On-field low-frequency fatigue measurement after repeated drop jumps

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Purpose: Monitoring fatigue is now commonly performed in athletes as it can directly impact performance and may further increase the risk of injury or overtraining syndrome. Among the exercise-induced peripheral alterations, low-frequency fatigue (LFF) assessment is commonly restricted to in-lab studies. Measuring LFF on-field would allow athletes and coaches to assess muscle fatigability on a regular basis. The aim of the present study was therefore to validate a new portable device allowing quadriceps LFF assessment in the field.

Methods: LFF was assessed in 15 active and healthy participants before (PRE) and after (POST) a series of drop jumps. LFF was assessed, thanks to a dedicated device recording evoked force to muscle submaximal electrical low- and high-frequency stimulation. Changes in the low- to high-frequency force ratio (further referred to as Powerdex® value) were compared to the changes in the ratio of evoked force induced by paired-pulse femoral nerve electrical stimulation at 10 and 100 Hz (i.e., DB10/DB100 ratio). Maximal voluntary contraction (MVC) and voluntary activation (VA) were also measured.

Results: MVC decreased (p < 0.001), whereas VA was not affected by the fatiguing task (p = 0.14). There was a decrease in the DB10/DB100 ratio (from 96.4% to 67.3%, p < 0.001) as well as in the Powerdex value (from 74.0% to 55.7%, p < 0.001). There was no significant difference between POST values (expressed in percentage of PRE values) of the DB10/DB100 ratio and Powerdex (p = 0.44), and there was a significant correlation between the changes in Powerdex® and DB10/DB100 (r = 0.82, p < 0.001).

Conclusion: The on-field device we tested is a valid tool to assess LFF after a strenuous exercise consisting of repeated drop jumps as it evidences the presence of LFF similarly to a lab technique. Such a device can be used to monitor muscle fatigability related to excitation–contraction in athletes.

KEYWORDS

drop jumps, eccentric contraction, fatigability, prolonged low-frequency force depression, athletic performance
Introduction

Athletes, especially elite athletes, are exposed to high training and competition loads, making the monitoring of fatigue extremely relevant (Thorpe et al., 2017). As defined by Enoka and Duchateau (2016), fatigue can be conceptualized as a disabling symptom in which physical and cognitive functions are limited by interactions between performance fatigability (i.e., the decline in an objective measure of performance) and perceived fatigability (i.e., changes in the sensations that regulate the integrity of the performer). Fatigue directly impacts sport performance, and may further increase the risk of injury or induce an overtraining syndrome in case of prolonged excessive imbalance between training/competition loads and recovery periods (Thorpe et al., 2017; Cheng et al., 2020).

A reduction in maximal force during an isometric maximal voluntary contraction (MVC) is thought to provide the most straightforward evidence of performance fatigability (Carroll et al., 2017). Part of the alterations within the neuromuscular system can occur at the central nervous system level, as evidenced by a decreased voluntary activation level (VA) assessed through the superimposed twitch technique (Merton, 1954). Alterations can also occur at the peripheral level through impaired muscle contractility (Allen et al., 2008), which can be assessed through peripheral nerve or muscle electrical stimulation (Millet et al., 2011). As such, performance fatigability can be ultimately defined to occur when the force output is lower than what is expected for a given voluntary or evoked stimulus (Maclntosh and Rassier, 2002). In other words, despite maximal voluntary contraction being preserved, performance fatigability may still exist if the force induced by certain types of stimulation is depreciated.

