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ORIGINAL ARTICLE

Local high-frequency vibration therapy following eccentric exercises reduces muscle soreness perception and posture alterations in elite athletes

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Abstract

Purpose Exercise-induced muscle damage produces painful sensations (delayed onset of muscle soreness, DOMS). DOMS causes compensatory postural adaptations, which in turn affect athletes' walking and running gait biomechanics. It is still debated whether the postural changes are due to impaired proprioception or pain perception. To disambiguate between these two contrasting hypotheses, we designed a study that tested post-exercise postural adjustments in two groups of athletes: a group who was administered a vibration therapy (VT), to attenuate pain perception, and a control group.

Methods Thirty professional futsal players were tested on five different occasions: baseline, eccentric exercises (EE) session day, 24, 48 and 72 h after EE. Vibration therapy (120 Hz) was applied on legs muscles for 15 min in the experimental group, while no vibration was applied in the control group. The measurements included: isokinetic evaluation, stabilometric test, perceived soreness evaluation and serum levels of creatine kinase, and lactate dehydrogenase.

Results 48 h after EE, the control group showed changes in biomechanical parameters (antero-rotations of pelvis, $p < 0.05$). A substantial alteration in the hip kinematics was found, associated to a reduced contractile force ($p < 0.01$) and soreness perception. On the contrary, the VT group did not show any change in posture and pain perception. High-intensity VT decreases EE effects on muscle strength and DOMS.

Conclusions DOMS significantly changes athletes' posture; but postural changes disappear following a VT therapy that decreases pain perception. It is concluded that soreness perception is the main cause of postural changes and that its effects can be counteracted using VT therapy.

Keywords Pain · Futsal · Vibration therapy · Muscle recovery · Balance · Isokinetic · Posture

Abbreviations

ANOVA	Analysis of variance
CK	Creatine kinase
COM	Centers of mass
COP	Center of pressure
CS	Cranio subsystem
CTRL	Control
DOMS	Delayed onset of muscle soreness
EC	Eyes closed
EE	Eccentric exercise
EIMD	Exercise-induced muscle damage
EMG	Electromyography
EO	Eyes open
ICC	Intraclass correlation coefficients
LDH	Lactate dehydrogenase
MVC	Maximal voluntary contraction
PPT	Pressure pain threshold
PS	Pelvic subsystem
SIAS	Spina iliaca anterior superior
SIPS	Spina iliaca posterior superior
VT	Vibration therapy
WBV	Whole body vibration

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Introduction

It is a long-standing observation that soccer players are often submitted to high eccentric actions during matches (e.g., when decelerating or changing direction) and training sessions (Reilly et al. 2007). Repetitive exercises involving eccentric actions of high intensity or duration can lead to muscle damage (Byrne et al. 2004). Exercise-induced muscle damage (EIMD) is associated with a protective inflammatory response (Peake et al. 2005) and changes in the afferent inputs from the muscle spindle, Golgi tendon organ and groups III and IV afferent nerve endings (Komi 2000). A painful sensation when contracting, stretching or putting pressure onto the exercised muscle (Weerakkody et al. 2001) is experienced within the first 24 h and last for 1–3 days after eccentric exercise (Proske et al. 2004). This physiological phenomenon is known as delayed onset of muscle soreness (DOMS).

DOMS decreases the stretch reflex sensitivity, impairs stiffness regulation of muscles and joints and reduces muscular performance for several days, after the damaging exercise (Howatson et al. 2009; Linnamo et al. 2000; Marklund et al. 2013; Molina and Denadai 2012). All these effects, in turn, cause significant postural modifications. These DOMS-induced alterations—and in particular a significant increase in pelvic rotation—have been reported in walking and running gait biomechanics, 48 h after eccentric exercise (Paschalis et al. 2007a; Tsatalas et al. 2010). However, little is known about the neuromuscular causes of DOMS-induced alterations. One hypothesis is that biomechanics alterations may be due to proprioceptive impairments (Paschalis et al. 2007b). This proposal is in keeping with evidence of impairments in joint position sense of the lower limbs following eccentric exercises (Saxton et al. 1995; Torres et al. 2010). An alternative possibility is that DOMS-induced alterations are due to pain perception. In this perspective, acute pain (e.g., low back pain) may increase postural muscles activation and impair anticipatory postural responses (Boudreau et al. 2011; Iodice et al. 2015a; Larsen et al. 2017).

We designed a study to disentangle between these two alternative hypotheses on DOMS-induced alterations. We firstly induced DOMS to two groups of athletes through an eccentric exercise session. Then, we administered a direct vibration therapy (VT) to reduce pain perception in one of the two groups (VT group) but not the other (in which a sham therapy was provided, control group). Finally, we compared postural adjustments and balance skills in the two groups. We reasoned that, if pain perception plays a causal role in postural changes, the group who was administered vibration therapy (and thus had reduced pain or muscle soreness perception) would have shown reduced postural changes compared to the control group. Support for the idea that VT decreases pain (muscle soreness) perception comes from previous investigations of therapeutic modalities used after sports activities (Bakhtiary et al. 2007; Barnes et al. 2012; Edge et al. 2009). Another line of research has demonstrated that VT directly applied to muscles increases pain thresholds by parallel changes in muscle spindle activity, leading to the increased reflexive neural activation of the muscle (Weerakkody et al. 2001). Recently, Cochrane (2017) demonstrated strong reduction in peak of muscle soreness (34%) after VT (120 Hz), applied during recovery phase, after eccentric exercise (Cochrane 2017). This main effect was associated with a large increase in joints range of motion (ROM) and a decrease in passive muscle stiffness (Cochrane 2017).

