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Elastic band exercise induces greater neuromuscular fatigue than phasic isometric contractions

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ABSTRACT

This study investigated the neuromuscular fatigue following an elastic band exercise (EB) of the plantar flexors, compared to an intermittent phasic isometric exercise (ISO). Eleven young healthy males (age: 24.2 ± 3.7) took part in the study, consisting of one experimental session involving two 5-min fatiguing protocols separated by 20 min rest and performed randomly. Both exercises were performed at maximal motor output of the plantar flexor muscles, EMG being used as a feedback signal. Neuromuscular fatigue was assessed through changes in maximal voluntary contraction (MVC) and in evoked responses of soleus and gastrocnemii muscles to posterior tibial nerve stimulation (H-reflex, M-wave, V-wave). Both conditions induced significant decrease in MVC force, but to a greater extent after EB (−20.0 ± 5.1%, $P < 0.001$) than after ISO (−12.3 ± 4.6%, $P = 0.037$). While no effect was observed in M-wave amplitude after both exercises, EB resulted in greater decrease of normalized H-reflexes compared to isometric condition. Normalized V-wave significantly decreased only after EB. As a conclusion, the greater fatigability found after EB as compared to ISO was underlain by muscular as well as nervous factors. This higher impact was attributed to the dynamic nature of elastic band exercise as compared to isometric contractions.

1. Introduction

Both in training and rehabilitation, the use of elastic bands has largely increased in the recent years. Initially used for rehabilitation purposes (Simoneau et al., 2001), they have progressively spread to the sport-practice (Mascarin et al., 2016). However, despite its popularity in training, less is known about the acute effects of one single exercise using elastic bands compared to traditional resistance exercise. Yet, the knowledge about the effects of fatigue following a bout of exercise performed under elastic resistance would help to optimize the implementation of such modality within a training session.

It is well known that neuromuscular fatigue may vary according to the type of exercise performed (e.g.: dynamic or static, phasic or tonic, intermittent or continuous). Exercising with elastic bands represents a combination of two contractions modalities that have different characteristics: dynamic contractions, i.e. successive concentric and eccentric phases, and phasic contractions, i.e. the variation of the produced force during the contraction. More importantly, the phasic contractions induced by the use of elastic bands are characterized by variable resistance throughout the movement: the load increases as the band is stretched. The specific effects of elastic exercise on strength development have been mostly attributed to the specificity of its eccentric loading component (Anderson et al., 2008; Wallace et al., 2006). The use of elastic resistance was also suggested to provide greater neural activation than free weight exercises, and will then lead to greater neuromuscular changes following repeated contractions under elastic resistance (Hughes and McBride, 2005; Melchiorri and Rainoldi, 2011).

Abbreviations: **EB**, Elastic Band exercise; $\mathbf{H_{max}}$, Maximal H-reflex; $\mathbf{H_{pot}}$, Maximal H-reflex potentiated (following the MVC); $\mathbf{H_{sup}}$, Maximal H-reflex superimposed (evoked during the MVC); **ISO**, Isometric exercise; $\mathbf{M_{atHmax}}$, M-wave accompanying H_{max}; $\mathbf{M_{atHpot}}$, M-wave accompanying H_{pot}; $\mathbf{M_{atHsup}}$, M-wave accompanying H_{sup}; $\mathbf{M_{max}}$, Maximal M-wave; $\mathbf{M_{pot}}$, Maximal M-wave potentiated (following the MVC); $\mathbf{M_{sup}}$, Maximal M-wave superimposed (evoked during the MVC); **MVC**, Maximal Voluntary Contraction; **RMS**, Root Mean Square of muscle electromyographic activity (EMG)

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The majority of the studies compared the effects of elastic resistance versus free weight exercise (e.g. Melchiorri and Rainoldi, 2011; Saeterbakken et al., 2016; Wallace et al., 2006). However, during free weight exercise the wide degree of freedom that this type of movement provides associated to the constant resistance (i.e. the carried weight) throughout the movement does not completely offer a comparable condition to elastic band exercise. Therefore, one of the main aim of the present study was to compare the effects of contractions performed under elastic resistance with a control task that involves similar conditions except for the elastic component. To this aim, the control task involved the repetition of isometric phasic contractions performed with a stiff belt, allowing to isolate the factor "elastic resistance" between both protocols. Then, while global muscle fatigue induced by elastic resistance versus free weight has already been assessed through the analysis of electromyography signals (Melchiorri and Rainoldi, 2011), no study has further investigated the neuromuscular mechanisms underlying the greater fatigue induced by elastic bands. The combination of surface EMG and peripheral nerve stimulation could help to determine the relative contribution of central and peripheral factors supporting the acute neuromuscular changes induced by both modalities (Rozand et al., 2015). Therefore, the purpose of the present study was also to investigate the acute effects of one single bout of elastic band exercise on spinal excitability, by means of evoking H-reflexes, and on maximal compound muscle action potential (M-waves), to account for neuromuscular fatigue of plantar flexors, compared to a control exercise consisting of repeating isometric contractions. It was hypothesized that, given the dynamic and phasic nature of the contraction induced by elastic resistance, greater neuromuscular fatigue will be observed after this condition.