Among the exercise-induced peripheral alterations, low-frequency fatigue (LFF), also known as prolonged low-frequency force depression (Allen et al., 2008), is a long-lasting form of muscle fatigability and is characterized by a larger decrease of force at low stimulation frequencies than at high stimulation frequencies (Edwards et al., 1977; Jones, 1996). LFF is suggested to reflect excitation–contraction coupling failure through decreased Ca$^{2+}$ release within muscle fibers (Edwards et al., 1977; Hill et al., 2001; Keeton and Binder-Macleod, 2006; Dargeviciute et al., 2013). LFF is notably believed to be a primary source of peripheral alterations after eccentric contractions (Martin et al., 2004; Iguchi and Shields, 2010; Skurvydas et al., 2016; Kamandulis et al., 2019). But LFF and/or alteration of Ca$^{2+}$ release has been observed following other types of fatiguing tasks such as intense exercise (Lattier et al., 2004; Skurvydas et al., 2016) or exercise inducing glycogen depletion (ørtenblad et al., 2011).

The gold standard to assess LFF is the ratio of low- to high-frequency force responses to trains of peripheral nerve electrical stimulation at supramaximal intensity (Allen et al., 2008). Due to the discomfort induced by such tetanic nerve stimulation, evoked forces to paired stimuli at 10Hz and 100 Hz have been proposed as an alternative method (Verges et al., 2009). But because of the complexity of this kind of measurements (i.e., electrode placement, specific material, and discomfort), LFF assessments are commonly restricted to in-lab studies. Measuring LFF on-field would however provide great insight to athletes and coaches on athletes’ muscle fatigability, allowing better management of training/competition loads. This is the goal of Myocene”, a new portable device allowing quadriceps LFF assessment on the field. For that purpose, it is composed of an easy-to-transport knee extensor dynamometer integrating an electrical stimulator for muscle transcutaneous stimulation. Considering that the relative decrease in the low- to high-frequency ratio after a fatiguing task is not different whether supramaximal nerve stimulation or submaximal muscle stimulation is applied (Martin et al., 2004), the device uses trains of submaximal stimuli applied to the quadriceps muscle to reduce discomfort and simplify its acceptability by athletes. But the outcome provided by this on-field device (i.e., the so-called Powerdex) remains to be validated when compared to laboratory measurements.

The aim of this study was to validate the use of a portable on-field device to measure LFF induced by a series of drop jumps, that is, exercise consisting of stretch-shortening cycles with a strong eccentric component. We therefore compared the exercise-induced decrease in Powerdex and the decrease in the ratio of 10- to 100-Hz doublets in an in-lab setting. We hypothesized that the magnitude of LFF would be correlated between both methods.

Methods

Participants

Fifteen active and healthy participants (11 men and four women; age: 26 ± 5 yr; body weight: 70 ± 10 kg; height: 174 ± 9 cm) participated in the present experiment. They self-reported their main strength as either explosive (n = 9) or enduring (n = 6). They reported no history of neurological or musculoskeletal impairment. Participants were asked to refrain from strenuous and unaccustomed physical activity for 48 h before testing to minimize the risk of prior fatigue or muscle damage. The study protocol was approved by the local Ethics Committee and was in accordance with the latest update of the Helsinki Declaration (except for registration in a database). All subjects gave their written informed consent before participation.

Study design

Participants visited the laboratory on two occasions. During the first session, participants were familiarized with the experimental procedures. At least seven days later,
participants went back to the laboratory for the evaluation session. This first evaluation consisted of quadriceps LFF assessment (PRE) using the on-field device. Then, participants moved to the laboratory dynamometer for a neuromuscular function evaluation: maximal voluntary contraction (MVC), maximal voluntary activation level (VA), and evoked responses to 10- and 100-Hz doublet on relaxed muscle. Participants were then asked to perform an intense eccentric exercise composed of repetitive drop jumps (DJs). Participants were then retested (POST) in the same order as in PRE. A 10-min resting period was observed between the last DJ and POST measurements to avoid the neuromuscular evaluation to be affected by metabolic fatigue. All measurements were performed on the right leg. The study design is described in Figure 1.

