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Adding Vibration During Varied-Intensity Work Intervals Increases Time Spent Near Maximal Oxygen Uptake in Well-Trained Cyclists

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Abstract

Purpose: Previous research suggests that the percentage of maximal oxygen consumption ($\dot{V}O_{2max}$) attained and the time it is sustained close to $\dot{V}O_{2max}$ (e.g., > 90 %), can serve as a good criterion to judge the effectiveness of the training stimulus. The aim of this study was to investigate the acute effects of adding vibration during varied intensity high-intensity interval training (HIIT) session on physiological and neuromuscular responses.
Methods: 12 well-trained cyclists completed a counterbalanced cross-over protocol, wherein two identical varied-intensity HIIT cycling sessions were performed with (VIB) and without (VAR) intermittent vibration to the lower intensity workloads of the work intervals (6 × 5-min work intervals, 2.5 min active recovery). Each 5-min work interval consisted of three blocks of 40-s performed at 100% of Maximal Aerobic Power (MAP) interspersed with 60-s workload performed at a lower power output, equal to the Lactate Threshold (LT) plus 20% of the difference between LT and MAP ($PO_{LT+20\%}$). $\dot{V}O_2$ and electromyographic (EMG) activity of lower and upper limbs were recorded during all 5-minutes work intervals.
Results: VIB induced a longer time ≥ 90%$\dot{V}O_{2max}$ than VAR (11.14(7.63) vs. 8.82(6.90) min, d=0.64, p=0.048) and an increase of EMG activity of lower and upper limb during the lower intensity workloads by 20(16) and 34(43) % (d=1.09 and 0.83; p=0.03 and 0.015), respectively.
Conclusions: Adding vibration during a varied HIIT session increases the physiological demand of the cardiovascular and neuromuscular systems, indicating that this approach can be used to optimize the training stimulus of well-trained cyclists.

Keyword: vibration plate, indoor cycling exercise, oxygen consumption, muscle activity

Introduction

High-intensity interval training (HIIT) is an intermittent mode of endurance training, characterised by short high-intensity work intervals. Its discontinuous nature, by design, allows for the accumulation of a greater amount of time spent near maximal oxygen consumption ($\dot{V}O_{2max}$),[1] than could be tolerated during a single bout of continuous exercise.[2] It has been suggested that to improve $\dot{V}O_{2max}$ which is a key determinant of endurance performance,[3] athletes should spend as much time as possible ≥ 90%$\dot{V}O_{2max}$ per HIIT session.[1,4] Therefore, designing HIIT that maximizes stress of the oxygen transport and utilization systems is important to stimulate further adaptation in athletes.

The five main components of a HIIT session i.e. work interval intensity, work interval duration, number of work intervals, recovery interval intensity and recovery interval duration[5] determine greatly the accumulating time ≥ 90%$\dot{V}O_{2max}$.[1,4] A less explored variable that may influence the acute physiological responses during a HIIT session is the work rate distribution within the work intervals.[6] Recently, it has been observed that work intervals containing shorter blocks (e.g. 30-40 seconds) at maximal aerobic power (MAP) interspersed with 60-90 seconds at lower exercise intensity (70-86% of MAP) induces longer time ≥ 90%$\dot{V}O_{2max}$ compared to work intervals with similar mean intensity performed at a constant workload.[7,8] During the periods with lower exercise intensity in the varied work intervals, the $\dot{V}O_2$ is reduced, while it increases at MAP intensities.[8] In an attempt to increase time ≥ 90%$\dot{V}O_{2max}$, Bossi et al.[9] added vibrations during a varied intensity work interval protocol. Adding vibration while pedalling can acutely increase $\dot{V}O_2$[10-12] and it has been observed that adding vibration to the work intervals of a traditional 6 × 5 min HIIT session increased total time ≥ 90%$\dot{V}O_{2max}$ by 58% compared with the non-vibration condition.[11] However, when only adding vibrations during the MAP intensities in a varied work interval protocol (and not during the lower exercise intensity), no extra effect on time ≥ 90%$\dot{V}O_{2max}$ was observed.[9] Previous research has suggested that $\dot{V}O_2$ increments due to vibration likely reflect an increased recruitment of fast twitch fibres,[13,14] which are known to have a larger $\dot{V}O_2$ per work unit compared with slow twitch fibres.[15] This is supported by the observation that whole body vibration reduces the recruitment thresholds of fast twitch fibres,[16] which in turn could increase $\dot{V}O_2$ sustained during cycling training. [10-12] Based on the latter, it can be suggested that a substantial recruitment of fast twitch fibres is already present at MAP intensity and thereby contributing to explain the lack of increased time ≥ 90%$\dot{V}O_{2max}$ when vibration was added during MAP intensity only.[9] Following this, it can be anticipated that adding vibrations while cycling at lower intensities during a varied work interval protocol has a larger potential to increase the recruitment of fast twitch fibres and thus prolong time ≥ 90%$\dot{V}O_{2max}$. However, to our knowledge this remains to be investigated. Finally, the recruitment of arms muscles to reduce vibrations transmissibility to upper body during cycling could also induce an increased $\dot{V}O_2$.[17,18]

The aim of the present study was to investigate the acute effect of adding intermittent vibration during the lower intensity workloads of varied-intensity work intervals protocol on $\dot{V}O_2$ and muscle activation in well-trained cyclists. Consistent with some previous findings,[9-12] we hypothesised that adding intermittent vibration during the lower intensity workloads of varied-intensity work intervals would increase total time ≥ 90%$\dot{V}O_{2max}$ and this increase would be related to a rise in electromyographic (EMG) activity in thigh and arm muscles.