2. Methods

2.1. Participants

Eleven recreationally active and healthy males (age: 24.2 ± 3.7 years old; height: 1.78 ± 0.05 m; body mass: 79.6 ± 11.6 kg) with no history of injury or neuromuscular disorder participated in the current study. The participants were informed about any potential risk due to the procedures and signed a written informed consent. The experimental design of the study was approved by the local Human Research Ethic Committee (CPP Est I 2016-A00511-50) and conducted in conformity with the latest version of the Declaration of Helsinki.

2.2. Experimental design

All tests were performed on the dominant limb in one-single 2-hour experimental session. Participants sat in a home-made experimental arrangement (see Fig. 1A). A stiff belt was fixed on a metallic structure on one side and on the participant's foot on the other side in order to be parallel with the leg. Particular care was taken so as the belt would remain around the feet at the level of distal heads of the first and fifth metatarsal phalanxes. Knee angle was set at full extension and hip-angle was adjusted from 100° to 120° according to participants' sensation of comfort. Furthermore, ankle-angle was set at 90° and controlled with a manual joint-goniometer. Ankle and hip were firmly strapped to the chair in order to avoid contribution of back and hip muscles to plantar flexion. Finally, the participants were instructed to keep their hands crossed against their chest, and particular care was taken so that the trunk stayed against chair's back. The participants were strongly encouraged to maximally perform the tests. Force was recorded by using a force transducer (Digital Transducer, MIE Medical Research, Leeds, United Kingdom, max. load: 2000 N) placed in line with the belt and simultaneously displayed on the monitor at a sampling frequency of 2 kHz using the Powerlab data acquisition system (LabChart 8, ADInstruments, Sydney, Australia).

First, nerve stimulation intensities were determined to evoke H-reflexes and M-waves responses at rest in the triceps surae muscles. Once the stimulations parameters were established, four trials were performed for each parameter at rest (H-reflex and M-wave). Then, participants performed a standardized warm up, consisting of 8–10 submaximal isometric contractions of the plantar flexors in order to determine maximal force and evoke superimposed responses. Participants were asked to focus on plantar flexion, avoiding any other unnecessary movement (e.g.: knee flexion and hips extension/flexion). They were asked to perform four maximal voluntary isometric contractions (MVC) separated by at least 1 min rest during which the superimposed stimulations were evoked: two MVCs to assess superimposed H-reflexes and two for superimposed M-waves. Each MVC lasted for approximately 4 s. Three stimulations were performed for each MVC and parameter: one at rest before, one during the plateau of MVC (superimposed) and one immediately after the end of the MVC (potentiated response). Further trials were performed if a variation in maximal performance exceeded 5%. These first measurement were noted as PRE 1 (Fig. 1B).

Then, a rest-period of 1-min was given after PRE 1-recordings before beginning the first experimental task. The two following fatiguing tasks were then performed in a random order: an isometric task (noted ISO) and an elastic band exercise (noted EB) of similar duration. These protocols are detailed hereafter. Immediately after the first task, two MVCs were performed by the participants: one for each evoked responses (H-reflexes and M-waves), noted as POST1 (Fig. 1B). The two fatiguing tasks were separated by 20 min of passive recovery, during which participants remained seated in the same position. Before starting the second fatiguing protocol, perceived exertion, MVC force and evoked responses were re-assessed (noted as PRE 2 measurements, see Fig. 1B) in a similar manner. Similarly to POST 1, POST 2-measurements were performed immediately after the end of the second fatiguing exercise.

2.3. Fatiguing protocols

Participants performed two fatiguing tasks of similar duration: an isometric task (ISO) and an elastic band exercise (EB). During both fatiguing protocols, soleus (SOL) EMG activity, measured as the root mean square (RMS) was monitored and displayed for a visual feedback on a monitor placed in front of the participant (Fig. 1A). The use of EMG as a biofeedback was chosen to match the activity between ISO and EB. This modality was shown to provide similar alteration on maximal force as using a feedback of force (Place et al., 2006). The participants were asked to reach their maximal SOL RMS (RMS_{max}) by exerting 25 contractions per minute, with a metronome set at 50 beeps per minute. They were instructed to reach their maximal RMS at one beep and to return to baseline at the following. The total number of contractions was fixed at 120 for both fatiguing protocols, lasting a little less than 5 min. Lastly, they were asked to rate their perceived exertion before and immediately after each protocol, from 1 (no fatigue perceived) to 10 (maximal exhaustion) (Borg and Kaijser, 2006).

This resulted for EB condition to alternate concentric and eccentric phases between each beeps. The green version of Theraband © elastic band was used (TheraBand, Hygienic Corporation, Akron, Ohio, USA). This band provides a 5-pound (2.268 kg) resistance at 100% of band length (no elongation), 8 lb (3.629 kg) at 200% and then increase in an exponential manner (Page, 2000). The length of the elastic band was adjusted to provide the maximal tension that the participants were able to manage in order to reach SOL RMS_{max}. For each participant elastic band exercise was performed through the maximal range of motion of the ankle, evaluated by means of a manual goniometer. This resulted in a range of 65° on average for each participant, from +20° dorsiflexion to −45° plantarflexion (0° = 90° of ankle angle between the foot and the leg). Particular care was given to ensure that participants went from maximal dorsiflexion to maximal plantar flexion angle during each

