Effectiveness of low-frequency vibration recovery method on blood lactate removal, muscle contractile properties and on time to exhaustion during cycling at $\dot{V}O_{2\max}$ power output

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Abstract The aim of the study was to determine the effectiveness of low-frequency vibration recovery (LFV-rec) on blood lactate removal, muscle contractile properties, and on time to exhaustion during cycling at maximal oxygen uptake power output ($\dot{p}VO_{2\max}$). Twelve active males carried out three experimental sessions. In session 1, participant's maximal oxygen uptake ($\dot{V}O_{2\max}$) and $\dot{p}VO_{2\max}$ were determined, and in sessions 2 and 3, the participants performed a fatiguing exercise (2 min of cycling at $\dot{p}VO_{2\max}$) and then a 15 min recovery period using one of two different methods: LFV-rec which consisted on sitting with feet on the vibratory platform (20 Hz; 4 mm) and passive recovery (P-rec), sitting without vibration stimulus. After that, participants performed an all-out exercise test on cycle ergometer at $\dot{p}VO_{2\max}$. In the recovery period, variables such as heart rate (HR), blood lactate concentration [Lac], and tensiomyographic parameters (D_m : maximal radial displacement; T_c : time of contraction maintenance, and T_r : relaxation time) were measured. In an all-out exercise test, mean time to exhaustion (TTE), total distance covered (TD), mean cycling velocity (V_m), and maximal

HR ($HR_{\max}$) were also assessed. The results showed no effect of recovery strategy on any of the assessed variables; nevertheless, higher values, although not significant, were observed in TTE, TD, and V_m after LFV-rec intervention. In conclusion, LFV-rec strategy applied during 15 min after short and intense exercise does not seem to be effective on blood lactate removal, muscle contractile properties, and on time to exhaustion during cycling at $\dot{p}VO_{2\max}$.

Keywords Recovery · Low-frequency vibration · TMG · Lactate clearance · All-out exercise performance

Introduction

Muscle recovery after physical activity is very important, especially in sports competitions. In many sports events, athletes must exercise at high intensities two or more times within the same competitive session and with limited rest periods between efforts. This may be the case of some qualification systems in sports where an athlete must complete several rounds during the same day. This often occurs in modalities in which athletes perform exercises lasting 2 min such as alpine skiing (downhill, super-combined), track and field (women 800 m), and speed skating (1,000–1,500 m inline/ice skating). Therefore, fast muscle recovery is needed in order to maintain or even increase performance in the subsequent efforts. In order to restore muscular function, a variety of postexercise recovery interventions are often employed to improve recovery from training and competition bouts (Mika et al. 2007). It is proposed that the use of recovery strategies ensures performance in subsequent exercise sessions (training and/or competition) is not unduly compromised by lingering muscle soreness or decrements in power, flexibility, speed,

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or agility (Dawson et al. 2005). Thus, an optimal balance between exercise load and recovery is required to maintain a high physical performance during subsequent exercise sessions.

For short intermittent exercises, performed under anaerobic conditions, it has been recommended to introduce active recovery between exercises rather than passive recovery in order to decrease blood lactate concentration ([Lac]) (Billat 2001; Billat et al. 2001). The lactate accumulation has been associated with a performance decline and hence lactate removal after effort seems to be important to improve the subsequent performance, mainly when the exercise is performed at high intensity (Ahmaidi et al. 1996). It has been suggested that active recovery methods improve muscle blood flow and blood velocity and enhance recovery by augmenting removal of [Lac] (Tiidus 1997; Begum et al. 2005; Suzuki et al. 2002; Steele and Duke 2003; Tiidus and Shoemaker 1995; Gupta et al. 1996; Monedero and Donne 2000). However, and although all seems to indicate that active recovery results in faster [Lac] removal than passive recovery, there are doubts about how these recovery types influence the performance of the subsequent exercise, probably due to methodological differences across studies, especially in relation with the task used as performance criterion (Franchini et al. 2003). Indeed, performing active versus passive recovery between high-intensity cycling efforts has been reported to significantly impair performance (Haseler et al. 1999; Dupont et al. 2007; Spencer et al. 2006; Spencer et al. 2008), although other studies have found opposite results (Bogdanis et al. 1996; Dorado et al. 2004; Spierer et al. 2004). Taking into account these conflicting results, it is important to find alternative recovery methods that allow athletes to recover as soon as possible after short-term and intense efforts and to perform a subsequent exercise under the best conditions.