Methods

Participants

A total of twelve male cyclists, aged 27.4 (8.7) years, were recruited to participate in the study. All participants who completed the testing protocol had undertaken their usual offseason training prior to the project (training volume 7.9 (2.7) h/week recorded during the 4 weeks preceding pre-testing) and had a history of 7.5 (6.8) years of competitive cycling. Based on physiological parameters, all cyclists were categorized as performance level 4 to 5 according to De Pauw et al[19], equal to well-trained athletes. The best results for each participant from preceding competition season varied from the best athlete having a top 10 in the Elite UCI Mountain Bike World Cup, via athletes having top 20 in UCI classification races (n=2) and Norwegian cup races (n=4) to athletes who trained well but participated only in Gran Fondo (n=5). Subject characteristics and physiological parameters are presented in Table 1. Before testing, all participants were informed of any potential risk and discomfort associated with the study, and they all gave their written informed consent to participate. The study was performed accordingly to the ethical standards established by the Helsinki Declaration of 1975, and were approved by the local ethical committee at Inland Norway University of Applied Sciences, and Data Protection Authority.

Design

The experimental approach was a counterbalanced cross-over study (Figure 1). The participants visited the laboratory on three occasions at the same time of the day, separated by at least 48 h. In the first visit, participants completed a preliminary test that included a submaximal lactate threshold test and a maximal incremental test to characterize their cycling ability and physiological profile. They were also familiarised with the vibration and HIIT workout used during subsequent visits. In visit two and three, participants performed two identical HIIT sessions with varied-intensity work intervals (VAR), as proposed by Bossi et al.[7] and Rønnestad et al.[8] Intermittent vibrations were added during all the lower intensity workloads of varied-intensity work intervals in one of the two HIIT sessions (VIB). Acute physiological and perceptual responses were compared between the two HIIT sessions (VAR and VIB).

Participants were instructed to refrain from all types of intense exercise 24 h before each laboratory visit and to prepare as they would for competition. They were instructed to consume identical meals 3 h before testing. All tests were performed free from distractions, under similar environmental conditions (16°C-17°C), with participants being cooled with a fan.

Methodology

Preliminary test

In the first visit, participant's height and body mass were measured. Subsequently, participants completed a lactate threshold (LT) test, which started at 125 W, increasing by 50 W every fifth minute (25 W if [La$^-$] was ≥ 2 mmol·L^{-1}), and terminated when [La] reached ≥ 4 mmol·L^{-1}. Blood samples were taken from a fingertip at the last 30 s of each 5-min step, and they were immediately analysed (Biosen C-Line, EKF Diagnostics, Penarth, UK). At the start, cyclists chose their cadence, which they subsequently held constant throughout the remainder of the test. Power output at LT which corresponded to a [La$^-$] of 4 mmol·L^{-1}, was linearly interpolated from the two datapoints of [La$^-$] and power output measured from the last two steps of the lactate threshold test. Pulmonary gas exchanges were measured during the last 3 min of each stage (30-s sampling time) using a computerized metabolic system with mixing chamber (Oxycon Pro, Erich Jaeger, Hoechberg, Germany). Prior to every test, the gas analyser was calibrated with certified calibration gases of known concentrations, and the flow turbine (Triple V, Erich Jaeger, Hoechberg, Germany) was calibrated with a 3-L syringe (5530 series, Hans Rudolph, Shawnee Mission, USA).

Following the lactate threshold test, cyclists rode for 10 min at a power output between 50 and 100 W before performing the maximal incremental test to determine $\dot{V}O_{2max}$ and maximal aerobic power (MAP), and maximal 1-minute work rate ($\dot{W}_{max}$). The test started at 200 W with work rate being increased by 25 W every minute until voluntary exhaustion or cyclist's inability to maintain cadence above 60 $rev \cdot min^{-1}$ despite verbal encouragement. Cadence was freely chosen, but participants were instructed to avoid abrupt changes. Pulmonary gas exchanges ($\dot{V}O_2$, $\dot{V}CO_2$, RER) and HR were continuously and measured, averaged every 10-s, and $\dot{V}O_{2max}$ was calculated as the highest 60-s mean oxygen uptake. MAP was calculated according to Daniels.[20] This method extrapolates the relationship between submaximal power output and respective measures of oxygen uptake to $\dot{V}O_{2max}$, by means of linear regression. Power output data were recorded continuously throughout the test, with $\dot{W}_{max}$ calculated as the mean of the last 60 s of the test. Immediately after the incremental test, a blood sample was taken from a fingertip to determine [La^-] and cyclists reported their RPE using Borg's 6-20 scale.[21]

HIIT sessions

In the second and third visits, participants started with a 13-min warm-up that included successively 2.5-min at 30% of MAP, 1-min at 40% of MAP, 1-min at 50% of MAP, 1-min at 60% of MAP, 1-min at 70% of MAP, 30-s at 80% of MAP, 30-s at 90% of MAP, 30-s at 100% of MAP, 5-min at 30% of MAP. Thereafter, the HIIT sessions included 6 repetitions of 5-min varied-intensity work interval interspersed with 2.5 min of active recovery period (Figure 1). The 5-min varied-intensity work intervals consisted of three 40-s workloads performed at 100% of MAP interspersed with a 60-s period performed at a power output equal to LT plus 20% of the difference between LT and MAP ($PO_{LT+20\%}$). This varied-intensity work intervals structure has been used in a previous study.[8]

$$PO_{LT+20\%} = PO_{LT} + 0{,}2 \times (MAP - PO_{LT})$$

During each 2.5-min active recovery periods, participants were asked to pedal 1.5-min at 30% of MAP followed by 1-min at 40% of MAP.

