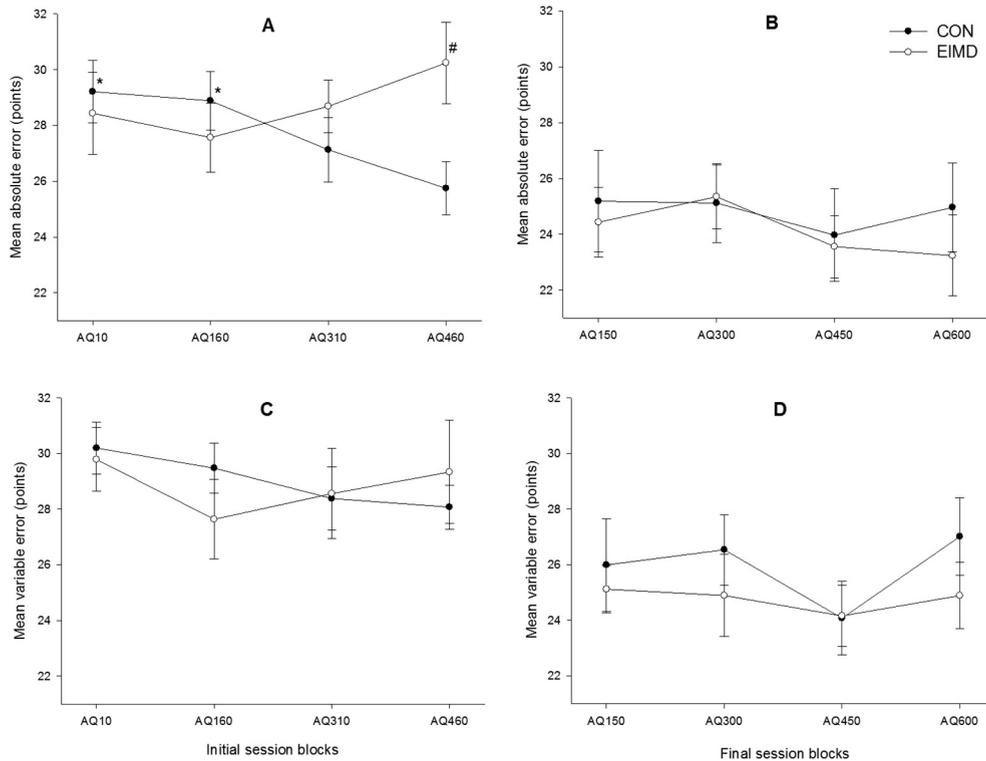


Fig. 6. (A). Mean absolute error in the initial blocks of acquisition trials in each of the four practice sessions (AQ10, AQ160, AQ310, AQ460). (B). Mean absolute error in the final blocks of acquisition trials in each of the four practice sessions (AQ150, AQ300, AQ450, AQ600). (C). Mean variable error in the initial blocks of acquisition trials in each of the four practice sessions (AQ10, AQ160, AQ310, AQ460). (D). Mean variable error in the final blocks of acquisition trials in each of the four practice sessions (AQ150, AQ300, AQ450, AQ600). CON, control group. EIMD, exercise-induced muscle damage. AQ, blocks of acquisition trials. (*) $p < 0.05$, different from AQ460. (#) $p < 0.05$, different from control group. Spread bars indicate sd error.

to understand our current results as proprioceptive feedback reaches cortical areas related to motor control and learning, and enables cortical reorganization and performance enhancement (Lotze et al., 2003). Moreover, proprioceptive information seems to play a specific role in internal model calibration. Muscle spindles, for example, are more sensitive to detect and to signalize kinematic changes at the beginning of the learning process when errors are high (Dimitriou, 2016). In addition, such characteristic appears to particularly contribute to the calibration of an internal model of the effector (Hwang & Shadmehr, 2005). Therefore, the impairment that EIMD causes on the proprioceptive function (Torres et al., 2010), may culminate in the negative long-term effects seen in the present results.