On the other hand, the effectiveness of different recovery strategies applied after short and intense exercises can be evaluated using surface electromyographic signals (EMG) or muscle contractile properties. Several studies have analyzed the EMG power spectrum during dynamic exercise (Mika et al. 2007) finding reductions of the median frequency with the onset of muscle fatigue (Singh et al. 2007). However, muscle contractile properties during or after fatiguing exercise remain unclear, mainly due to a lack of an adequate assay system. In the last few years, measurements of contraction time by tensiomyography (TMG) have been successfully implemented on different muscle groups (Valencic and Knez 1997) to investigate endurance and fatigue among other muscular responses (Grabljevec et al. 2005; Krizaj et al. 2008). By using TMG, fatigued muscle responses as well as the effects of different recovery methods on muscle contractile properties could be tested.

In any case, to find an effective recovery strategy after short and intense exercises which facilitates [Lac] removal, decreases muscle tone and improves the performance in subsequent efforts is a difficult task. Whilst contrast water therapy, stretching and massage have previously been widely investigated (Barnett 2006), the impact of low-frequency vibrations (LFV) on muscle recovery has not (Edge et al. 2009). In a recent study, Edge et al. (2009) found no benefit of whole body vibrations (WBV) on running performance recovery following high-intensity interval training. These authors used WBV at a frequency of 12 Hz, lower than that applied by Bakhtiary et al. (2007) who reported that administering 50 Hz of local vibration to each lower limb significantly reduced 24 h postexercise creatine kinase levels and increased the recovery of isometric force production. Moreover, Green and Stannard (2010) found no significant increases in intermittent isometric handgrip exercise capacity after local LFV compared with passive rest in trained and untrained climbers. Although LFV may act as a mechanical massage to accelerate the recovery process by increasing blood flow to and from the damaged muscle (Cochrane and Hawke 2007; Kerschman-Schindl et al. 2001; Yamada et al. 2005; Lohman et al. 2007), removing waste products, increasing muscle temperature and oxygenation recovery rate (Cochrane et al. 2008; Coza et al. 2010), and stimulate the muscle receptors to ease muscular tension (Cafarelli et al. 1990), different vibration stimulus used in the above mentioned investigations (local or whole body application, and different vibration characteristics) can lead to lack of consensus on the usefulness of LFV as recovery method, being important to clarify its recovery effects on metabolic and muscular systems after short and intense exercise. In this way, the purpose of this study was to evaluate the effectiveness of LFV as a recovery strategy on blood lactate removal, muscle contractile properties and on exercise performance after a short and intense cycling effort.

Methods

Participants

Twelve healthy male volunteers (mean $\pm$ SEM; age, 24.16 $\pm$ 0.62 years, height 172.02 $\pm$ 1.21 cm, body mass 71.84 $\pm$ 2.19 kg, BMI 24.42 $\pm$ 0.70 kg m⁻²) were recruited for this study. All were recreationally active who were not engaged in a systematic exercise program. Participants were asked to abstain from food and caffeine beverages for 2 h before testing and to not perform heavy exercise during the 24 h preceding the tests. After being fully informed about the purpose of the experiments, each participant signed an informed consent. The Local Research Ethical Committee

164 approved the experimental protocol and the procedures
165 involved.