The vibrations were applied during all 1-min periods performed at $PO_{LT+20\%}$ of all varied-intensity work intervals in one of the two HIIT sessions. All the cyclists were required to pedal in a seated position throughout all work intervals without changing their hand position during and between the two HIIT sessions. Participants self-selected their cadence, and water consumption was allowed only during the active recovery periods between the varied work intervals.

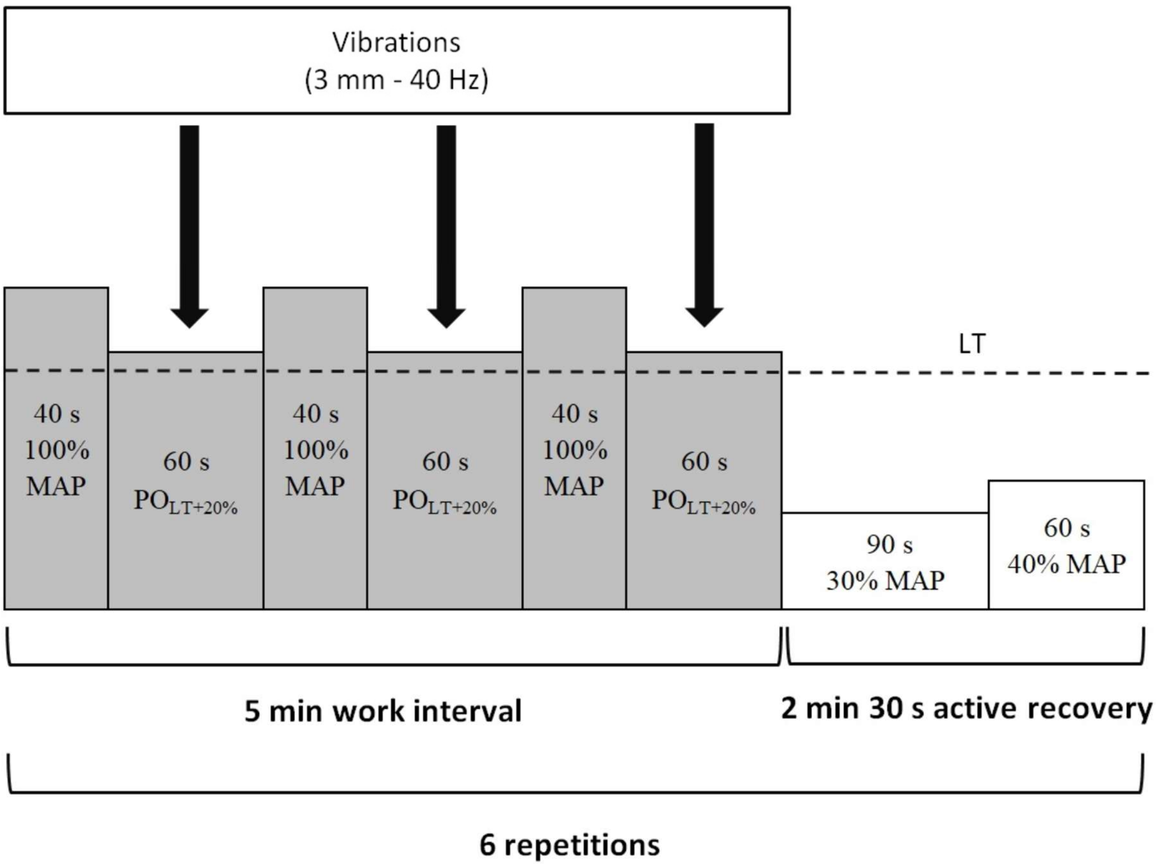

Figure 1 Graphical representation of the varied intensity work intervals protocol. Each 5-min work interval consisted of three 40-s blocks performed at 100% of MAP interspersed by a 60-s periods performed at power output equal to LT plus 20% of the difference between LT and MAP (POLT+20%). The 2 min 30 s active recovery period consisted of 1 min 30 s exercising at 40% of MAP followed by 60-s exercising at 30% of MAP. The 5-min work interval - 2 min 30 s active recovery period sequence was repeated 6 times per HIIT session. During one of the two HIIT sessions, in a counterbalanced order, vertical vibrations of 3 mm amplitude with a vibratory frequency of 40 Hz were added during all 60-s periods performed at POLT+20%. MAP: Maximal Aerobic Power; LT : Lactate Threshold.

Equipment and measures

All participants performed all the tests on the same road bike (2017 Roubaix One. 3 size 56, Fuji, Taichung, Taiwan), mounted on a direct drive cycle trainer (KICKR, Wahoo Fitness, Atlanta, USA) that was attached to a synchronous vertical vibration platform (PneuVibe Pro, Pneumex, Sandpoint, USA; dimensions: 81 cm × 102 cm) with straps. Saddle position, i.e., saddle height and horizontal distance between the tip of the saddle and handlebar, was individually adjusted, and measures were noted for replication. The front wheel was put on a fitness step to ensure the horizontal stability of the bike. With this setup, vibration was applied directly to the rear part of the bike at a frequency of 40 Hz (the validity of the vibration frequency has been controlled prior the study with a tri-axis accelerometer). According to the manufacturer (http://www.pneumex.com/vibration.html), the PneuVib Pro vibrating platform which made of industrial steel, can generate synchronous vertical vibrations (both sides of the platform move up and down at the same time) with an amplitude of 3 mm up to an external load of 544 kg.