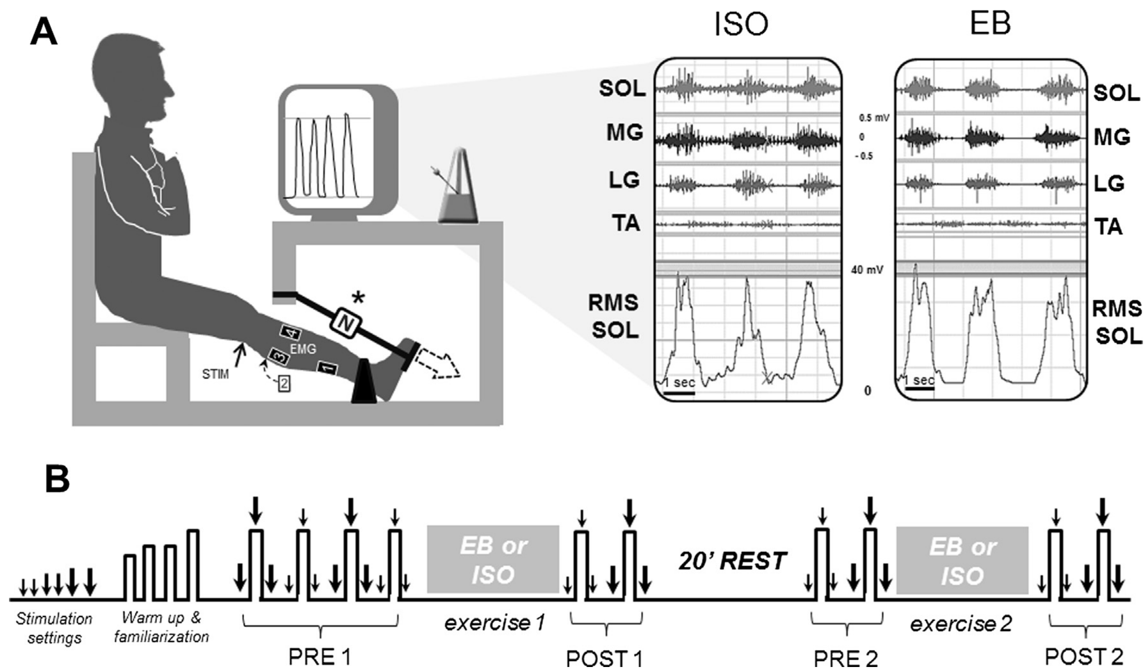

Fig. 1. Experimental protocol. A. Schema of the experimental setup with participants' positioning, EMG arrangement, screen for monitoring and metronome. Electromyography are positioned as follow: 1: soleus (SOL), 2: medial gastrocnemius MG, (placed behind), 3: lateral gastrocnemius (LG), 4: tibialis anterior (TA). STIM: site of stimulation in the popliteal fossa. *: here is pictured the belt normally used during the isometric protocol (N: force transducer), and replaced by elastic band B. Screen captures of the EMG recordings at the beginning of each protocols, i.e. isometric (ISO) or elastic band (EB). In upper panels raw EMG signals of SOL, GM, GL and TA. In the bottom panel rectified EMG activity (Root Mean Square, RMS) of SOL, used for bio-feedback. Participants were asked to try reaching the grey area in each contraction, representing the RMS_{max} value. C. Schematic description of the experimental design including the two exercises performed randomly and separated by 20 min of recovery. Each PRE and POST measurements were performed randomly and included H-reflex (thin arrows) and maximal M wave recording (thick arrows). Each black rectangle represents the maximal force performed by the participants.

contraction.

For ISO protocol, participants' ankle was fixed at 90° of ankle angle, in order to avoid any stretch of the plantar flexor muscles during the whole protocol. During the ISO protocol, participants had to perform successive isometric MVCs with the same setup used for measuring PRE MVC force.

2.4. EMG recordings

EMG activity was recorded from soleus (SOL), medial gastrocnemius (MG), lateral gastrocnemius (LG) and from the tibialis anterior (TA). After shaving and dry-cleaning the skin with alcohol to keep low impedance (< 5 kΩ), EMG signals were obtained by using Trigno sensors (Delsys, Natick, Massachusetts, USA). The sensors were firmly strapped to the leg with skin rubber and positioned 2 cm below the insertions of the gastrocnemii over the Achille's tendon for SOL, and over the mid belly of the gastrocnemii muscles for MG and LG (Hermens et al., 2000). Because the EMG of the plantar flexor muscles can be affected by concurrent activation of antagonist activity, TA EMG activity was also recorded by placing the sensor at 1/3 of the distance on the line between the fibula and the tip of the medial malleolus (Hermens et al., 2000).

EMG signals were amplified with a bandwidth frequency ranging from 0.3 Hz to 1 kHz and simultaneously recorded on a computer at a sampling frequency of 2 kHz using the Powerlab data acquisition system (LabChart 8, ADInstruments, Sydney, Australia).