166 Testing procedures

167 All participants reported to laboratory for three visits. The
168 first one was dedicated to determine participants' VO_{2max}
169 and power associated with VO_{2max} (pVO_{2max}); for that, the
170 participants carried out a maximal graded test on a cycle
171 ergometer. Then, on two separate sessions (48 h), and in a
172 random order, they performed 2 min of cycling at pVO_{2max}
173 (intense exercise) followed by 15 min of LFV (LFV-rec) or
174 passive recovery (P-rec). After the recovery period par-
175 ticipants performed an exercise test to exhaustion on a
176 cycle ergometer at pVO_{2max} (Fig. 1). Heart rate, blood
177 lactate concentrations and TMG measures were assessed in
178 LFV-rec and P-rec. In order to avoid any interference of
179 food ingestion on lactate response to exercise, participants
180 were submitted to eat a known amount of carbohydrates
181 (72%) during the previous 48 h to the experiments (ses-
182 sions 2 and 3). All testing procedures were performed
183 during the same period (between 9:00 and 11:00 am) in a
184 room at an ambient temperature 22–24°C.

185 Maximal graded exercise test

186 After a standardized warm-up consisting of 5 min of ped-
187 aling on a cycle ergometer (Kettler Axiom P2, GmbH &
188 Co.KG, Ense-Parsit, Germany) at a load of 50 W, partici-
189 pants performed a maximal graded exercise test. The initial
190 load was 50 W and increased by 25 W every min until
191 exhaustion with a pedaling frequency of 60 rpm. Gas
192 analyses were performed using a breath-by-breath gas
193 analyzer (VO2000 Portable Metabolic System, Med-
194 graphics, St. Paul, MN), whose validity was previously
195 proved by Byard and Dengel (2002). Before each test,
196 VO2000 was manually calibrated according to the manu-
197 facturer's guidelines. VO_{2max} corresponded to the highest
198 VO_2 attained in two successive 15 s periods for the max-
199 imal graded test. In addition, HR was continuously moni-
200 tored (Polar 800 CX, Polar Electro, Kempele, Finland). It
201 was considered that participants had reached their VO_{2max}
202 when three or more of the following criteria were met: (a) a
203 steady state of VO_2 despite increasing load (changes in

VO_2 at $VO_{2max} \leq 150$ ml); (b) a final respiratory exchange
ratio higher than 1:1; (c) visible exhaustion; (d) an HR at
the end of the exercise (HR_{max}) within the 10 bpm of the
predicted maximum (220-age). In addition, pVO_{2max} was
defined as power output (W) developed by the participants
on the cycle ergometer when VO_{2max} was reached.

Intense exercise

In sessions 2 and 3, and to avoid exercise time or intensity
influence, the participants performed 2 min of cycling at
 pVO_{2max} . These exercise characteristics were chosen taking
into account previous studies with samples of well-trained
athletes in which cycling TTE at the same relative intensity
was between 2.9 ± 0.7 and 5.2 ± 2.4 min (Billat and
Koralsztein 1996; Lepretre et al. 2004). Considering that
our sample was only composed of healthy individuals (non-
athletes), we decided to establish a duration of 2 min to
ensure that participants could complete this fatiguing pro-
tocol. The pedaling frequency was kept at 60 rpm and HR
was continuously monitored during the exercise in order to
determine HR_{max} (tHR_{max}). Before each testing session
($[Lac]_{pre}$), and just at the end of the intense exercise
($[Lac]_0$), capillary blood samples were taken from the
earlobe for blood lactate analyses (Dr. Lange Photometer
LP 450, Konisburg, Germany).