The bike was equipped with a crank-based powermeter (SRAM S975, SRM, Jülich, Germany), from which power output and cadence were recorded. An indoor cycling training software (TrainerRoad v1.0.0.49262, TrainerRoad, Reno, USA) was used to customize all testing sessions, which were performed in ergometer mode. A laptop was connected to the KICKR and to the SRM through an ANT+ dongle. With this setup, the resistance of the KICKR was controlled by the power output from the SRM. Power output, cadence, and heart rate were recorded by a cycle computer (PowerControl 8, SRM, Jülich, Germany) at 1 Hz and subsequently analysed using a customized Microsoft Excel spreadsheet (Microsoft Office Professional Plus 2018, version 16.23). The KICKR and the SRM were calibrated by the manufacturer prior to the study. Before each use, a member of the research team warmed-up the KICKR by riding for 10 minutes at 100 W and then performed the "spin down" through the TrainerRoad software, which is a zero-offset calibration of the strain gauges based on bearing and belt friction. The zero-offset procedure of the SRM was performed according to the manufacturer's recommendations.

Pulmonary gas exchanges ($\dot{V}O_2$, $\dot{V}CO_2$, RER) and HR were recorded and averaged at 10-s intervals during the varied intensity work intervals only, using the same equipment and calibration procedures as utilized during the preliminary testing. Mean $\dot{V}O_2$ and mean HR during the HIIT sessions was calculated as the mean values across all work intervals. Total time ≥ 90 % of $\dot{V}O_{2max}$ and ≥ 90 % of HR_{max} were determined as the sum of $\dot{V}O_2$ and HR values that were ≥ 90 % of the $\dot{V}O_{2max}$ and HR_{max} during the work intervals only (not during the active recovery). Immediately after the end of each work interval, fingertip blood samples were taken to determine [La^-], and participants were instructed to report their RPE using Borg's 6-20 scale and their leg muscle sensation on a 9-point graduated scale, from 1 ("very very good") to 9 ("very very heavy") after each work interval.[22]

Surface electromyography (EMG) activity of the vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), biceps femoris (BF), long head of biceps brachii (BB) and lateral head of triceps brachii (TB) of the right and left sides was measured at 1926 Hz by wireless sensors (TrignoTM, Delsys Inc, Boston, USA), including two dry bar electrodes (1 × 10 mm) spaced 10 mm apart. According to the SENIAM (i.e., Surface Electromyography for the Non-Invasive Assessment of Muscles project) recommendations, the EMG sensors were positioned on the middle of the muscle's belly and aligned in the direction of the muscle fibres.[23] The skin was shaved, rubbed with an abrasive paste (Nutriprep, AD Instrument, New South Wales, Australia), and cleaned with an alcohol swab. The EMG sensors were attached to the skin with a double-sided adhesive interface that matched the contour of the sensor and were secured by a medical adhesive (Transpore, 3M, Cergy, France) and an elastic net bandage (Bastos Viegas, S.A., Penafiel, Portugal). The EMG signals were recorded with a 16-bit amplifier system (TrignoTM Wireless Lab System, Delsys Inc., Boston, USA) with a gain of 1,000 and a common mode rejection of 80 dB. All EMG signals were filtered with a band-pass filter (20–500 Hz) and were stored and analysed by a physiological data acquisition and analysis software (LabChart v8.1, AD Instruments, New South Wales, Australia). Muscular activity of each muscle was quantified by the mean root-mean-square (RMS) of the EMG signal computed for the two sides over each 5-min work interval, each 40-s workload performed at 100% of MAP and each 1-min workload performed at $PO_{LT+20\%}$. The global muscular activity of the lower limbs and upper limbs was computed by the mean RMS of the 8 lower limb muscles and the 4 upper limb muscles, respectively. All RMS values were normalised in % to the mean RMS value measured during the 30-s pedalling period performed at 100% of MAP over the warm-up.

Statistical analysis

Data normality was checked from the Kolmogorov–Smirnov test. Two sample paired t-tests were used to test the null hypothesis that the means of $\dot{V}O_2$, total time ≥ 90%$\dot{V}O_{2max}$, total time

≥ 90%HR_{max}, VE, RER, HR, [La^-], RPE, leg RPE and RMS parameters are equal between VAR and VIB conditions. Effect sizes were calculated using Cohen *d* based on the distribution of mean score. As it has been proposed for highly trained subjects,[24] effect sizes were interpreted as follows: <0.25 = trivial effect, 0.25-0.49 = small effect, 0.5-1.0 = moderate effect, and >1.0 = large effect. All statistical analysis was performed using an open source software (Past, Paleontological Statistics Version 4.05, Øyvind Hammer, Natural History Museum University of Oslo). Results are reported as mean and SD with 95%CI and were considered significant at P < .05.

Results

Participants' characteristics are presented in Table 1 and physiological responses during the two HIIT sessions are shown in Table 2. The mean power output during all work intervals was 334 (40) W, which corresponded to 90 (4%) of MAP.

Table 1 Participants' characteristics and preliminary testing results.

	Mean (SD)	Min-Max
Age (years)	27 (9)	19-43
Body height (cm)	182 (4)	176-190
Body mass (kg)	72.7 (5.3)	66-84
VO_{2max} (ml·kg^{-1}·min^{-1})	72.5 (8.0)	59-86
VO_{2max} (L·min^{-1})	5.27 (0.64)	4.15-6.34
$\dot{W}_{max}$ (W·kg^{-1})	6.1 (0.6)	5.1-7.2
$\dot{W}_{max}$ (W)	430 (32)	356-504
MAP (W·kg^{-1})	5.2 (0.7)	3.8-6.4
MAP (W)	375 (58)	292-484
HR_{max} (beats·min^{-1})	188 (9)	173-206
[La^-]$_{peak}$ (mmol·L^{-1})	13.8 (2.2)	10.3-18.1
VE_{peak} (L·min^{-1})	200.2 (22.7)	167-225
RER_{peak}	1.15 (0.03)	1.11-1.19
RPE_{peak}	19.3 (0.5)	19-20
LT (W)	299 (28)	252-355
LT (% of MAP)	81 (9)	64-95%
$PO_{LT+20\%}$ (W)	307 (30)	262-272
$PO_{LT+20\%}$ (% of MAP)	83 (7)	71-96