Furthermore, in this study we were also interested in studying whether proprioceptive impairments due to eccentric exercise would be sufficient to decrease athletes' balance skills. A failure of eccentric exercise to reduce athlete's balance would suggest that exercise-induced proprioceptive impairments are minor, and thus insufficient to cause the widespread impairments associated to DOMS.

Our study aims to shed light on the phenomena underlying the claimed postural alterations caused by an EE. For the first time, postural changes, muscular damage, contractile muscle function, balance and pain perception will be observed throughout the recovery phase. Reducing the perception of pain through high-intensity vibratory therapy will allow us to clarify whether the alterations are due to pain or to proprioceptive impairments.

This knowledge as well as a scientific interest has an evident applicative importance in the management of the training load and in the injuries prevention of athletes.

Materials and methods

Participants

Forty professional futsal players (no goal-keepers) [30 men; M_{age} = 23, SD 1 year, M_{height} 175, SD 9 cm, M_{weight} = 70, SD 8 kg, $M_{\text{peak power output}}$ 280, SD 56 W, $M_{\text{maximal oxygen uptake}}$ = 59, SD 8 ml kg^{-1} min^{-1}, M_{BMI} 20.45 ± 2.13] participated in this study. The sample size was calculated based on a power analysis [G*Power 3.1.9.2 (http://www.gpower.hlu.de/en.html)]. The analysis was based on a desired η_p^2 of 0.14 [corresponding to a Cohen's $f = 0.40$, and to a power ($1 - \beta$ err. Prob.) = 0.95] for the F tests, and on a desired ρ^2 of 0.25 for the correlation analysis, which are interpreted as an index of a large effect size (Cohen 1988; Richardson 2011). We used as reference for this calculation the study performed by Cochrane et al. (2017) where VT led to the post-exercise recovery of delayed onset of muscle soreness

(DOMS), maximum voluntary contraction (MVC) and creatine kinase (CK).

The results of these analyses indicated a required sample size ranging from 13 to 18 participants; we also observed 20 to be a critical number of participants, as the effect size and observed power remains stable above this number.

Informed consent was obtained from each participant and the study protocol conforms to the ethical guidelines of the Declaration of Helsinki (BMJ 1991; 302; 1194) as reflected in prior approval by the institution's human research committee (ISTC-CNR, Rome).

The eligibility criteria were aimed at identifying participants without endocrine, cardiovascular, pulmonary, neurological and orthopedic disorders, with a BMI in the range of normality ($18.5 < \text{BMI} < 25$ kg m^{-2}).

Additionally, individuals with low back pain or musculoskeletal disorders affecting the spine or limbs were excluded.

Experimental design

Before testing, participants performed three familiarization sessions over a week's time. These sessions included anthropometric measurements and familiarization with all experimental measures. We introduced participants to all testing protocols at least once during the three sessions and assessed DOMS during every session, to show reliability of measurements.

After familiarization sessions, athletes performed testing sessions on 4 consecutive days. They were assigned randomly to either the "direct VT" or "control" groups.

During the first day at 08:00 a.m., blood samples were drawn, at 08:30 a.m., and baseline data (maximum voluntary contraction, posture data, stabilometric measures and muscle damage indicators) were collected. Afterwards, all participants performed a high-intensity exercise designed to induce DOMS (see below). Eccentric exercise was followed by an isometric test in order to assess the loss of strength immediately after the eccentric exercise. Next, a second blood sample was collected. Successively, we assessed participants for DOMS tests.

Two hours after the high-intensity exercise protocol, all participants were prepared to receive VT in prone position. However, the cup-shaped transducer generated appropriate vibratory stimuli only for the "VT group", while the same machine was switched on but unable to generate vibratory stimuli in the case of the "control" group. After the VT or control treatment protocol, participants' stabilometric measurements and DOMS were tested.

Since the muscle damage symptoms typically begin 12–24 h after exercise and peak 24–72 h post-exercise (Paschalis et al. 2007a), participants returned to the laboratory 24, 48, and 72 h after the eccentric exercise protocol. Subsequent sessions consisted of VT or control treatment procedure and stabilometric, posture and DOMS measurements evaluations, with the same procedure as in the first session.

We instructed participants to adhere to the restrictions of the study and to refrain from any other treatment (i.e., icing, stretching, heating).

Isometric protocol test: maximum voluntary contraction

An isokinetic dynamometer (Cybex International Inc., Medway, MA, USA), previously used in studies of similar nature (Paschalis et al. 2007a), was used for maximum voluntary contraction (MVC) evaluation and execution of the exercise protocol.

Subjects were in a seated position. The distal pad of the dynamometer arm was placed in the proximity of the malleoli. The axis of rotation of the Cybex dynamometer was adjusted so that the device was aligned with the joint margin of the knee. Fifteen warm-up trials and preconditioning of the testing device were performed prior to data sampling at 70% of subjective maximal effort.

Knee extensor and flexor MVC were determined with the knee at 60° and 90° of flexion, respectively (0° = full knee extension), the test consisted of three 5-s isometric contractions of the knee extensors of the dominant leg. The highest torque value of the three trials was used for analysis. The dynamometer was calibrated weekly according to the instructions provided by the manufacturer. Gravitational corrections were also employed.