Recovery period

Following intense exercise, participants were invited to rest
during a 15 min recovery period using different recovery
methods (LFV-rec or P-rec) that were applied in random
order. This recovery period was applied since as previous
studies reported, complete muscle recovery can be
achieved with 10–15 min rest periods (Lariviere et al.
2003). In addition, P-rec strategies used for less than
10 min are insufficient to reproduce the maximal voluntary
contraction (Esposito et al. 1998; Seiler and Hetlelid 2005).
In LFV-rec, and in order to focus the vibratory stimulus on
exercised muscles avoiding a weight-bearing effect
(maintenance of isometric contraction typical of WBV),
participants were seated with their feet on a vibratory
platform (Physio Wave 700, Globus, Italy) keeping their
thighs abducted and the knees and hips flexed 90°. Being

Fig. 1 Schematic illustration of testing protocol

an oscillatory platform, and according to the manufacturer's instructions, participants' feet had to be separated from the central axis of the platform at the distance required to generate 4 mm of amplitude. Additionally, this position was already marked on the platform surface by the manufacturer and the feet were placed 30 cm apart. The participants then performed five sets of 2 min exercises with 1 min rest between sets at a frequency of 20 Hz. These vibratory characteristics were chosen according to the conclusions of previous studies in which a frequency of 12 Hz and 6 mm of amplitude (peak to peak) were not sufficient to increase blood flow, muscle temperature, and other neurogenic changes required for enhancing recovery (Edge et al. 2009), and based on the assumption that resonance effects appear when frequencies between 2.5 and 16 Hz are used (Goel et al. 1994; Randall et al. 1997). In P-rec, participants kept the same position on the vibratory platform, but no vibratory stimulus was applied.

In both protocols, LFV-rec and P-rec, HR was continuously recorded (HR_{rec}) and capillary blood samples were taken from the earlobe at minutes 2 ($[Lac]_{rec2}$), 5 ($[Lac]_{rec5}$), 8 ($[Lac]_{rec8}$), 11 ($[Lac]_{rec11}$), and 14 ($[Lac]_{rec14}$) of the recovery period.

TMG measures

TMG is a measuring method for detection of skeletal muscles' contractile properties based on a muscle contraction characteristic: when a muscle contracts, its belly enlarges. With a displacement sensor, the radial enlargement of the muscle belly can be measured. Displacement-time curve recordings allow muscle contractile properties to be assessed, obtaining different parameters which can inform about muscle tone (Valencic and Knez 1997) (Fig. 2).

The main muscle contraction parameters are: maximal radial displacement (D_m), time from the onset of electrical

stimulus to 10% of D_m (T_d), time from 10 to 90% of D_m in the ascending curve (T_c), time between 50% of D_m on both sides of the curve (T_s), and time from 90 to 50% of D_m on the descending curve (T_r). Recently, reliability of TMG has been established (Tous et al. 2010).

In our study, before session 1 (TMG_{pre}), after intense exercise (TMG_{post}) and after recovery period (TMG_{rec}), tensiomyography analysis of rectus femoris (RF) of the right leg was performed. Radial displacements were measured under static and relaxed conditions, with the participants in the supine position and the knee joint fixed at a 120° angle (180° corresponding to full extension of the knee). The measured limb was positioned on a triangular wedge foam cushion to keep a fixed knee angle. A digital displacement transducer (GK 40, Panoptik d.o.o., Ljubljana, Slovenia), which incorporates a spring of 0.17 mm^{-1} , was set perpendicular to the muscle belly to acquire RF radial displacement. Sensor location was determined anatomically according to Delagi et al. (1975) and marked with a dermatological pen. Two square ($5 \times 5 \text{ cm}$) 2 mm thick self-adhesive electrodes (Compex Medical SA, Ecublens, Switzerland) were placed symmetrically 5 cm ($\pm 5 \text{ cm}$) distal and proximal to the sensor tip. A TMG-S1 (EMF-Furlan and Co. d.o.o., Ljubljana, Slovenia) stimulator was used.

Regarding electrical stimulation procedures, pulse duration was 1 ms and the initial current amplitude was 30 mA. For each of the TMG assessment, current amplitude was progressively increased by 10 mA increments until there was no further increase in D_m or maximal stimulator output (110 mA). Rest periods of 15 s were interspersed between consecutive measurements to minimize the effects of fatigue and potentiation. For each participant, two consecutive measurements were performed at the highest current amplitude, and they were recorded and averaged for subsequent analyses (mean amplitude used was $98.89 \pm 4.60 \text{ mA}$). In any case, none of the participants reported discomfort during electrical stimulation.