**LFF assessment using the on-field device**

This study was performed using the on-field Myocene® device (Figure 2). Participants sat on the seating of the device with their leg in contact with the "Myo-sensor," that is, a dedicated force sensor recording evoked forces at a rate of 4 kHz. Muscle electrical stimulations (biphasic square wave with a pulse width of 400 µs) were applied using three electrodes (MyoPro-1-electrode, Myocene, Liège, Belgium). The cathode (5 × 10 cm) was placed transversely across the width of the proximal portion of the quadriceps femoris, and the anodes (5 × 5 cm) were, respectively, placed over the vastus lateralis and vastus medialis muscles. Pre-programmed electrical stimuli trains were directly sent by the device that was driven by the Myocene® software. The series of stimuli consisted of sets including 1) a single pulse, 2) a train of...
Participants performed 149 ± 27 DJs (range: 100–180). At POST, MVC decreased to 87.8 ± 10.5% of the PRE value (from 651 ± 152 N to 571 ± 140 N; \( p < 0.001; d = 1.2 \) and \( \eta^2 = 0.33 \)). The effect size was calculated using the mean difference between the PRE and POST values (expressed as a percentage of the PRE). The correlation between the changes in postural control and muscle strength was also calculated using the Pearson correlation coefficient. The correlation coefficient was found to be significant \( r = 0.45; p < 0.05 \), indicating a moderate-to-large effect size. The results suggest that eccentric exercise can lead to significant reductions in muscle strength, which may have implications for athletic performance and rehabilitation programs.
DB100 decreased to 80.6 ± 13.9% of the PRE value (from 257 ± 39 N to 208 ± 48 N; \( p < 0.001; \ d = 1.4 \)). On the contrary, VA did not change significantly (94 ± 3% vs. 92 ± 3%; \( p = 0.14; \ d = 0.4 \)).

At POST, Powerdex fell to 71.0 ± 12.0% of the initial value (from 74.0 ± 6.4% to 55.7 ± 10.9%; \( p < 0.001; \ d = 2.4 \); Figure 3A). The DB10/DB100 ratio fell to 69.5 ± 8.6% of the initial value at POST (from 96.4 ± 10.9% to 67.3 ± 13.0%; \( p < 0.001; \ d = 3.7 \); Figure 3B). There was no significant difference between POST values (expressed in percentage of PRE values) of the DB10/DB100 ratio and Powerdex (\( p = 0.44 \)), and there was a significant correlation between those values (\( r = 0.82, \ p < 0.001 \); Figure 4).

**Discussion**

The present study aimed to compare LFF measurement after an intense eccentric task obtained either using an on-field device or through classic in-lab procedures. The main findings are that...
1) on-field and in-lab methods detected similar amount of LFF and 2) the amplitudes of LFF were correlated between the two methods.

In the present study, participants performed a series of DJs, ranging from 100 to 180 jumps. Such exercises consisted of stretch-shortening cycles (i.e., an eccentric contraction during the ground contact phase followed by a concentric contraction during propulsion), with a strong eccentric component. As a result, we observed a marked maximal force depression in POST, which is indicative of performance fatigability, as already reported in the literature after a similar exercise (Kamandulis et al., 2019). As previously reported by others (Kamandulis et al., 2010), this decrease in MVC was not associated with an alteration of the central drive (i.e., no change in VA). On the contrary, it was accompanied by an alteration of muscle contractility as suggested by the significant decrease in evoked forces on relaxed muscles. Because a 10-min rest period was provided before this measurement, most of the acute metabolic perturbations were probably gone, especially considering the nature of the task, that is, eccentric contractions with a low metabolic cost. Altogether, our results suggest that performance fatigability mainly originated within muscle fibers and was mostly independent of metabolic perturbations.