Isokinetic protocol: eccentric contractions

Immediately after the stretching and warm-up exercises, the volunteers performed the eccentric contraction protocol, which consisted of 75 eccentric maximal voluntary actions of the knee flexor and extensor muscle groups at $60°s^{-1}$ (5 sets of 15 repetitions, 30-s rest interval between sets). At each contraction, the dynamometer automatically (passively) positioned the knee at 30; the dynamometer then flexed the knee until reaching 90. The volunteers were instructed to resist against knee flexion–extension movement imposed by the dynamometer with maximum force. Both legs were exercised randomly in two separate bouts with a 5-min recovery between them. Knee flexor and extensor muscle groups of each leg were tested simultaneously during the same eccentric exercise bout. Before starting the exercises, the volunteers received instructions on how to execute the maneuver; while during the exercise, they received verbal encouragement and visual feedback from the computer screen (Kellis and Baltzopoulos 1996). Volunteers performed five submaximal repetitions as a familiarization procedure before the tests. The procedure to induce muscle damage to both knee flexors and extensors was based on previous studies of Tsatalas and colleagues (Tsatalas et al. 2010); note that damaging more than one muscle groups is common during futsal training sessions.

Vibration therapy

Immediately after the completion of the eccentric exercise bout, and at 24 and 48 h post-exercise, subjects were exposed to 15 min of direct local acoustic vibration (VT) or an identical protocol with the machine switched on, but unable to generate vibratory stimulus (CTRL).

The direct VT was applied using the Vibra Plus device (Vibra Plus; A Circle s.p.a. Company, San Pietro in Casale, Bologna, Italy) capable of producing acoustic waves of different frequencies and pressure/depression on the skin. The experimental technique consisted of applying 15 min of local acoustic vibration (continuous mode) over the base of the following muscles: vastus intermedius, rectus femoris, vastus lateralis, vastus medialis, gluteus maximus, biceps femoris, adductor longus and magnus. The cup-shaped transducer had a contact surface of 2 cm^2, so that the amplitude of vibration was approximately 1.2 mm. During the procedure, subjects were not required to maintain isometric contraction of the treated muscle. This protocol (15 min vibration at 120 Hz with an amplitude of 1.2 mm) was selected in agreement with the manufacturer's instructions, and in keeping with a recent study reporting that applying 15 min of direct VT at 120 Hz significantly alleviate muscle soreness (Cochrane 2017); see also Weerakkody et al. 2001.

Muscle damage indicators

DOMS

All participants palpated their muscle belly and the distal region of the vastus medialis, vastus lateralis, rectus femoris, adductors (longus and magnus) and hamstrings (biceps femoris, semimembranosus, semitendinosus) in a seated position with the muscles relaxed. The participants verbally reported their perceived soreness to the investigator, using a numerical rating scale (NRS), which ranges from 1 (normal) to 10 (very, very sore) (Clarkson et al. 1992). The reliability of a similar measurement protocol has been previously assessed (Nosaka et al. 2002).

Pressure pain threshold (PPT)

PPT was assessed over vastus lateralis (2/3 distal) in a seated position, using an electronic digital algometer with a probe size of 1 cm^2 and values range from 0 to 100 lbs, with a precision of 0.1 lbs (Baseline, Parma, Italy).

The algometer was calibrated before each recording session and the same person performed all the measurements. The subjects were instructed to respond verbally when the applied pressure became painful. For baseline PPT was also measured on one site on the tibialis anterior 20 mm distal to the tibial process.

Creatine kinase (CK) and lactate dehydrogenase (LDH)

Blood samples were drawn from an antecubital vein into plain evacuated test tubes, in order to evaluate the concentration of CK and LDH. The blood was allowed to clot at room temperature for 30 min and centrifuged at 1500×*g* for 10 min. The serum layer was removed and frozen at − 20 °C until analyzed. CK and LDH were determined spectrophotometrically (Milton Roy, Spectronic 401, Ivyland, USA) in duplicate using the corresponding biochemical kits (Megalab, Athens, Greece; Randox laboratories LTD, UK). As described by the manufacturer, the normal reference range of CK and LDH activity for men using this method is 45–130 IU and 120–240 IU, respectively. Blood samples were collected before (Pre) and 48 h after the eccentric exercise protocol.

Stabilometric measures

Static stability was evaluated using the AMTI Biomechanics Force Platform (model BP6001200-1000). During the assessment of static stability, subjects stood barefoot in a natural position, arms at their sides, and forefoot open to 30°, in two conditions: with eyes open (EO) facing a target 1.5 m away, and with eyes closed (EC). To calculate the mean values of each stabilometric center of pressure (COP) parameter, three trials were performed for each condition, each lasting 51.2 s (in accordance with the guidelines of the French Posturology Association). The sampling frequency was 120 Hz. The key dependent variables of the COP displacements are its length and its surface area, calculated as the surface of the confidence ellipse enclosing 90% of COP sway (Iodice et al. 2015a).

Posture analysis

The test of the posture analysis included a 3D posture examination, using the Fastrak system (Polhemus Inc., Colchester, VT, USA). The placement of the sensors operating at the rate of 30 Hz was designed to assess posture at rest of the body. The position of each sensor was detected by the stationary system. A specific probe was used for the collection of spatial points on the subject, and then, by means of RS-232 interface, recorded in a computer. Data obtained from Fastrack were stored and processed off-line in the Matlab (MathWorks, Inc., Natick, MA, USA) environment; see

Iodice et al. 2015b for more details. The centers of mass (COM) were calculated as the arithmetic mean of the points of interest in the *x*, *y* and *z* axes of the reference system (Grimshaw 2007).

All the measurements were performed in the absence of a magnetic field and with a constant temperature of 23 ± 1 °C. Furthermore, care was taken to ensure that patients were not wearing any metal objects. All the equipment used for the acquisition of the data was calibrated every time, 1 week before the date of measurement (Pezzulo et al. 2017).

The subjects maintained a comfortable posture with their feet placed shoulder width apart while standing barefoot, arms at their sides and forefoot open to 30°. The anatomical reference landmarks on the subjects of the population taken into consideration were as follows (see Fig. 1): nasion, right tragus, left tragus, gnathion (cranio subsystem in—CS) and right and left S.I.P.S., left and right S.I.A.S (configuration pelvic subsystem—PS).