In the present study, D_m , T_s , and T_r were registered in each testing session; therefore, these parameters seem to show largest influence to muscle fatigue rate and are also expected to be the best measure of the fatigue rate (Krizaj et al. 2008).

Exercise test to exhaustion

Following the recovery period and once TMG assessment was completed, participants performed an exercise test to exhaustion (ETEX) on the cycle ergometer at pVO_{2max} maintaining a pedaling frequency of 60 rpm. This type of exercise test has been widely used to investigate the effectiveness of both warm-up and recovery strategies (Wittekind and Beneke 2009; Miladi et al. 2010). HR was

Fig. 2 TMG parameters definition

monitored during the effort. The test finished when participants were unable to maintain the frequency of pedaling for more than 15 s. The variables selected were $HR_{\max}$ ($a\text{-}oHR_{\max}$), time to exhaustion (TTE), mean velocity (V_m), and total distance covered (TD).

Statistical analyses

Means and standard errors of the mean were calculated for each variable. Normality assumption was checked using the Kolmogorov–Smirnov test and all variables were normally distributed. A 2×7 analysis of variance (ANOVA) for repeated measures was used to compare [Lac] values across recovery method (LFV-rec, P-rec) and time (before and after intense exercise, and min 2, 5, 8, 11, and 14 of recovery period). A 2×6 analysis of variance (ANOVA) for repeated measures was used to compare HR values across recovery method (LFV-rec, P-rec) and time (after intense exercise, and min 2, 5, 8, 11, and 14 of recovery period). Intra-class correlation coefficient of TMG parameters was assessed using two measures of each one during session 1. Furthermore, a 2×3 ANOVA for repeated measures was performed to compare TMG parameters across recovery method (LFV-rec, P-rec) and time (before session 1, after intense exercise, and after recovery period). Moreover, one-way ANOVA was performed to analyze the effects of recovery method (LFV-rec and P-rec) on ETEX variables. Eta-squared (η^2) was used for the calculation of effect size. Statistical significance was set at $p < 0.05$.

Results

In session 1, mean $VO_{2\max}$ measured during maximal graded exercise test was $53.44 \pm 2.67 \text{ ml kg}^{-1} \text{ min}^{-1}$, reaching a mean $pVO_{2\max}$ of $270.83 \pm 8.61 \text{ W}$.

In sessions 2 and 3, physiological responses to intense exercise performed before LFV-rec and P-rec showed no statistical differences in terms of $[Lac]_{\text{pre}}$ ($1.46 \pm 0.07 \text{ mmol l}^{-1}$ vs. $1.36 \pm 0.07 \text{ mmol l}^{-1}$, respectively; $F = 0.867$, $p = 0.362$), $[Lac]_0$ (5.85 ± 0.31 vs. $5.84 \pm 0.51 \text{ mmol l}^{-1}$; $F = 0.001$, $p = 0.989$), and $fHR_{\max}$ ($166.3 \pm 2.1 \text{ bpm}$ vs. $163.2 \pm 2.6 \text{ bpm}$, respectively; $F = 0.851$, $p = 0.366$).

During recovery period, a similar trend was observed in [Lac] dynamics in both LFV-rec and P-rec strategies (Fig. 3). [Lac] peak was reached 2 min after intense exercise ($8.90 \pm 0.54 \text{ mmol l}^{-1}$ and $8.84 \pm 0.70 \text{ mmol l}^{-1}$, respectively), dropping to levels of $5.68 \pm 0.39 \text{ mmol l}^{-1}$ and $6.18 \pm 0.55 \text{ mmol l}^{-1}$, respectively, at min 14 of recovery period. No significant differences were found at each time point for [Lac] during LFV-rec and P-rec ($F = 0.372$; $p = 0.715$), although towards the end of recovery

Fig. 3 Blood lactate concentrations during recovery period

period [Lac] removal in LFV-rec was slightly higher than that observed in P-rec.