2.5. Tibial nerve stimulation

Single rectangular pulses (1 ms width) were delivered to the posterior tibial nerve with a Digitimer stimulator (model DS7, Hertfordshire, UK) to evoke H-reflexes of the triceps surae muscles. A self-adhesive cathode (8 mm diameter, Ag-AgCl) was placed in the popliteal fossa and an anode (5 × 10 cm, Medicompex SA, Ecublens, Switzerland) was placed over the patella. Once the optimal stimulation site providing the greatest response peak-to-peak amplitude was located, the stimulation electrode was firmly fixed with straps. The intensity of the stimulation was then progressively increased from SOL, MG and LG H-reflex threshold with 2 mA increment to maximal H-reflex (H_{max}) and then with 5 mA increment until M wave of the three muscles no longer increased. This last stimulation-intensity was then increased by 20% to ensure supramaximal stimulation and used to record maximal M wave (M_{max}). Four stimulations were performed at each intensity. These stimulations allowed to build the whole recruitment curve to determine the optimal stimulation intensities to record each parameter (H-reflex and M-waves) before starting the fatiguing protocols.

Maximal H-reflexes and M-waves were evoked at three different times: at rest without prior MVC (noted H_{max} and M_{max}), superimposed to the MVC (noted H_{sup} and M_{sup}) and after the MVC to assess response potentiation (noted H_{pot} and M_{pot}). Responses at rest were assessed without any prior activity of the plantar flexor muscles, at an interval of 10 s. Superimposed responses were manually triggered once the plateau of maximal voluntary contraction was attained. Potentiated responses were evoked 5 s after the end of the contraction.

It can be noticed that contrary to M_{max} (M-wave at rest), M_{sup} (M-wave during MVC) is followed by a reflexive response, called V-wave. This response is the result of a collision occurring in motor axons between the antidromic impulse generated by the stimulation and the descending neural drive (Upton et al., 1971). V-wave amplitude is assumed to reflect both reflex excitability and presynaptic inhibition of Ia afferents, i.e. spinal processes, and the level of neural drive in descending corticospinal pathways, i.e. supraspinal processes (DelBalso and Cafarelli, 2007). Therefore, by assessing the evolution of potentiated reflex (H_{sup}) concomitantly with V-wave modulation, such technique allows to obtain an index of supraspinal modulations

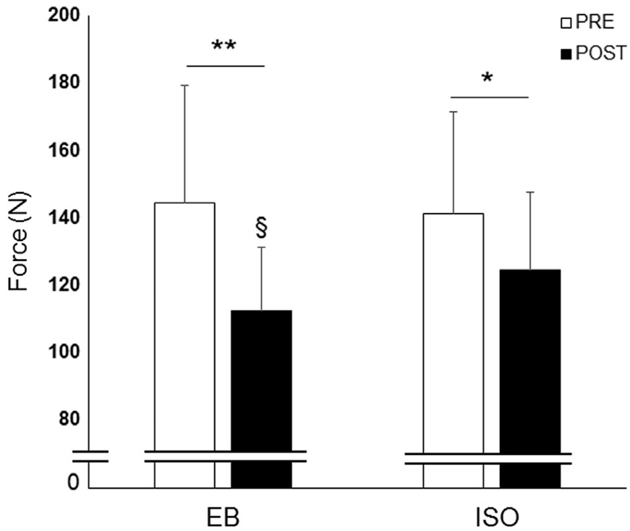

Fig. 2. Plantar flexion force after the two fatiguing protocols. Forces before (PRE, white bars) and after (POST, black bars) elastic band (EB) and isometric (ISO) exercises. Data are mean ± SD. *,**: significant differences at $P < 0.05$ and $P < 0.01$, respectively. §: significant difference with POST of ISO condition.

(Gondin et al., 2006). The magnitude of this evoked potential, along with the evolution of superimposed H-reflexes (H_{sup}), was then used in the present study as an index of descending supraspinal neural drive during the pre and post MVC.

2.6. Data analysis

For each muscle, the average peak-to-peak amplitudes of evoked responses were calculated, and normalized to the maximal M-wave evoked in the same condition. Thus, H_{max}/M_{max}, H_{sup}/M_{sup}, H_{pot}/M_{pot} and V/M_{sup} were considered as dependent variables and compared in EB vs ISO. The M-waves accompanying the maximal H-wave were also measured and normalized by the corresponding maximal M-wave (M_{atHmax}/M_{max}, M_{atHsup}/M_{sup}, M_{atHpot}/M_{pot}). The small M-waves (M_{atH}) accompanying these reflexes were used to ensure the consistency of stimulus condition during the whole duration of the experiment (Grosprêtre and Martin, 2012; Racinais et al., 2013). Similar normalized MatH (M_{atH}/M_{max}) indicated that the recorded H-reflex lied in the same portion of the recruitment curve, with stable nerve stimulation conditions.

The maximal root mean square (RMS_{max}) of EMG activities of the four muscles (SOL, MG, LG, TA) was calculated during the 120 maximal contractions performed during each fatiguing protocols. RMS was evaluated and displayed in real time within the software through a moving window of 200 ms, and the peak value of each contraction was then considered. The duration of each RMS burst of the 120 contractions during both protocol was measured and taken in consideration to ensure that similar contraction duration were performed. To assess muscle activity changes during the fatiguing protocols, RMS of each muscle were averaged every twelve contractions and plotted against time. To normalize muscle activity, each set of contraction was expressed as a percentage of the first set.

The H- and M- wave potentiations were assessed comparing resting responses (H_{max} or M_{max}) to the responses evoked after the MVCs (H_{pot} or M_{pot}). The H_{pot}/H_{max} and M_{pot}/M_{max} ratios were then expressed as percentages.

To account for the supraspinal and spinal contributions mechanisms to the evolution of V-wave after the fatiguing protocols, PRE-POST differences (expressed as a percentage of PRE value) were calculated and compared between H_{sup} and V for each muscle.