In contrast to the difference between EIMD and CON group observed in the delayed posttest, there was no significant difference between groups in the immediate retention (Fig. 5A). Similar results were observed in the analysis of the initial and final trials of the practice sessions during the acquisition phase. In the initial trials, the absolute error of the CON group decreased and became significantly different from EIMD (Fig. 6A). In turn, the absolute error of the final trials did not differ between groups (Fig. 6B). Thus, either in the acquisition phase or in the tests, it was necessary a period without practice to highlight the difference between groups. These results reinforce the possibility that disrupted proprioceptive information impairs internal models consolidation.

In addition to not increasing accuracy, the EIMD group increased performance variability in the tests (Fig. 6), which is not expected in a normal learning process (Wolpert et al., 2011). This effect may be considered as a consequence of deficits in sensorial integration or unbalanced information, responsible for internal model calibration (Wolpert et al., 2011). Muscle recovery process following muscle damage may suggest an incompatibility between information provided by proprioception and vision, as muscle recovery occurs gradually after EIMD with a dissociated time-course recovery of muscle damage variables (Ferreira et al., 2017). The initial process of muscle recovery is marked by DOMS cessation and by the increased perception of recovery, followed by an improvement in muscle performance (Table 2). Considering that under normal conditions muscle spindles are tuned with practice (Dimitriou, 2016) and that EIMD group was recovering across the study period but did not achieve a complete recovery, one may assume that, during the entire period of practice, the internal model was fed with untuned proprioceptive information. Consequently, that may have increased the EIMD group variability and also hindered its accuracy on the task.

Muscle damage caused by the current resistance exercise protocol is in accordance with previous studies that have evaluated muscle recovery after resistance exercise in untrained men (Ferreira et al., 2017; Nosaka, Newton, & Sacco, 2002; Zaheer, Moiz, Shareef, & Hussain, 2014) and may be considered severe (Paulsen et al., 2012). Other muscle damage protocols are considered less

severe (Clarkson & Hubal, 2002; Paulsen et al., 2012) and, therefore, they may have a different effect on learning. Further studies comparing different EIMD protocols are required in order to evaluate the effect of different muscle damage level on motor skill learning.

Finally, the present study is not without limitation as proprioceptive parameters (i.e., muscle spindles and position sense), cortical areas activity, and shoulder flexors muscle activity were not measured. Therefore, caution is warranted when interpreting the current results. Moreover, factors such as pain sensation and muscle swelling might also play important roles in learning impairment due to EIMD. Inflammatory processes and chemical mediators released as a result of EIMD activates nociceptors (Clarkson & Hubal, 2002; Peake, Nosaka, & Suzuki, 2005), which also send information to the central nervous system and may relate body movement to muscle pain. Muscle swelling, in turn, may alter muscle and limb dynamics, which might require an update of the internal model of the body (Ivanenko et al., 2011). Such factors may not be discarded as a source of bias, thus contributing to motor learning impairments, and may also be a subject of investigation in future EIMD vs. motor learning studies.

5. Conclusion

To our knowledge, this is the first study to investigate the effects of EIMD on motor learning and its results showed that exercise-induced muscle damage is a factor that might largely hinder motor skill learning ($f > 0.4$). Neurological aspects such as proprioceptive information and CNS reorganization corroborate our results as impairment in such aspects may disturb the calibration of internal models related to the task. From a practical standpoint, although we consider it is early to establish practical implications, the current results suggest that sports training and rehabilitation professionals should be cautious when applying motor learning sessions following unaccustomed exercise or a stressful training session, conditions that are known to cause EIMD (Clarkson & Hubal, 2002; Paulsen et al., 2012). These professionals should take into consideration EIMD's potential for hindering immediate motor skill learning.

Acknowledgments

The authors thank Chris Bach for relevant comments on an early version of this manuscript. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.humov.2019.102504>.

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