As occurred with recovery [Lac], no significant differences were found in HR values during the recovery period when LFV-rec and P-rec were contrasted ($F = 0.165$; $p = 0.884$). In both cases, HR values showed an important drop during the first 2 min into recovery period; after that, the rate of HR decline was lower, although HR values in LFV-rec remained slightly higher than that measured in P-rec (Fig. 4).

Figure 5a–d shows ETEX results. TD, V_m , $a\text{-}oHR_{\max}$, and TTE showed no statistical differences when LFV-rec and P-rec were contrasted. However, data from LFV-rec are higher than those observed in P-rec; indeed, the mean total distances covered by participants after the recovery period was $1.71 \pm 0.16 \text{ km}$ and $1.56 \pm 0.21 \text{ km}$ for LFV-rec and P-rec strategies, respectively ($F = 0.344$; $p = 0.563$) (Fig. 5a). Mean V_m was $22.70 \pm 0.39 \text{ km h}^{-1}$ after LFV-rec and $22.28 \pm 0.39 \text{ km h}^{-1}$ after P-rec ($F = 0.550$; $p = 0.466$). In addition, mean $a\text{-}oHR_{\max}$ values measured in

Fig. 4 Heart rate dynamics during recovery period

Fig. 5 Mean distance covered (**a**), cycling velocity (**b**), HR_{max} (**c**), and time to exhaustion (**d**) measured in the exercise test to exhaustion

ETEX were 186.2 ± 2.8 beats min^{-1} and 184.0 ± 2.9 beats min^{-1} for LFV-rec and P-rec, respectively ($F = 0.287$; $p = 0.598$), whereas mean TTE was also slightly higher in LFV-rec compared to P-rec (248.00 ± 22.64 and 239.91 ± 28.01 s, respectively; $F = 0.050$, $p = 0.825$).

As shown in Table 1, ICC scores (95% CI) for TMG variables obtained in the current study reached an acceptable level, being comparable to those reported by Tous-Fajardo et al. (2010). Finally, Table 2 shows TMG data obtained at different time points of the experimental testing. It is important to note that there were no statistical differences in TMG_{pre} , TMG_{post} , and TMG_{rec} variables

measured on RF of the right leg. However, significant differences were observed for D_m and T_s between time points when the recovery method was not considered as a factor. D_m dropped remarkably from TMG_{pre} to TMG_{post} ($p < 0.001$), and then increased at TMG_{rec} ($p < 0.001$), reaching values that were significantly lower than those found in TMG_{pre} ($p = 0.002$). T_s showed no significant increase from TMG_{pre} to TMG_{post} ($p = 0.130$) and a significant decrease from TMG_{post} to TMG_{rec} was observed ($p = 0.005$), reaching values that were also significantly lower than those found in TMG_{pre} .

Table 1 ICC scores of tensiomyographic variables

TMG variables	ICC test-retest (95% CI)	
	Tous-Fajardo et al. (2010)	Current study
D_m (mm)	0.97 (0.92–0.99)	0.92 (0.87–0.97)
T_c (ms)	0.92 (0.81–0.97)	0.83 (0.79–0.86)
T_d (ms)	0.86 (0.86–0.95)	0.89 (0.86–0.94)
T_r (ms)	0.77 (0.49–0.91)	0.88 (0.81–0.94)
T_s (ms)	0.96 (0.90–0.99)	0.90 (0.84–0.95)

ICC intra-class correlation coefficient, CI confidence interval

Discussion

The ability to recover following intense training or competitive bouts is important so that performance can be maintained during subsequent efforts. Different recovery strategies have been compared to determine their effectiveness on physiological and exercise performance responses. Several of these studies showed that during maximal and supramaximal exercises, active recovery results in a decrease in performance when considered as the TTE (Dupont et al. 2003; Dupont et al. 2004; Buchheit et al.