In the present study, a series of DJs resulted in evoked force depression which was more marked in response to low-(i.e., DB10) than high-frequency (i.e., DB100) nerve stimulation. Consequently, there was an alteration in the DB10/DB100 ratio at POST, suggesting the presence of LFF in the quadriceps. While it must be acknowledged that the use of doubllets may underestimate the magnitude of LFF compared to low- and high-frequency tetanic stimulations (Ruggiero et al., 2019), it still allows a valid detection of LFF with limited discomfort for the participants, especially when using femoral nerve stimulation (Verges et al., 2009). Alternatively, evoked force to trains of muscle submaximal stimulation can be used as a less painful assessment method (Martin et al., 2004). Accordingly, several in-lab studies previously reported decreases in low- to high-frequency force responses to trains of quadriceps muscle stimulation applied at either submaximal (Skurvydas et al., 2002; Martin et al., 2004) or supramaximal (Kamandulis et al., 2010; Skurvydas et al., 2016; Kamandulis et al., 2017; Kamandulis et al., 2019; Muanjai et al., 2020) intensity after repeated DJs.

Similar to the DB10/DB100 ratio, the Powerdex obtained through the on-field device decreased after DJs. When comparing LFF evaluation through the on-field device with peripheral nerve electrical paired stimulation, no significant difference was found between POST values (expressed in percentage of PRE values). Moreover, values obtained with these two methods were highly correlated. These findings suggest that the on-field device can effectively evidence the presence of LFF, but also provide a valid measurement of LFF, at least when considering doubllets as a reference in-lab method. These results are promising and suggest the on-field device could be an alternative method to in-lab technics for the measurement of LFF in the field.

As mentioned earlier, the causes of LFF after DJs in the present study are likely not associated with metabolic factors because of the 10-min resting period before POST measurements and the nature of the fatiguing task. Instead, mechanical factors probably contributed to the presence of LFF. For instance, eccentric contractions may lead to muscle damage that can alter connections between the sarcoplasmic reticulum and the T-tubules. More specifically, the coupling between the dihydropyridine receptor and the ryanodine receptor can be damaged (Balog, 2010), limiting the amount of Ca2+ released from the sarcoplasmic reticulum for each action potential. As a result, the amount of force that can be produced when the action potential comes into the fiber is decreased (Keeton and Binder-Macleod, 2006). This is notably more evident at low frequency than at high frequency due to the sigmoidal relationship between the Ca2+ concentration and the force output. Consequently, a small reduction in the Ca2+ concentration will have more effect on the steep part of the curve (corresponding to low frequency) than on the horizontal part (corresponding to high frequency) (Jones, 1996; Keeton and Binder-Macleod, 2006; Allen et al., 2008).

Because the on-field device can evidence the presence of those LFF consequences similar to the in-lab methods, this device could integrate the athletes’ routine in order to assess LFF in their quadriceps on a daily basis, especially considering that its use is very easy and short (i.e., 2 min for one leg), contrary to current existing in-lab methods. This on-field measurement has potential implications for athletes. For instance, LFF assessment with such an on-field device could be easily performed on both legs, allowing to highlight a possible imbalance in the decrease of their respective Powerdex, likely indicating a greater work on one leg than on the other one. Consequently, the results can help to optimize training with tailored exercises. The measurements can also be performed continuously throughout the season to evaluate the fatigue state of the athletes and thus adapt the volume or type of training to avoid injuries or overtraining.

In conclusion, while the assessment of LFF is generally restricted to laboratory settings, our results suggest that its assessment can also be performed on the field with dedicated devices such as the Myocene® device we tested in the present study. For instance, similar results we obtained with the in-lab and on-field procedures suggest that the on-field device is a valid device to assess LFF after a strenuous eccentric exercise (i.e., repeated DJs in the present study). Using such a device could provide better accessibility and acceptability for the on-field assessment of muscle fatigability in athletes. It is thought that better monitoring of fatigue in athletes could help improve performance (i.e., through tailored training prescriptions) and may further decrease the risk of injury or overtraining syndrome.
Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the Institutional Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

Author contributions

JR, VR, GM, and TL conceived and designed research; JR performed experiments; JR analyzed data; JR, VR, GM, and TL interpreted results of experiments; JR prepared figures; JR, VR, GM, and TL drafted the manuscript; JR, VR, GM, and TL approved the final version of the manuscript.

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Conflict of interest

GM is a member of Myocene’s scientific advisory board.

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