Abbreviations: VO_{2max}, maximal oxygen consumption; $\dot{W}_{max}$, maximal 1-minute workload during the incremental test; MAP, maximal aerobic power; HR_{max}, maximal heart rate; [La^-]$_{peak}$, peak blood lactate concentration; VE_{peak}, peak minute ventilation; RER_{peak}, peak respiratory exchange ratio, RPE_{peak}, peak rating of perceived exertion; LT, lactate threshold power measured with a blood lactate concentration equal to 4 mmol.L^{-1}.$PO_{LT+20\%}$, power output equal to LT plus 20% of the difference between LT and MAP. Note: Data are presented as mean (SD) and minimum to maximal values of the 12 cyclists.

VIB induced a higher mean $\dot{V}O_2$ (mean difference = 1.9 (2.1) %; *P* = .010; *95%CI* = [0.7 ; 3.1%]; *d* = 0.89, moderate), a longer time ≥ 90% of $\dot{V}O_{2max}$ (mean difference = 26.3 (41.1) %; *P* = .048; *95%CI* = [3.1 ; 49.6%]; *d* = 0.64, moderate), and a lower RPE (mean difference= -6.1 (7.0)%; *P* = .017; *95%CI* = [-10.1 ; -2.1%]; *d* = 0.87, moderate) during the work intervals than VAR. Mean and individual data from the two last variables are presented in Figure 2. Mean percentage of $\dot{V}O_{2max}$ across all work intervals was higher in VIB than VAR (86.2 (3.5) vs. 84.6

(3.8) %, respectively, P = .011; *95%CI* of mean difference = [0.7 ; 3.1%]; $d = 0.91$, moderate). Mean values of HR, time ≥ 90% HR_{max}, $\dot{V}E$, RER, [La^-] and leg muscle sensation during the work intervals showed no significant difference between VIB and VAR (Table 2)

Table 2 Data from the 6 × 5 min varied-intensity work intervals HIIT session with vibration during the submaximal workload (VIB) or without vibration (VAR).

	VIB	VAR
VO_{2mean} ($L.min^{-1}$)	4.53 (0.50) #	4.45 (0.49)
VO_{2mean} ($ml.min^{-1}.kg^{-1}$)	62.5 (7.3) #	61.3 (7.1)
VO_{2mean} (%VO_{2max})	86.2 (3.5) #	84.6 (3.8)
VO_{2peak} (% VO_{2max})	99.0 (4.3) #	96.3 (4.5)
Total VO_2 (L)	135.9 (15.1) #	133.3 (14.5)
Total time ≥ 90%VO_{2max} (min)	11.1 (7.6) #	8.8 (6.9)
HR_{mean} ($beats.min^{-1}$)	169 (9)	167 (8)
HR_{mean} (% HR_{max})	89.7 (1.8)	88.9 (2.5)
Total time ≥ 90%HR_{max} (min)	17.7 (4.2)	14.1 (6.6)
VE_{mean} ($L \cdot min^{-1}$)	141.2 (21.6)	137.0 (0.5)
RER	0.96 (0.02)	0.97 (0.02)
[La^-]$_{mean}$ ($mmol \cdot L^{-1}$)	8.8 (3.1)	8.5 (2.8)
[La^-]$_{peak}$ ($mmol \cdot L^{-1}$)	10.5 (4.2)	9.8 (3.6)
RPE_{mean}	15.4 (1.6) #	16.4 (0.9)
RPE_{peak}	17.4 (1.6)	17.7 (1.2)
Leg muscle $sensations_{mean}$	6.7 (1.9)	6.6 (1.7)

Abbreviations: VO_{2mean}, mean oxygen consumption during the work intervals; VO_{2peak}, peak of oxygen consumption during the work intervals; total VO_2, total oxygen volume consumed during the work intervals; total time ≥ 90%VO_{2max}, total time spent above 90% of maximal oxygen consumption during the work intervals; HR_{mean}, mean heart rate during the work intervals; HR_{peak}, peak of heart rate during the work intervals; total time ≥ 90%HR_{max}, total time spent above 90% of maximal heart rate during the work intervals; VE_{mean}, mean minute ventilation during the work intervals; RER_{mean}, mean respiratory exchange ratio during the work intervals; [La^-]$_{mean}$, mean blood lactate concentration after the work intervals; [La^-]$_{peak}$, peak of blood lactate concentration after the work intervals; RPE_{mean}, mean rate of perceived exertion after the work intervals. RPE_{peak}, peak of rate of perceived exertion after the work intervals. Note: Data are presented as mean (SD) and minimum to maximal values of the 12 cyclists. # Significant difference compared to VAR ($P < .05$).