Statistical analysis

The muscle damage indicators (DOMS, PPT, MVC) of the subjects from the rest (Pre), after exercise (Post-EE), after vibration therapy (Post-VT), 24 h (24 h), 48 h (48 h) and 72 h (72 h) from the eccentric exercise session were compared using two (extensor and flexor muscles) 2 × 6 repeated measure analysis of variance (ANOVA), with the group (VT and CTRL group) and time (Pre, Post-EE, Post-VT, 24 h, 48 h, 72 h) as factors.

Moreover, CK and LDH variables were entered in a two-way ANOVA (2 × 2). Within-subject factors were: group (VT-group and CTRL-group) and time (Pre and 48 h).

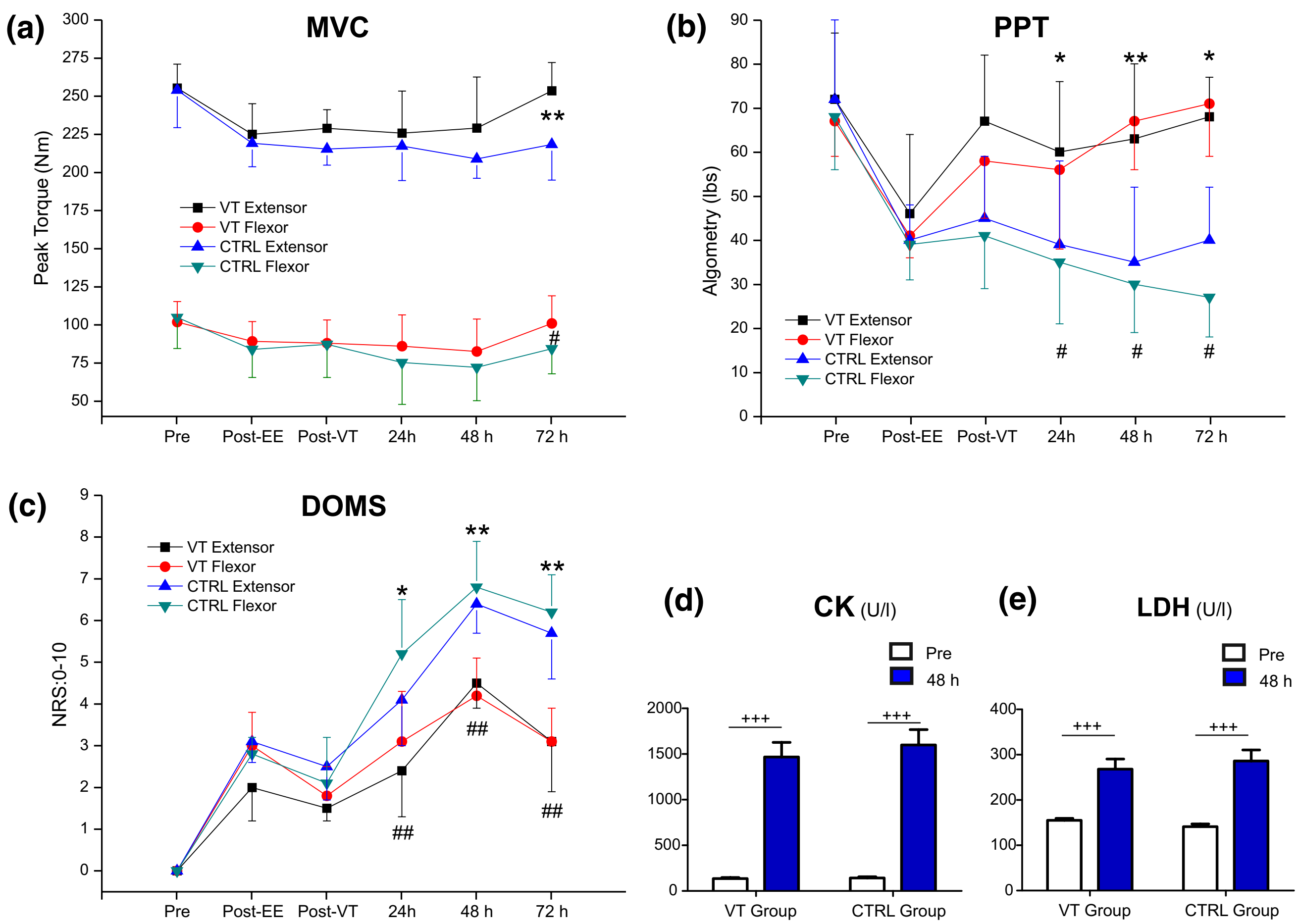

Fig. 1 Maximum voluntary contraction (MVC) and muscle damage indices. MVC (**a**), PPT (**b**) and DOMS (**c**) values for both groups (VT and CTRL) and muscles (extensor and flexor) were reported before (Pre), after eccentric exercise (Post-EE), after vibration therapy (Post-VT) and 24 (24 h), 48 (48 h) and 72 (72 h) from the eccentric exercise session. Post hoc significant differences between groups were reported: VT extensor (black) vs. CTRL extensor (blue) *($p < 0.05$), **($p < 0.01$); VT flexor (red) vs. CTRL flexor (green) $^{\#}$($p < 0.05$), $^{\#\#}$($p < 0.01$). CK (**d**) and LDH (**e**) serum levels (U l^{-1}), with standard error bars, before and 48 h after eccentric exercise session of both groups, VT and CTRL. $^{+++}$($p < 0.001$): significant difference between evaluations

In this study, we were interested in testing whether the differences in balance and posture parameters, after a eccentric exercise, was related to perception of soreness, due to DOMS, or whether instead it was ascribable to proprioceptor impairment. To this aim, three (plane *X, Y* and *Z*) 2×4 repeated measure ANOVA were conducted on the COM of cranium (CS) and pelvic (PS) subsystem, with the group (VT vs. CTRL) and the time (Pre, 24 h, 48 h, 72 h) as factors.