2.7. Statistical analyses

All data are expressed by their mean ± standard deviation. The normality of the data was verified by the Shapiro-Wilk test ($P > 0.05$) in order to ensure that traditional analysis of variance (ANOVA) could be used. All distribution followed a normal law.

For each muscle, two way repeated measures ANOVAs were performed with the factors *exercise* (EB vs. ISO) and the factor *pre-post* (PRE vs POST) for each variables. Evolution of RMS_{max} was assessed by a two-way repeated measures ANOVA with factors *time* (from the first set of twelve contractions to the 10th set) and exercise (EB vs. ISO). Perceived exertion was compared through a two-way repeated measures ANOVA with factors *time* (PRE-POST) and exercise (EB vs. ISO).

When a main effect or an interaction was found, a post-hoc analysis was made, using an HSD (honest significant difference) Tukey's test. Statistical analysis was performed using STATISTICA (8.0 version, Statsoft, Tulsa, Okhlaoma, USA). The level of significance was accepted at $p < 0.05$. The effect size was calculated by the partial eta-squared method (Levine and Hullett, 2002).

3. Results

3.1. Force and EMG activity

A significant interaction between *pre-post* and *exercise* was found for MVC force ($F_{1,10} = 5.48$, $P = 0.041$, $\eta_P^2 = 0.60$). MVC force significantly decreased after EB by 20.0 ± 5.1% ($P = 0.001$) and after ISO by 12.3 ± 4.6% ($P = 0.042$) (Fig. 2). The post-EB MVC force was smaller than the post-ISO ($P = 0.002$). On the contrary, self-estimation of perceived exhaustion (CR-10 RPE) similarly increased after both EB (7.3 ± 1.5) and ISO (7.4 ± 1.3).

Regarding muscle activity during the exercises, no modulation of RMS bursts duration during both protocols was observed, ensuring similar duration of each contraction. An interaction effect was observed between the factor *time* and the factor *exercise* for RMS peak of SOL ($F_{9,90} = 1.99$, $P = 0.04$, $\eta_P^2 = 0.17$), MG ($F_{9,90} = 2.02$, $P = 0.04$, $\eta_P^2 = 0.17$) and LG muscles ($F_{9,90} = 3.32$, $P = 0.001$, $\eta_P^2 = 0.25$). While no significant variation in time-course of RMS activity in SOL, MG and LG was observed during ISO, significant decreases resulted during the EB (Fig. 3). Regarding antagonist activity, no significant changes were observed for TA RMS, neither during EB nor during ISO.

3.2. Muscular changes

No main effect nor interaction were found for maximal or submaximal M-waves during both EB and ISO in the three muscles ($P > 0.40$ for all comparisons). Regarding M-wave potentiation, a significant interaction between factors *exercise* and *pre-post* was observed in SOL ($F_{1,10} = 6.47$, $P = 0.029$, $\eta_P^2 = 0.39$). Then, PRE SOL M-wave potentiation, of +18.1 ± 8.0% on average, was statistically different from POST EB (−4.0 ± 7.8%, $P = 0.005$) but not from POST ISO (+10.7 ± 13.9%, $P = 0.607$). No main effect or interaction were found for MG and LG regarding M-wave potentiation (all $P > 0.70$).

3.3. Spinal adaptations

Significant interactions between *exercise* and *pre-post* were found in SOL for H_{max}/M_{max} ($F_{1,10} = 7.68$, $P = 0.019$, $\eta_P^2 = 0.43$), H_{sup}/M_{sup} ($F_{1,10} = 9.28$, $P = 0.012$, $\eta_P^2 = 0.48$) and H_{pot}/M_{pot} ($F_{1,10} = 5.65$, $P = 0.038$, $\eta_P^2 = 0.36$). Regardless of the type of response, H-reflexes were lower after both EB and ISO exercises (Fig. 4A). It can be observed that H-reflexes POST-EB were lower than H-reflexes POST-ISO ($P < 0.05$ for all responses). For MG and LG, only H_{max}/M_{max} showed a significant interaction between *exercise* and *pre-post* ($P = 0.04$ and $P = 0.03$ respectively). No significant H-reflex potentiation was observed in any of the three muscles, whatever the exercise ($P > 0.10$ for