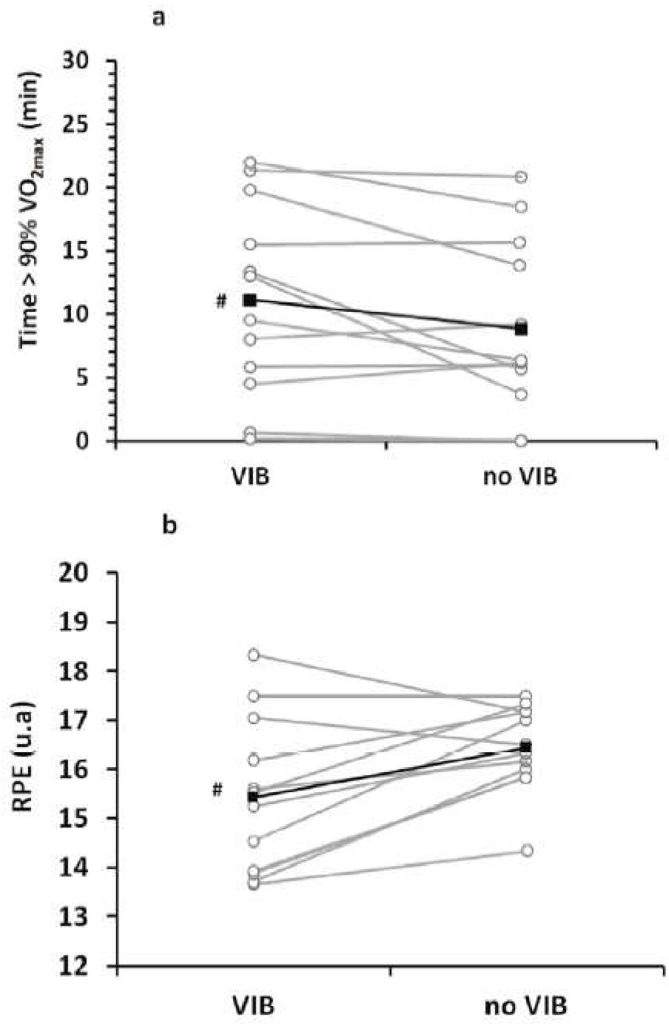

Figure 2 - Individual data points (circle) and mean values (square) for total time ≥ 90% of maximal oxygen uptake (VO2max; panel a) and rate of perceived exertion (RPE) after the work intervals (panel b) during a 6 × 5 min varied-intensity work intervals HIIT session performed with vibration during the lower intensity workloads (VIB) or without vibration (VAR). # Significant difference between treatments ($P < .05$).

Muscular activity during the two HIIT sessions are shown in Figure 3. Mean RMS of BF muscle was higher in VIB than VAR during the 5-min work intervals (117.9 (18.8) % vs. 86.2 (15.7) %, respectively; $P < .001$; $d = 1.57$, large; Figure 3a) and during the 1-min workloads performed at $PO_{LT+20\%}$ (136.8 (31.5) % vs. 82.4 (16.1) %, respectively; $P < .001$; $d = 1.91$, large; Figure 3c). Mean RMS during the 1-min workloads performed at $PO_{LT+20\%}$ was higher in VIB than VAR for BB muscle (98.5 (58.5) % vs. 68.5 (39.9) %, respectively, $P = 0.026$; $d = 0.74$, moderate; Figure 3c), for lower limbs (98.8 (13.9) % vs. 83.5 (13.8) %, respectively; $P = .003$, $d = 1.96$, large; Figure 3c), and for upper limbs (101.1 (39.1) % vs. 77.2 (23.4) %, respectively; $P = 0.015$, $d = 0.94$, moderate; Figure 3c). There was no significant difference between the two HIIT sessions in EMG activity for all muscles during the 30-s workloads performed at 100% of MAP (Figure 3b), nor for VM, VL, RF and TB muscles during the 5-min work intervals (Figure 3a) and during the 1-min workloads performed at $PO_{LT+20\%}$ (Figure 3c).

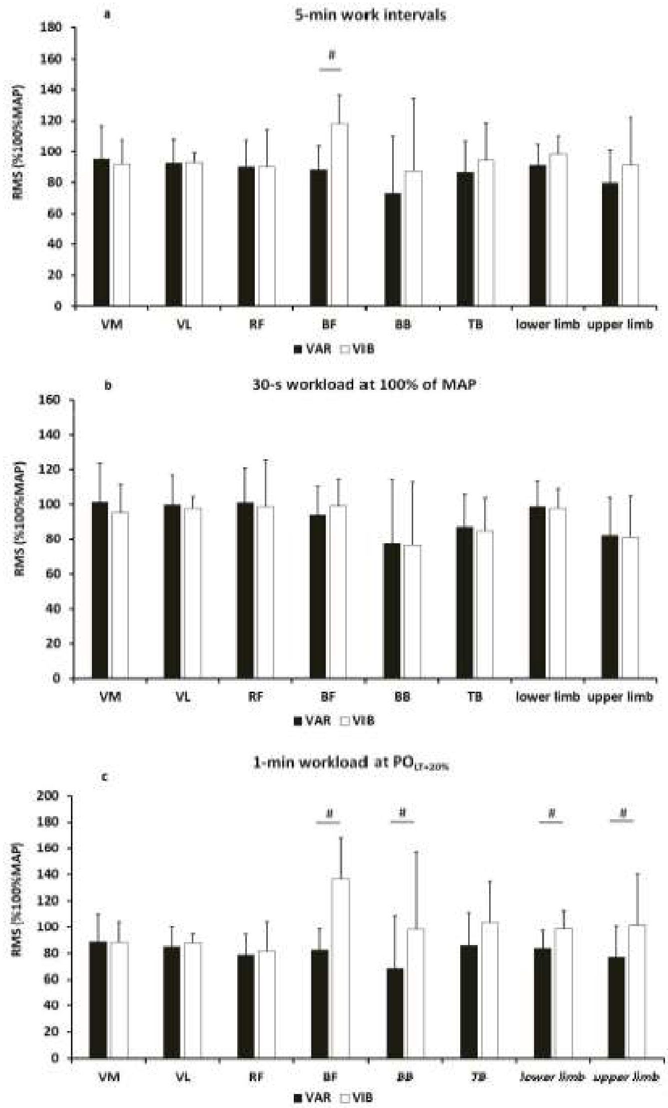

Figure 3 - Mean EMG activity (mean RMS expressed as percentage of RMS measured at 100% of MAP during the warm-up) of vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), biceps femoris (BF), biceps brachial (BB), triceps brachial (TB), lower limbs (mean of VM, VL, RF and BF) and upper limbs (mean of BB and TB) during a 6 × 5 min varied-intensity work intervals HIIT session performed with vibration during the lower intensity workloads (VIB) or without vibration (VAR). Data are displayed as mean (SD) across all the entire work intervals (panel a), across all the 30-s workload performed at 100% MAP (panel b), and across all the 1-min submaximal workload performed at LT+20% (panel C). # Significant difference between treatments ($P < .05$).