Table 2 TMG measurements

		TMG _{pre}	TMG _{post}	TMG _{rec}	F	sig	η ²
D _m (mm)	LFV-rec	7.57 ± 0.92	4.37 ± 0.67	6.46 ± 0.65	1.004	0.375	0.044
	P-rec	7.86 ± 0.43	4.57 ± 0.58	5.80 ± 0.44			
T _s (ms)	LFV-rec	141.06 ± 18.01	165.32 ± 20.79	124.72 ± 20.79	0.341	0.713	0.015
	P-rec	132.3 ± 13.59	178.68 ± 27.88	130.12 ± 16.31			
T _r (ms)	LFV-rec	54.84 ± 6.37	52.73 ± 8.28	50.13 ± 8.06	0.396	0.675	0.018
	P-rec	74.54 ± 11.84	73.44 ± 9.23	59.0 ± 7.42			

Data are expressed as mean ± SEM. TMG_{pre} before session 1, TMG_{post} after fatiguing exercise; TMG_{rec} after recovery period. F sig, and η² values are related to time × recovery method intersection. In all cases, sphericity was assumed (Mauchly's W > 0.05)

2009). An innovation of the present study is the local administration of LFV-rec evaluating its effect on blood lactate clearance, muscular contractile properties, and TTE in maximal cycling exercise. To our knowledge, and with the exception of the study conducted by Edge et al. (2009), the LFV-rec method applied here is quite different from WBV used in prior studies since the participants sat in front of the platform with their feet on it focusing the vibratory effect only on their lower extremities. In any case, these recovery methods are based on the mechanical massage effect of LFV, which could accelerate the recovery process by increasing blood flow to and from the damaged muscle, remove metabolites in muscle that inhibit tissue repair and stimulate the muscle receptors to ease muscular tension (Cafarelli et al. 1990). However, it does not seem that both WBV and local LFV-rec strategies lead to induce recovery effects on fatigued muscles. The results of this study indicate that LFV-rec strategy applied after short and intense exercise have similar efficacy than P-rec on [Lac] removal, muscle contractile properties and on TTE during cycling at pVO_{2max} .

Although there are several differences related to experimental protocol (vibratory characteristics, duration of recovery periods, and fatiguing exercises) our results are consistent with those of previous studies in which WBV or local vibrations were tested as recovery methods. In one of these investigations, the effect of acute WBV (12 Hz) on recovery following a 3 km time trial and high-intensity interval training was examined (Edge et al. 2009). Neither metabolic nor performance variables showed differences after WBV recovery period (15 min) when these data were compared to those of P-rec. In addition, in a recent study in which the effectiveness of two recovery strategies (shaking the hand vigorously and grasping a handgrip vibration device) applied on fatigued forearm and hand muscles was compared in trained and untrained climbers, neither shaking out nor LFV-rec significantly improved intermittent isometric handgrip exercise capacity compared with P-rec (Green and Stannard 2010). However, Bakhtiary et al. (2007) reported that administering 50 Hz of local vibration to each lower limb significantly increased the recovery of isometric force production.

Nevertheless, vibration stimulus has been shown to increase peripheral circulation (Kersch-Schindl et al. 2001), muscle blood flow (Lohman et al. 2007), and muscle temperature (Cochrane et al. 2008). These circulatory effects could facilitate blood lactate clearance during recovery period allowing higher performance on a subsequent exercise. However, our results demonstrate that LFV-rec has no positive effect on [Lac] removal since no statistical differences between LFV-rec and P-rec were observed in any of the recovery time point analyzed. Yet under the LFV-rec condition, [Lac] removal was slightly higher during the last minutes of the recovery period, such trend that can be explained by the higher HR levels for most of the recovery periods under LFV-rec intervention. In fact, previous studies reported higher HR values during active recoveries, increasing blood flow to the fatigued muscles and enhancing the removal of metabolites (Bogdanis et al. 1996; Ahmaidi et al. 1996; Draper et al. 2006). However, although HR shows an increase following active recovery, it does not seem to indicate a subsequent reduction in [Lac] (King and Duffield 2009). The lack of effect of LFV-rec on [Lac] removal observed in our study corresponds with the findings of previous research (Edge et al. 2009; Green and Stannard 2010).