Moreover, four 2×4 repeated measure ANOVA were conducted on both total length and its surface area of stabilometric test, with the group (VT vs. CTRL) and the time (Pre, 24 h, 48 h, 72 h) as factors.

To test the hypothesis that pain might generate (possibly maladaptive) compensatory postural adjustments, we conducted a series of Pearson's correlations between the subject-specific DOMS rate of the VT and CTRL groups and the COM modifications in CS and PS subsystems. We also conducted a series of robust linear regressions—MATLAB Robust Fit (Holland and Welsch 1977; O'Leary 1990)—with the DOMS of the VT and CRTL groups as dependent variable and the postural changes index as regressor.

Results

All athletes recruited completed all assessments performed in the study, and therefore, there were no dropouts.

Reliability and variability of muscle damage indicators

Measurements of reliability were quantified through the calculation of intraclass correlation coefficients (ICC) with 95% confidence intervals. The ICC value for DOMS, PPT and MVC were 0.90, 0.91 and 0.93, respectively. We analyzed the coefficient of variation within each familiarization day and baseline measures for DOMS, PPT and MVC. The average values from all 4 days were used for analysis; the coefficients of variation were DOMS 11.7%, PPT 9.4% and MVC 8.6%.

Maximum voluntary contraction and muscle damage indicators

Figure 1a–e shows MVC and all muscle damage indices of thigh muscles pre, post-exercise, post-vibration therapy and after 24, 48 and 72 h from eccentric exercise session. On MVC average peak torque of extensor muscle, we found a significant main effect of group ($F_{(1,14)} = 9.65$, $p < 0.01$, e.s. = 0.86), time ($F_{(5,84)} = 6.22$, $p < 0.05$, e.s. = 0.66) and the interaction group by time ($F_{(5,84)} = 4.85$, $p < 0.05$, e.s. = 0.68). Bonferroni-corrected pairwise comparisons reveal greater contractile force in the VT-group than CTRL-group at 48 h ($t_{(14)} = 2.64$, $p < 0.05$, $d = 0.66$) and 72 h ($t_{(14)} = 4.34$, $p < 0.01$, $d = 0.79$); see Fig. 1a. MVC average peak torque of flexor muscle data show a significant main effect of group ($F_{(1,14)} = 4.38$, $p < 0.05$, e.s. = 0.86), time ($F_{(5,84)} = 4.05$, $p < 0.05$, e.s. = 0.71) but no significant interaction effect ($F_{(5,84)} = 1.54$, n.s.). However, the post hoc analysis showed a significant difference between groups 48 h after EE session ($t_{(14)} = 3.14$, $p < 0.05$, $d = 0.77$); see Fig. 1a.

Analysis of DOMS and PPT (see Fig. 1b, c) shows the same pattern as MVC for both extensor and flexor muscles. We found a significant main effect of group (DOMS—extensor: $F_{(1,14)} = 1.88$, $p > 0.05$, e.s. = 0.79; flexor: $F_{(1,14)} = 2.32$, $p > 0.05$, e.s. = 0.68. PPT—extensor: $F_{(1,14)} = 2.28$, $p > 0.05$, e.s. = 0.67; flexor: $F_{(1,14)} = 1.99$, $p > 0.05$, e.s. = 0.71.) and time (DOMS—extensor: $F_{(5,84)} = 2.08$, $p > 0.05$, e.s. = 0.64; flexor: $F_{(5,84)} = 2.13$, $p > 0.05$, e.s. = 0.74. PPT—extensor: $F_{(5,84)} = 2.81$, $p > 0.05$, e.s. = 0.77; flexor: $F_{(5,84)} = 2.34$, $p > 0.05$, e.s. = 0.74.) but not interactions (group ×time) were observed (DOMS—extensor: $F_{(5,84)} = 0.38$, n.s.; flexor: $F_{(5,84)} = 0.21$, n.s. PPT—extensor: $F_{(5,84)} = 0.52$, n.s.; flexor: $F_{(5,84)} = 0.51$, n.s.). More in depth, post hoc analysis reveal a reduced soreness perception in vibration therapy group, in both flexor and extensor muscles, after 24 h (DOMS—extensor: $t_{(14)} = 2.11$, $p < 0.05$, $d = 0.71$; flexor: $t_{(14)} = 2.23$, $p < 0.05$, $d = 0.63$. PPT—extensor: $t_{(14)} = 2.21$, $p < 0.05$, $d = 0.61$; Flexor: $t_{(14)} = 3.41$, $p < 0.01$, $d = 0.69$), 48 h (DOMS—extensor: $t_{(14)} = 3.24$, $p < 0.01$, $d = 0.76$; flexor: $t_{(14)} = 2.03$, $p < 0.05$, $d = 0.64$. PPT—extensor: $t_{(14)} = 3.52$, $p < 0.01$, $d = 0.77$; flexor: $t_{(14)} = 3.13$, $p < 0.01$, $d = 0.64$) and 72 h (DOMS—extensor: $t_{(14)} = 2.41$, $p < 0.05$, $d = 0.62$; flexor: $t_{(14)} = 2.09$, $p < 0.05$, $d = 0.72$. PPT—extensor: $t_{(14)} = 4.01$, $p < 0.01$, $d = 0.89$; flexor: $t_{(14)} = 3.63$, $p < 0.01$, $d = 0.82$); see Fig. 1b, c.