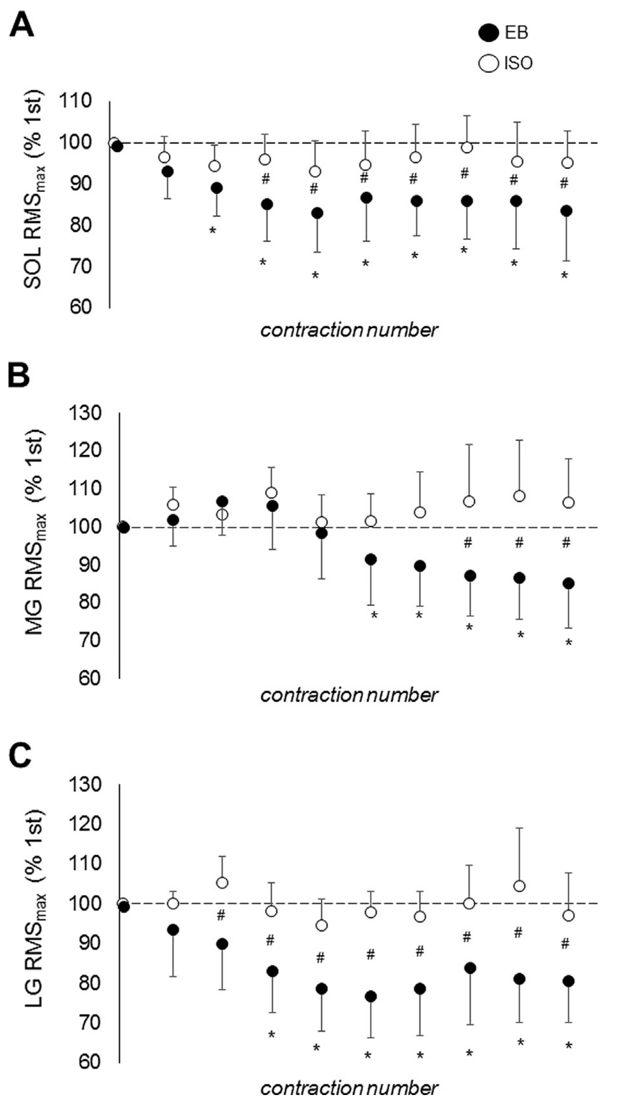

Fig. 3. RMSmax values of triceps surae muscles during isometric and elastic band exercises. Data are depicted for soleus muscle (SOL, A), medial gastrocnemius (MG, B) and lateral gastrocnemius (LG, C). Each point in isometric condition (ISO, empty circles) and elastic band condition (EB, full circles) represents the average of 12 contractions of all participants. Data are normalized by the first set of contractions of each condition. Data are mean ± SD. *: in EB, significant differences with the first set of contractions, at $P < 0.05$. #: significant difference between ISO and EB conditions, for the corresponding set of contractions, at $P < 0.05$.

all comparisons).

3.4. Supraspinal adaptations

Regarding V/M_{sup} modulations, significant interactions between factors *pre-post* and *exercise* were found in SOL ($F_{1,10} = 5.14$, $P = 0.04$, $\eta_P^2 = 0.34$), MG ($F_{1,10} = 6.40$, $P = 0.02$, $\eta_P^2 = 0.39$) and LG ($F_{1,10} = 7.10$, $P = 0.02$, $\eta_P^2 = 0.41$). For the three muscles, V/M_{sup} was significantly reduced after EB exercise but not after ISO (Fig. 4). When comparing PRE-POST evolutions of H_{sup} and V-wave after EB protocol, significant difference were observed for SOL (V-wave: −44.8 ± 8.4%; H_{sup}: −7.8 ± 5.9%; $P < 0.001$), MG (V-wave: −42.9 ± 8.4%; H_{sup}: +5.8 ± 11.4%; $P = 0.005$) and LG (V-wave: −43.9 ± 8.7%; H_{sup}: +7.9 ± 9.0%; $P < 0.001$).

4. Discussion

The aim of the present study was to investigate the neuromuscular fatigue induced by one session of elastic band exercise of the plantar flexors, compared to a conventional isometric exercise. Both fatiguing protocols induced significant decreases in MVC, but the decreases were greater after elastic band exercise. Compared to ISO, in SOL, GM and GL, EB induced greater decreases in muscular potentiation, spinal excitability (H-reflex) and descending neural drive (V-wave).

4.1. Different extents of fatigue between EB and ISO

It is well known that an phasic high-intensity isometric exercise induces significant loss in MVC, both in lower- (Duchateau and Hainaut, 1985) and upper-limb muscles (Corcos et al., 2002). The combined phasic and dynamic nature of EB exercise compared to phasic only in ISO suggests that the phasic characteristic of exercise alone may not be the unique cause of the greater neuromuscular fatigue induced by EB. The greater mechanical constraint brought by EB compared to isometric or free-weight exercise performed at the same load (Ebben and Jensen, 2002) was attributed to the variable resistance along the contraction. Indeed, this variation may optimize the muscle length-tension relationship throughout the whole movement (Mutungi et al., 2003), i.e. providing the maximal force generation at each of the joint angle. Indeed, elastic bands can add supplemental resistance at full extension when the musculoskeletal system is not able to provide further amount of force (Behm, 1988; Wallace et al., 2006), particularly during the eccentric compared to the concentric phase of the movement (Anderson et al., 2008; Wallace et al., 2006).

Based on the present results, the greater fatigue induced by elastic resistance does not seem to involve only mechanical properties but also neural mechanisms. Indeed, the present results showed significant decreases in maximal EMG activity during EB for the three triceps surae muscles, without any change during ISO. This is the first clue that the neuromuscular fatigue triggered by both protocols relied on different mechanisms. The absence of changes in EMG activity observed in ISO can be attributed to the short and a-priori fixed duration of the fatiguing protocol, while such changes are mainly observed during isometric tasks involving repetition-to-failure or sustained contractions (e.g. Bigland-Ritchie et al., 1986; Christensen and Fuglsang-Frederiksen, 1988). EMG measurement is however a global index of the neural changes that may occur during a fatiguing exercise, and complementary techniques such as peripheral nerve stimulation can bring supplemental clues on the underlying neural mechanisms.