Another innovation of the present study is the use of TMG to evaluate the effects of LFV-rec and P-rec on contractile properties of fatigued muscles. From all TMG parameters, D_m , T_s , and T_r seem to provide the most useful information in evaluation of muscle fatigue (Krizaj et al. 2008). D_m , which could be equated to electrically evoked peak twitch torque, is determined by both the number and the type of muscle fibers recruited by the electrical stimulus, being considered as a measure of muscle belly stiffness (Pišot et al. 2008). Contraction time parameters such as T_s (time between 50% of D_m on both sides of the curve) and T_r (time from 90 to 50% of D_m on the descending curve) show largest influence to muscle fatigue rate (Krizaj et al. 2008). In the present study, TMG analysis of RF of the right leg was performed before session 1 (rest condition), after intense exercise, and after recovery period in both LFV-rec and P-rec interventions. There were no

statistical differences in TMG data when time $\times$ recovery method intersection analysis was performed. These results indicate that there was no recovery effect of LFV on the fatigued RF since its contractile properties after P-rec intervention were similar. However, when the recovery method was not taken into account as a factor, we observed a non-significative decrease in D_m values after intense exercise indicating a lower contractile capacity due to a fatigue state. In addition, T_s values increased after intense exercise as a consequence of muscular fatigue and then decreased after the recovery period reaching values below those measured before session 1; in any case, no statistical differences were observed. On the other hand, no changes were observed in T_r along experimental time points. These results seem to define a general contractile response to muscular fatigue, independently of the recovery strategy applied, and they could also be explained by the duration of recovery period. As previous studies reported, complete muscle recovery can be achieved with 10–15 min rest periods (Lariviere et al. 2003) since P-rec strategies used for less than 10 min are insufficient to reproduce the maximal voluntary contraction (Esposito et al. 1998; Seiler and Hetlelid 2005). In the present study the recovery period was 15 min, which could explain that T_s and T_r values would revert to their initial levels after LFV-rec or P-rec period. Unlike T_r and T_s , D_m values remained below their initial levels after recovery period, a result that could indicate lack of muscle recovery. In any case, future research on TMG is needed to clarify the dynamics of TMG parameters during fatigue and recovery status.

Finally, no statistical differences were obtained when LFV-rec and P-rec were contrasted in terms of TTE during cycling at pVO_{2max} . In addition, neither mean TD, nor $a\text{-}oHR_{max}$ nor V_m showed statistical differences between LFV-rec and P-rec strategies, although higher values in these variables (TTE included) were observed under LFV-rec intervention. These results indicate that LFV-rec seems to have a small but no significative beneficial effect on subsequent maximal exercises. Although previous studies have shown that cycling performance during repeated sprints is enhanced after active compared with passive recovery (Bogdanis et al. 1996; Dorado et al. 2004; Spierer et al. 2004), other authors have found contradictory results (Buchheit et al. 2009), especially when performance was evaluated through TTE (Dupont et al. 2003; Dupont et al. 2004). Based on aforementioned results LFV may be used as recovery method if intense exercise must be repeated after short periods of time since a slight increase (and no decreases) in exercise performance can be achieved.

In conclusion, LFV-rec strategy applied during 15 min after short and intense exercise does not seem to be effective on blood lactate removal, muscle contractile properties and on time to exhaustion during cycling at

pVO_{2max} . Future studies are needed in order to define the optimal vibration stimulus attending to factors such as position on the platform, frequency, or amplitude.

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

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