Serum CK and LDH levels were significantly elevated 48 h after EE in both groups. ANOVA analysis reveals a significantly main effect of time (CK: $F_{(1,14)} = 15.58$, $p > 0.001$, e.s. = 0.89; LDH $F_{(1,14)} = 12.24$, $p > 0.001$, e.s. = 0.88) but not of group ($F_{(1,14)} = 0.96$, n.s.) or of interaction ($F_{(1,28)} = 1.24$, n.s.); see Fig. 1d and e. Taken together, these results indicate that, first, the eccentric exercises appropriately induce DOMS; and second, that the vibration therapy appropriately reduces soreness perception in the VT group.

Postural analysis

To study the effects of vibration therapy and decreased pain perception on post-exercise DOMS we studied the postural changes (cranio and pelvis subsystems) before (baseline) and 24, 48 and 72 h after eccentric exercise sessions in both groups (VT and control). The results of the repeated measures ANOVA (2×3) conducted to compare the posture changes parameters associated with the two groups in the three plans showed a statistically significant main effect of group ($F_{1,14}$ = 24.76, $p < 0.001$, $d = 85$). Table 1 shows the biomechanical modification of COM position of the subsystems in the different evaluations times for each groups. It permits to appreciate that in VT group there are not significant differences between Pre and one or more of the successive periods (plane X—CS: $F_{(3,56)} = 0.44$, n.s., PS: $F_{(3,56)} = 0.62$, n.s.; plane *Y*—CS: $F_{(3,56)} = 0.71$, n.s., PS: $F_{(3,56)} = 0.48$, n.s.; plane *Z*—CS: $F_{(3,56)} = 0.69$, n.s.; PS: $F_{(3,56)} = 0.61$, n.s.). Conversely, our data showed a statistically significant main effect of time for CTRL-group (plane X—CS: $F_{3,56}$ = 19.21, $p < 0.001$, $d = 0.89$, PS: $F_{3,56}$ = 17.23, $p < 0.001$, $d = 0.81$; plane *Y*—CS: $F_{3,56}$ = 1.11, n.s, PS: $F_{3,56}$ = 5.72, $p < 0.05$, $d = 0.61$; plane *Z*—CS: $F_{3,56}$ = 22.87, $p < 0.001$, $d = 0.87$, PS: $F_{3,56}$ = 18.88, $p < 0.001$, $d = 0.79$; see Table 1). Our results indicate a general anteroposition in plane X of body mass center. Rather, in plane *Z* the subsystems are involved in different ways, with a lifting of pelvis subsystem' COM associated with an antero-rotation of pelvis (see Table 1 for all the post hoc analysis significances). Taken together, our data show that vibration therapy—and reduced pain perception—prevents postural changes that are instead observed in the control group. This result indicates that pain perception plays an important role in the biomechanical modification of posture after eccentric exercise sessions.

Stabilometric measures

To assess whether eccentric exercise affects participants' balance, we measured length and surface area of COP movements during a stabilometric test, measured before and after 24, 48 and 72 h from eccentric exercise session (see Fig. 2). We found no significant change in the COP displacements between two groups (surface: $F_{(1,14)} = 0.34$, n.s.; total length: $F_{(1,14)} = 0.51$, n.s.). Nor was there a difference between time points (surface: $F_{(3,56)} = 0.63$, n.s.; total length: $F_{(3,56)} = 0.44$, n.s.). In both EO and EC conditions, the changes in COP displacements were negligible. These results thus show that athletes' balance capacity seems to be not affected by exercise-induced muscle damage.

Discussion

The main goal of this study was to disambiguate between two alternative hypotheses that have been proposed in literature as the main reason for postural changes after EE: alterations of afferent/proprioceptive signals or pain perception.

Our findings significantly extend the current state of the art by showing that, first, modifications of orthostatic posture are not an automatic byproduct of eccentric exercise (EE) but are eliminated by vibration therapy that reduces pain and

Table 1 Biomechanical modification

	Plane X antero(+)/posterior (−)				Plane *Y* latero Rx(+)/laterale Lx(−)				Plane *Z* superior(+)/inferior(−)			
	Pre	24 h	48 h	72 h	Pre	24 h	48 h	72 h	Pre	24 h	48 h	72 h
VT group												
CS	0.00 ± 0.00	0.12 ± 0.44	0.14 ± 0.81	0.10 ± 0.31	0.00 ± 0.00	0.07 ± 0.59	0.12 ± 0.39	0.02 ± 0.63	0.00 ± 0.00	0.06 ± 0.34	0.07 ± 0.67	0.11 ± 0.75
PS	0.00 ± 0.00	0.15 ± 0.63	0.18 ± 0.39	0.13 ± 0.34	0.00 ± 0.00	0.13 ± 0.39	− 0.15 ± 0.22	0.13 ± 0.56	0.00 ± 0.00	0.13 ± 0.39	0.15 ± 0.72	0.07 ± 0.52
CTRL group												
CS	0.00 ± 0.00	0.22 ± 0.74*	0.28 ± 0.59†	0.31 ± 0.34#	0.00 ± 0.00	0.17 ± 0.44	− 0.10 ± 0.64	0.06 ± 0.53	0.00 ± 0.00	− 0.17 ± 0.64*	− 0.18 ± 0.44†	− 0.08 ± 0.73
PS	0.00 ± 0.00	0.33 ± 0.56*	0.31 ± 0.66†	0.24 ± 0.65	0.00 ± 0.00	0.13 ± 0.86	0.24 ± 0.76	0.09 ± 0.25	0.00 ± 0.00	0.40 ± 0.68*	0.47 ± 0.49†	0.33 ± 0.60#