Figure 4 showed the mean value of oxygen consumption (panel a), global muscular activity of upper limbs (panel b) and global muscular activity of lower limbs (panel c) during the 5 min varied-intensity work intervals performed with vibration (VIB) or without vibration (VAR). Compared to VAR, VIB involved a significant increase in $\dot{V}O_2$ and global muscular activity of upper and lower limbs but only during the 1-min workloads performed at $PO_{LT+20\%}$.

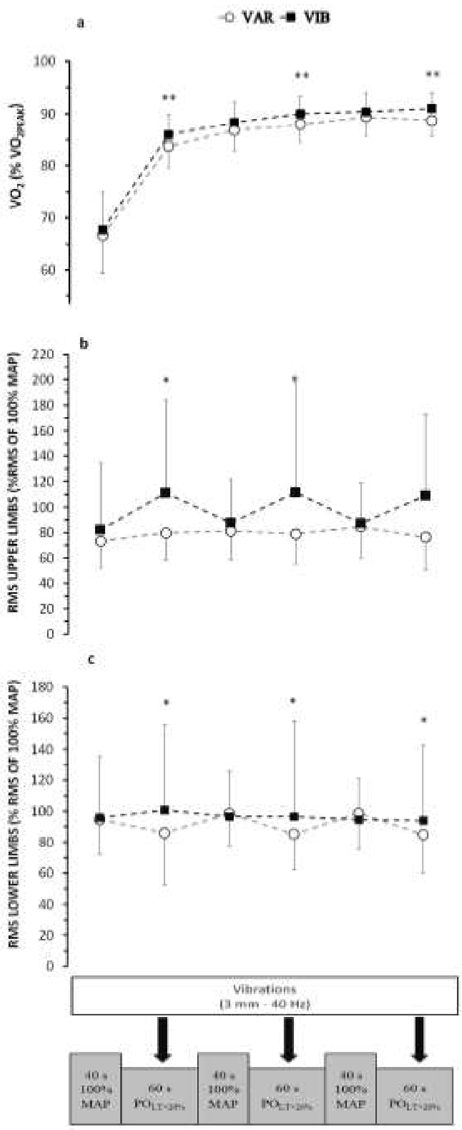

Figure 4 -Mean value of oxygen consumption (panel a), global muscular activity of upper limbs (panel b) and global muscular activity of lower limbs (panel c) measured during the 6 × 5 min varied-intensity work intervals HIIT session performed with vibration (VIB) or without vibration (VAR) during the lower intensity workloads. Data correspond to the average values of the 6 work intervals and were computed for each 40-s workload performed at 100% of MAP and during each 60-s workload performed at power output equal to LT plus 20% of difference between LT and MAP (POLT+20%). VIB were applied only during each POLT+20 workload. Mean RMS was expressed as percentage of RMS measured at 100% of MAP during the warm-up.
* Significant difference between treatments ($P < .05$).

Discussion

The main finding of the present study was that adding intermittent vibration to varied-intensity work intervals during all the lower intensity workloads of varied-intensity work intervals increased total time ≥ $90\%\dot{V}O_{2max}$ by 26% compared with the non-vibration condition.

These results are in agreement with two other studies investigating acute effects of adding vibration to cycling.[10,12] Although these two former studies were performed on recreational to moderate trained individuals, they observed higher $\dot{V}O_2$ when vibration was added to cycling exercise.[10,12] Furthermore, it has been observed that adding vibration during the entire work interval in a HIIT session increased total time ≥ $90\%\dot{V}O_{2max}$ by 58% compared with the non-vibration condition.[11] The smaller increase in total time ≥ $90\%\dot{V}O_{2max}$ in the present study can be related to the difference in total exposure time to vibration during the 6 × 5 min HIIT session. While the intermittent exposure to vibration within each 5-min work interval amounted to 180 s in the present study, making up a total of 18 min with vibration, the former study applied continuous vibration throughout all 5-min work intervals, making up a total of 30 min. Nevertheless, despite this difference, the total time ≥ 90%$\dot{V}O_{2max}$ in both vibration conditions is almost similar between the two studies (11.1 (7.6) min vs. 11.0 (7.0), respectively) and thus the main difference might be the lower time ≥ 90%$\dot{V}O_{2max}$ in the non-vibration condition in Rønnestad et al.[11] The latter is likely explained by the longer time ≥ 90%$\dot{V}O_{2max}$ in varied work intervals compared to evenly distributed work intervals.[7,8] However, not all studies report increased $\dot{V}O_2$ when adding vibration to cycling[25,26] and the present results contradicts the findings of Bossi et al.[9] who observed no additional benefits of adding vibration to varied-intensity work intervals on time ≥ 90%$\dot{V}O_{2max}$. This discrepancy can be related to methodological differences, where Bossi et al.[9] added vibrations during the higher exercise intensity periods within the work intervals, while the present study added vibrations during the lower exercise intensity periods within the work intervals. The methodological difference resulted in only 9 min of vibration in the Bossi et al.[9] study (6 x 5 min protocol), while it was 18 min in the present 6 x 5 min study. Furthermore, it has been observed increased $\dot{V}O_2$ compared with the non-vibration only after more than 15 minutes of exposure to vibration,[12] indicating that time with vibration might contribute to its effect on time ≥ 90%$\dot{V}O_{2max}$. Bossi et al.[9] used vibration during the MAP intensity only (30-s) and thus it might be suggested that a large proportion of fast-twitch muscle fibres were already recruited due to the high intensity,[27,28] potentially reducing the effect of vibration.