4.2. Origin of the neuromuscular fatigue

It was suggested that the decreases in force and EMG activity observed after a dynamic exercise can be associated with alterations in muscular intra-cellular processes, i.e peripheral, rather than changes occurring at central level (Oza et al., 2016). In the present study, the lack of M-wave modulation after both EB and ISO suggested that the neural portion between the stimulation site and the neuromuscular junction was poorly involved in the fatigue mechanisms. This is consistent with previous findings that showed no effects on M-wave amplitudes after a dynamic repetitive fatiguing exercise (Klass, 2004). However, the significant changes in M-wave potentiation observed after EB, assessed through changes in M_{max}/M_{pot} ratio, does not fully exclude alterations in muscle intrinsic properties. Indeed, in absence of changes in absolute M-wave amplitude, the variation in M-wave pre-to-post MVC may reflect a modulation of the electrogenic Na^+-K^+ pumping efficiency (Cupido et al., 1996). Klass (2004), who also found alterations of M-wave potentiation after dynamic exercise but no changes in absolute M-wave amplitude, suggested that the excitation-contraction coupling, mediated by muscle intracellular Ca^{2+} concentration, might also play a major role in the decreases in force observed after such an

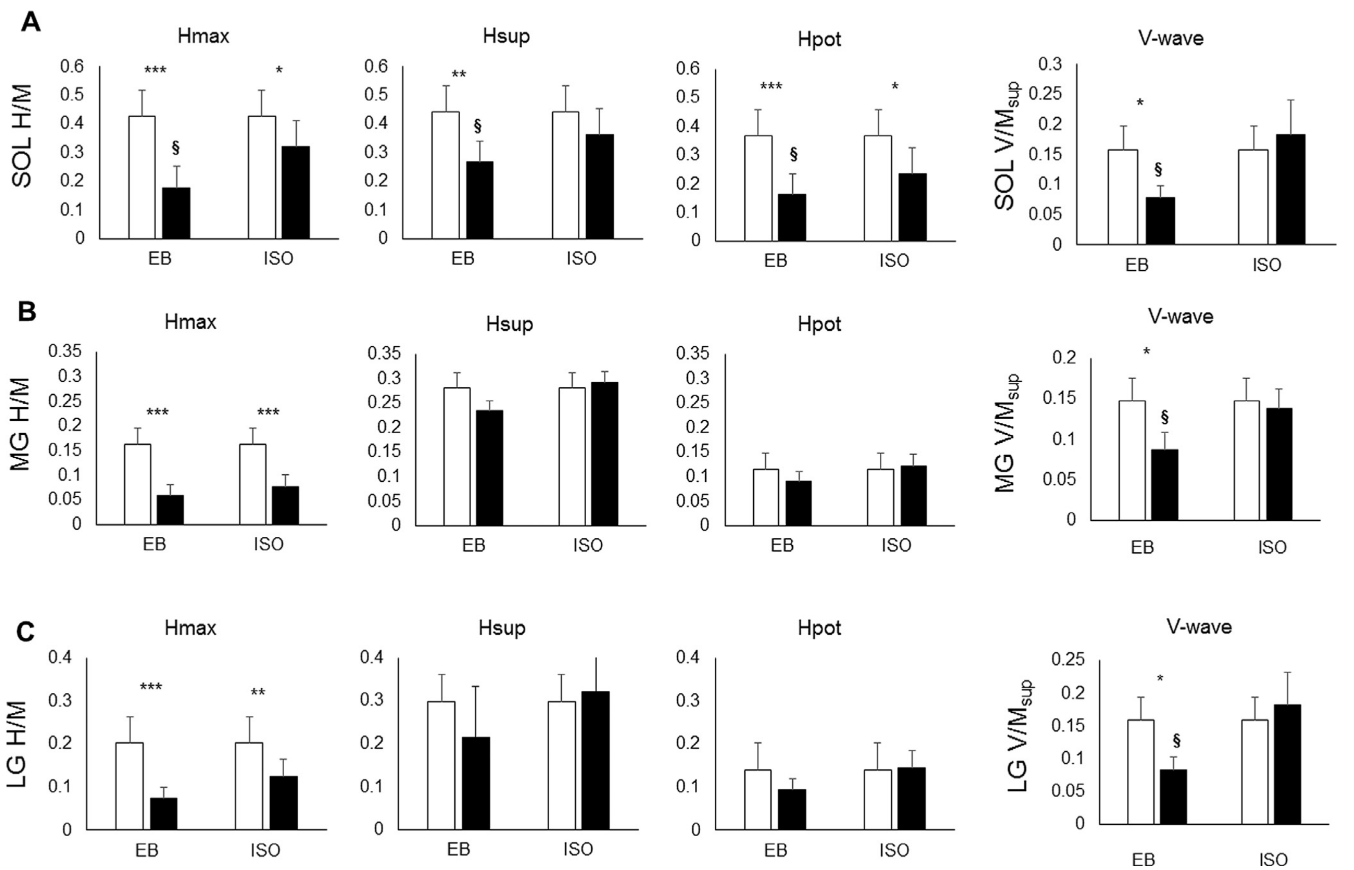

Fig. 4. H-reflex and V-wave recordings before and after both fatiguing exercises. Data are depicted for soleus (SOL, A), medial gastrocnemius (MG, B) and lateral gastrocnemius (LG, C), before (white bars) and after (black bars) elastic band (EB) and isometric (ISO) exercises. H-reflexes are normalized by the corresponding maximal M-wave, recorded at rest (H_{max}/M_{max}), superimposed during maximal contractions (H_{sup}/M_{sup}) or after maximal contractions (H_{pot}/M_{pot}). Data are mean ± SD. *, **, ***: significant differences with PRE value at $P < 0.05$, $P < 0.01$ and $P < 0.001$, respectively. §: significant difference with POST of ISO condition.

exercise. Finally, it was suggested that muscle metabolites accumulation during fatiguing protocols provokes motorneurone reflex inhibition (Duchateau and Hainaut, 1993). This last assumption raises the fact that peripheral changes are strongly linked with neural changes.