Values represent means ± SD of biomechanical modification in VT and CTRL groups in 4 periods: Pre, assumed to be 0.00 (base line), 24 h, 48 h and 72 h after eccentric exercise session. Cranio (CS) and pelvic (PS) systems positions are reported on plane *X* (the positive sign represents an anteriorization and negative sign represents a retroposition in centimeters), on plane *Y* (the positive sign represents a right lateralization and negative sign represents a left lateralization in centimeters) and on plane *Z* (the positive sign represents a rise and negative sign represents drop of COP in centimeters); post hoc analysis significance: *$p < 0.05$ Pre vs. 24 h; †$p < 0.05$ Pre vs. 48 h; #$p < 0.05$ Pre vs. 72 h

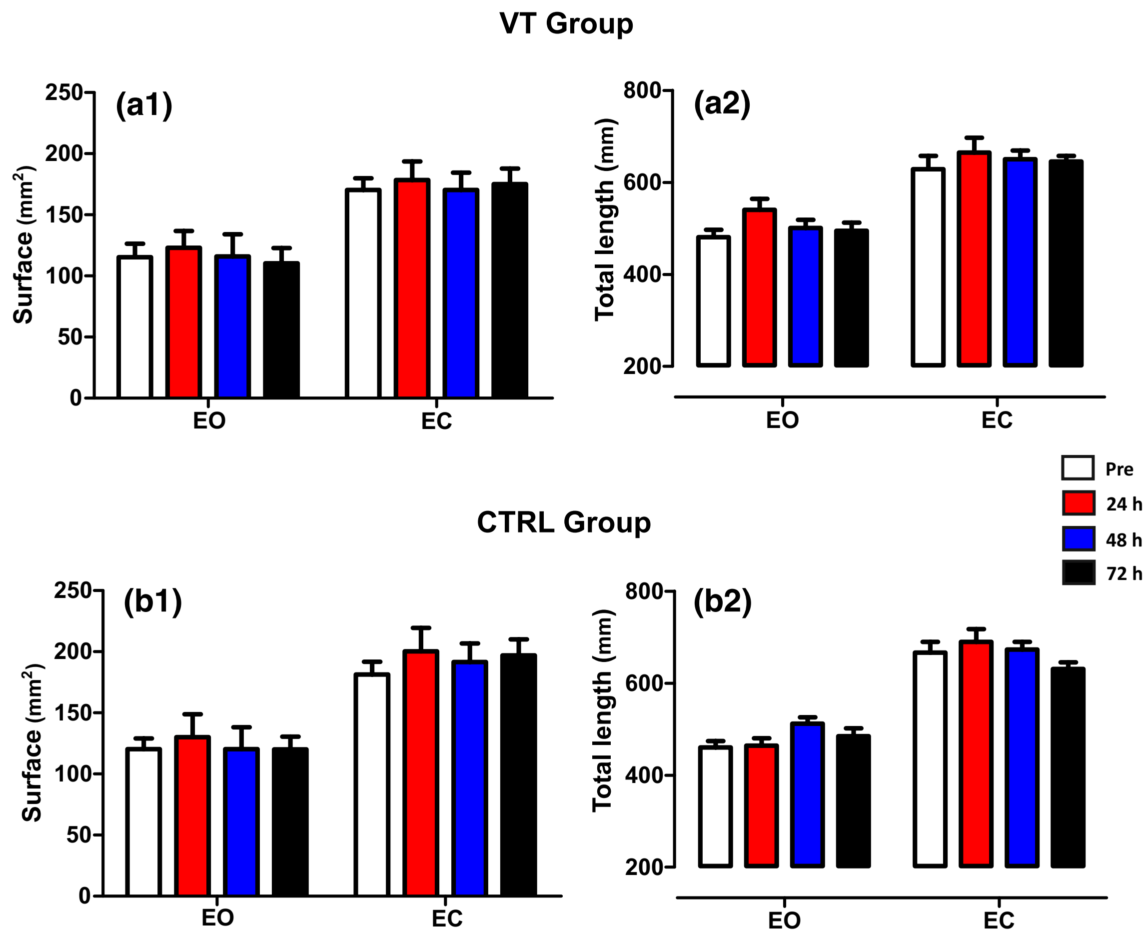

Fig. 2 Stabilometric measures. Surface (mm^2) and total length (mm) of stabilometric test (52.2 s), with standard error bars, in both VT and CTRL groups. Data were reported before (Pre), and 24 (24 h), 48 (48 h) and 72 (72 h) from the eccentric exercise session, in two different conditions eyes open (EO) and eyes closed (EC)

soreness perception; and second, that eccentric exercise does not significantly affect subjects' balance abilities.

Posture alteration due to pain perception

We report that the COM position of head (CS) and pelvis (PS) significantly shifts in athletes' posture after EE session in the presence of all muscle damage indices. Specifically, we found significant antero-rotations of pelvis (lowering of SIAS and raising of SIPS) that may alter the hip kinematics to compensate the pain perceived during quadriceps contraction. These results are in keeping with the idea that gait alterations may be due to self-protection mechanisms to prevent further pain (Paschalis et al. 2007a; Tsatalas et al. 2010). Importantly, these changes in COM subsystems were not observed in athletes having reduced pain perception (i.e., DOMS and PPT), despite clearly showing the markers of a disrupted sarcomere structure (i.e., high level of CK and LDH). This finding corroborates the idea that pain (soreness) perception plays a key role in inducing post-exercise postural adjustments. A neuroimaging (fMRI) study addressed the neural bases of DOMS-related pain in the quadriceps muscle, revealing a widespread activation in the primary somatosensory and motor (S1, M1) cortices—thus stretching beyond the cortical areas somatotopically related to the quadriceps—as well as the involvement of cingulate cortex and premotor cortex (Zimmermann et al. 2012). This study thus lends support to the idea that DOMS-related pain is a diffuse rather than a localized phenomenon in the brain.