The longer time ≥ 90%$\dot{V}O_{2max}$ in VIB condition may be connected to the rise in EMG activity in lower limb (notably in biceps femoris) and in upper limb (notably in biceps brachii). Unlike some previous studies,[11,18,26] we found no significant increase in EMG activity of the knee extensor muscles (VM, VL, RF) and elbow (TB) extensor muscles when vibrations were added while cycling. This difference could be related to the intermittent nature of vibration exposure used during the present study, the shorter time and lower intensity workload when vibrations were applied, and the location of vibration entry (i.e., under the rear part of the bike).

It has been proposed that during submaximal contractions, vibration may induce an Ia afferent inflow that exceeds the pre-existing fusimotor-driven Ia afferent discharge, resulting in more motor units being recruited.[13] Increased muscle activation could in theory increase the metabolic demand, thus increase $\dot{V}O_2$. Consequently, mean $\dot{V}O_2$ across all work intervals was higher in VIB than VAR. The increase in $\dot{V}O_2$ can also be explained by the suggestion that 1) vibration primarily increases recruitment of fast twitch muscle fibers, which are thought to utilize more $\dot{V}O_2$ than the slow twitch muscle fibers,[15] 2) previously exhausted muscle fibers may be additionally reactivated by vibration,[14] thereby increase $\dot{V}O_2$, or 3) muscle activation notably in the upper-body is increased to reduce the vibration transmissibility.[17,18] If an increased activation of fast twitch fibres took place, one could expect an increased [La^-], but this did not occur. Based on the present findings, although HR and time spent above 90% HR_{max} were not significantly increased, it might be suggested that adding vibration to a HIIT session speed up the $\dot{V}O_2$ responses. The latter is supported by the observation that VIB had a higher $\dot{V}O_2$ than VAR during the lower intensity blocks only (coincidental with the added vibrations; Fig 4). No group differences in HR response might be surprising, as there in general is a relationship between HR and $\dot{V}O_2$. Unfortunately, the present study has no data to explain this. However, it has been observed that vibration induced increase in $\dot{V}O_2$ despite a lack of an increase in central cardiovascular responses like HR, mean arterial pressure, cardiac stroke volume and cardiac output, suggesting either redistribution of the cardiac output, increased the arterio-venous difference, or both (Yarar-Fisher et al. 2013). Furthermore, other studies are also observing that temporal characteristics of changes in HR do not correspond to those of the changes in $\dot{V}O_2$, suggesting that HR responses may not be a precise reflection of the metabolic stress induced by HIIT (Shi et al. 2018, Smiliios et al. 2018, Bossi et al. 2020, Rønnestad et al. 2022).

Although VIB increased mean $\dot{V}O_2$ and total time ≥ 90%$\dot{V}O_{2max}$, the participants reported lower RPE during VIB than during VAR. It has been suggested that applying mechanical vibration may influence the activation of afferent input from sensory units in muscle fibers and attenuate pain sensation associated with exercise[29] and thus potentially mask a higher effort with vibration condition. However, if the vibrations masked a higher effort, from a physiological perspective, one would expect higher heart rate and blood lactate values, but this was not the case. Alternatively, adding vibration to cycling has been hypothesized to induce additional opening of blood vessels and thereby increases in blood distribution that could favour blood lactate elimination of lactate within the muscle tissue,[12] but this remains to be investigated.

Some limitations of the present study may be related to the fact that this is an acute study, where we do not measure any training adaptations. It is therefore impossible to conclude on whether there are differences in training adaptation between VIB and VAR. The effect of vibrations on VO_2 and muscle activity may have been suboptimal in the present study since the vibrations were only generated by a single vibrating plate placed under the rear part of the bicycle. This effect could be greater if the front of the bike would also vibrate at the same time, as was realized for example in Vielleher's study.[18] However, the present study shows that using only one vibrating plate is sufficient to increase time ≥ 90%$\dot{V}O_{2max}$. A verification test of VO_{2max} was not applied in the present study, possibly inducing extra noise in our data. However, there are studies indicating no need for a verification test (Rositer et al. 2006, Murias et al. 2018) and despite potential extra noise in our data, we observed group differences.

Practical applications

Since it has recently been indicated that the HIIT session that elicits the longest time near $\dot{V}O_{2max}$ induces the largest training adaptations,[30] adding vibration to HIIT cycling sessions can be a method to improve the quality and adaptations to HIIT training for well-trained cyclists. In addition to the prolonged time ≥ 90%$\dot{V}O_{2max}$, the added vibrations during the indoor trainer cycling adds specificity for both the vibration conditions that mountain bike cyclists meet and the vibrations that occur during cobble stone races for road cyclists. In terms of practicality, a trainer can be mounted on a large vibration plate allowing for vibration cycling, but this vibration training must be performed indoor. However, the long-term effects and training adaptations to this training method remains to be investigated. Furthermore, the long-term demands of recovery are also uncertain, so it is important to carefully monitor the training response and recover needs if this training method is used.

Conclusion

The present study suggests that adding vibration during the lower intensity workloads in varied-intensity work intervals of a HIIT cycling session induces longer time ≥ 90%$\dot{V}O_{2max}$, which is associated with a lower RPE compared with a non-vibration condition. This may at least partly be due the increased EMG activity in m. biceps femoris and biceps brachii.

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