In the present study, a particular decrease in spinal excitability following the EB fatiguing protocol was also found. This loss might then be attributed to the dynamic component of EB compared to ISO, and more particularly to the eccentric phase. Indeed, it is well known that eccentric contraction affects the spinal excitability, which remains unchanged during isometric or concentric contractions, exerted at both sub-maximal (Grosprêtre et al., 2014) and maximal force-level (Duclay et al., 2011). The decreases in MVC observed after eccentric exercise has already been strongly associated with spinal alterations (Avela and Komi, 1998). The decreases in H-reflex following multiple muscle lengthening, as during EB exercise, may reflect a depletion of neurotransmitter in the Ia-alpha motoneuronal synapse due to high rates of Ia discharge, i.e. an homosynaptic post-activation depression (Hultborn et al., 1996). However, other mechanisms may be responsible for such impairment of the reflex pathway. Particularly, it was also suggested that eccentric exercise induced a strong depression of the H-reflex amplitude due to presynaptic inhibition of Ia afferent fibres by group III and IV afferents (Vangsgaard et al., 2013). These free-nerve endings are activated when important mechanical constraints may cause muscle pain and metabolic alterations during high intensity exercise (Cresswell and Löscher, 2000; Kaufman et al., 2002) and were proposed to play a major role in spinal and supraspinal fatigue (Gandevia, 2001).

Regarding supra-spinal modulations, no significant changes in V-waves occurred after ISO, suggesting that the decreases in force might be accounted for spinal excitability changes rather than supraspinal modulations. As V-wave involves both spinal and supraspinal mechanisms, the comparison of the evolution of superimposed H reflex (H_{sup}) and V-wave itself was proposed as a tool to estimate the relative contribution of both levels to V-wave changes (Gondin et al., 2006). Therefore, in the present study the decrease of V-wave in gastrocnemii muscles in absence of significant change for H_{sup}, as well as the greater decrease of V-wave as compared to Hsup in SOL, accounted for a supraspinal component in the neuromuscular fatigue observed. Again, the eccentric phase within EB could be one of the main causes for this decrease. Indeed, it is well known that lengthening contractions have a greater impact at supraspinal levels than isometric contractions (Duclay et al., 2011). A greater magnitude of brain activations was shown in the motor regions during lengthening as compared to shortening contractions (Fang et al., 2004). On the contrary, concentric contractions does not provide such modulations, at spinal nor at supraspinal levels (Duclay et al., 2011). Most of the studies analysing the impact of eccentric versus isometric and concentric contractions on the cortical output using transcranial magnetic stimulation techniques showed a great impact of eccentric contraction on motor evoked potentials, while no effect of isometric or concentric could be observed (See Duchateau and Enoka, 2016 for review).

4.3. Study limitations

Firstly, in the present study EMG biofeedback was used to fix the intensity of the exercise between ISO and EB. EMG signals represent the central command and its link with the developed muscular force is not linear, particularly when neuromuscular fatigue is involved (Place et al., 2006). Therefore, in the present study the muscular force developed during the elastic band protocol cannot be directly determined by using EMG signals amplitude.

Secondly, the different indexes of fatigue, aiming to decipher the modulation that occurred at several level (muscular, spinal and supraspinal), were obtained from indirect measurements from nerve stimulations. Such technique, commonly used to assess spinal excitability through the recording of H-reflexes, has inherent limitations. A modulation of H-reflex amplitude for instance cannot be interpreted as a marker of motoneuronal plastictiy, since many other spinal structures can be involved in the size of the response (Misiaszek, 2003). As well, the dissociation between spinal and supraspinal levels by means of H-reflex and V-wave should be performed with caution, as different populations of afferents and moto-neurons can be recruited for both responses (Carroll et al., 2011). Therefore, the present results are indirect clues of spinal and supraspinal modulations with neuromuscular fatigue that complementary methods can confirm for each level, such as electroencephalography for supraspinal changes and H-reflex conditioning methods to specify the spinal pathways involved.

5. Conclusion

To summarize, both EB and ISO, performed at maximal EMG activity, induced significant impairments in maximal force generation capacity. However, the impairments were greater after EB. As hypothesized, a greater modulation of central factors was observed with the use of elastic bands compared to isometric condition. Indeed, EB showed greater impairments in the tested neuromuscular parameters, from muscular to spinal and supraspinal levels, while ISO showed small decreases in muscular and spinal levels but no changes in supraspinal level. It was suggested that the eccentric phase of contractions under elastic resistance could be particularly involved in the greater neuromuscular fatigue observed after EB than ISO. This particular acute effects of EB should be considered when implementing such a modality of exercise in rehabilitation or strength training programs.

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We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines. None of the authors has any conflict of interest to disclose.

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