Furthermore, our findings shows that changes in proprioception (here, joint position sense), which are unanimously reported after eccentric exercise (Brockett et al. 1997; Paschalis et al. 2007b, 2008; Torres et al. 2010), do not decrease athletes' balance skills. The dysfunction of muscle spindles and the reduced feedback from muscle receptors after EE (Gandevia et al. 1995; Taylor et al. 2000) do not appear to alter postural schemas in primary somatosensory cortex (Iodice et al. 2015b; Longo and Haggard 2012; Mazzocchi et al. 2014). This finding suggests that a local proprioceptor impairment associated with the eccentric session would not be sufficient to affect athletes' balance skills and their ability to preserve a standing position. This finding thus provides further support for the idea that proprioceptor impairments may not be the most important cause of postural adjustments following high-intensity exercise.

This finding suggests that muscular soreness after EE was mainly due to alterations of the peripheral factor. In contrast with previous studies on chronic pain (i.e., neck pain) who had proposed that pain increased pre-synaptic inhibition of muscle afferents, correspondingly dominancy of nociception (III and IV afferents) over proprioception information in postural control system (Ruhe et al. 2013). Our results are in line with Souron et al. (2018) who suggested that eccentric exercise related decrease in maximal voluntary contraction were due to alterations of the peripheral factor and not by a supra-spinal modulation of muscle activation.

In sum, our results contribute to shed light on the causes of DOMS-induced alterations by showing that decreased pain perception prevents postural adjustments, and that proprioceptive impairments do not automatically imply balance deficits. These results then lend support for the hypothesis that pain perception may be the most prominent cause of DOMS-induced alterations.

Muscular recovery after high-intensity focused vibration therapy

We report a novel and surprising result that implies VT in the improvement of muscular recovery. While our main reason for selecting VT was reducing post-exercise muscle soreness and pain (Broadbent et al. 2010; Cochrane 2017; Rhea et al. 2009), we found that it additionally attenuates force loss in both extensors and flexors muscles, as measured by maximum voluntary contraction (MVC), 72 h after the exercise session. This effect may not have been apparent in previous studies, due to various differences between the experimental protocols. In our experiment, participants were in seated position during VT; they were not subjected to gravitational load or not required to maintain isometric contraction of the treated muscle. Furthermore, we used a different VT stimulus for intensity (120 Hz vs. 26–50 Hz) and method of application (direct stimulus vs. whole body vibration (WBV) compared to previous studies. WBV performed on platform can be classified as an eccentric–concentric activity (Cochrane et al. 2009; Rittweger et al. 2001). It is possible that an additional volume of fast-velocity muscle contractions reduces muscle force (Chapman et al. 2008) and does not promote recovery. Conversely, using stimuli having longer duration and a higher vibration frequency, and which are able to stimulate specific muscles rather than the whole body, may help attenuating pain sensations by influencing the afferent discharge of various structures to reduce pain perception of Meissner and Vater–Pacinian corpuscles, and muscle spindles (Cochrane 2017). Recently, Cochrane (2017) used a vibratory stimulus similar to ours on biceps brachii, reporting a significantly higher EMG in treated muscle 72 h after VT, which was however not associated to an increase in force contraction. The differences between our results and Cochrane's (2017) may be due to the size and blood supply of the different muscles or to the fact that our experimental group comprises elite athletes. Given the relative paucity of studies on high-intensity direct vibratory therapy and muscle performance (Iodice et al. 2011; Pietrangelo et al. 2009), and the lack of studies that directly tested post-exercise effects, these or other hypotheses remain to be tested in future experiments. A study by Casale et al. (2009) using the same device as ours suggests a possible neurophysiological mechanism mediating recovery. This study showed that a high frequency (300 Hz) VT induces modifications at the central level, changes motoneuron recruitment strategies, optimizes mechanical output, and reduces the myoelectric manifestations of fatigue. This study thus suggests that the MVC increase that we observed may be related to the ability of direct vibration to improve motor units synchronization (Casale et al. 2009).

Whilst we cannot be sure as to the reasons of improved recovery, it is likely to be due to increased muscle blood flow due to vibration therapy (Manimmanakorn et al. 2015). Similar to active recovery programs, it has been suggested that the elevated blood perfusion induced by vibrational training enhances removal of blood lactate, H+, and other pain-causing substances, as well as reducing the inflammation process (Ahmaidi et al. 1996). Our results further support the notion that lactate production was reduced in the present study. Lactate measurement could have provided more insight on our results, especially because lactate accumulation can significantly increase the response of group III and IV nociceptive afferents (Kennedy et al. 2014). We acknowledge the limitation of our study and without these muscle measures this assumption is speculative.

Furthermore, it is important to note that the population of this study was elite athletes specifically trained to anaerobic performance; untrained subjects usually suffer more pain after intense exercise such as those in this study (Edge et al. 2009).

Conclusions

Our results may have important implications for risk prevention in athletes, for at least two reasons. First, it has been proposed that pain may generate maladaptive compensatory postural adaptations, which in turn may cause more severe musculoskeletal injury for the athletes and/or associate syndromes (i.e., groin) (Bisciotti 2015). Decreasing pain perception after intense exercise using VT may help preventing this sort of risks. Second, and intriguingly, our results indicate that high-intensity (120 Hz) VT directly improves recovery—possibly, by promoting blood flow and muscle neurogenic aspects—above and beyond decreased pain perception. This result thus suggests novel potential applications of VT in the training and recovery of athletes.

Author contributions PI conceived and directed the study, carried out the experiments, analyzed the data and wrote the paper. PR supervised the eccentric exercise procedures, performed blood samples preparation and analysis, contributed to data interpretation and discussion. GP supervised the project, contributed to data interpretation, discussion and wrote the paper.

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