Localized muscle vibration reverses quadriceps muscle hypotrophy and improves physical function: a clinical and electrophysiological study

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Quadriceps weakness has been associated with knee osteoarthritis (OA). High-frequency localized muscle vibration (LMV) has been proposed recently for quadriceps strengthening in patients with knee OA. The purpose of this study was (a) to investigate the clinical effectiveness of high-frequency LMV on quadriceps muscle in patients with knee OA and (b) to disentangle, by means of surface electromyography (sEMG), the underlying mechanism. Thirty patients, aged between 40 and 65 years, and clinically diagnosed with knee OA were included in this randomized, controlled, single-blinded pilot study. Participants were randomly assigned to two groups: a study group treated with LMV, specifically set for muscle strengthening (150 Hz), by means of a commercial device VIBRA, and a control group treated with neuromuscular electrical stimulation. Clinical outcome was measured using the Western Ontario and McMaster Universities Osteoarthritis Index, Visual Analogue Scale, knee range of motion, Timed Up and Go test, and Stair climbing test. To assess changes in muscle activation and fatigue a subgroup of 20 patients was studied with the use of sEMG during a sustained isometric contraction. The LMV group showed a significant change in Western Ontario and McMaster Universities Osteoarthritis Index score, Visual Analogue Scale score, Timed Up and Go test, Stair Climbing Test, and knee flexion. These improvements were not significant in patients treated with neuromuscular electrical stimulation. sEMG analysis suggested an increased involvement of type II muscle fibers in the group treated with LMV. In conclusion, the present study supports the effectiveness of local vibration in muscle function and clinical improvement of patients with knee OA. *International Journal of Rehabilitation Research* 00:000–000 Copyright © 2017 Wolters Kluwer Health, Inc. All rights reserved.

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Introduction

Knee osteoarthritis (OA) is a complex disorder due to multiple pathogenic biochemical and biomechanical factors. It is widely believed that, as quadriceps strength is pivotal in knee control as it attenuates knee joint shock during weight-bearing activities, its weakness is associated with a higher risk of developing knee OA (Bennell *et al.*, 2013; Fransen *et al.*, 2015; Øiestad *et al.*, 2015). Although scientific evidence emphasizes the importance of quadriceps strengthening in the prevention as well as in the rehabilitation of knee OA (Bennell *et al.*, 2016), studies on the efficacy of physical therapies in improving quadriceps muscle function are lacking, and basically related to the use of electrical stimulation and mechanical vibration. Neuromuscular electrical stimulation (NMES) is a well-established technique for quadriceps strengthening and has been used to treat patients with knee OA (Monaghan *et al.*, 2010; Vaz *et al.*, 2013). Vibration therapy has also been proposed as supplement to exercise in various rehabilitation settings in its two main forms: whole-body vibration and localized muscle vibration (LMV) (Casale, 2015). Whole-body vibration induced by means of oscillating platforms at a frequency not greater than 50–60 Hz has been hypothesized to increase sensitivity of the stretch reflex through stimulation of Ia-afferents (Cardinale and Bosco, 2003; Roelants *et al.*, 2004). However, higher vibration frequencies have been shown to be more appropriate in eliciting motor response (Eklund *et al.*, 1978), spinal and supra spinal reflexes (De Gail *et al.*, 1966; Bongiovanni and Hagbarth, 1990), in the activation of suprasegmental structures (Forner-Cordero *et al.*, 2008), and in the modification of motor command strategies (Casale *et al.*, 2009). High-frequency vibration can be reached only using mechanical as well as mechanoacoustic vibration devices locally applied.Although pieces of evidence suggest that high-frequency LMV applied on

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quadriceps function is effective both in healthy (Pamukoff *et al.*, 2016a, 2016b) and in patients after orthopedic surgery (Pamukoff *et al.*, 2016a, 2016b) and with OA (Rabini *et al.*, 2015), as far as we know the studies have neither compared the efficacy of LMV versus NMES nor the possible underlying neurophysiological mechanisms by means of surface electromyography (sEMG).The purposes of this study were (a) to investigate the clinical effectiveness of high-frequency LMV compared with a standard NMES of the quadriceps muscle in patients with knee OA and (b) to disentangle, by means of sEMG, the underlying neurophysiological mechanism.

The hypothesis is that the (possible) clinical improvement is due to a central more than a peripheral adaptation enhanced by LMV.

Patients and methods

Patients

Thirty consecutive patients were recruited for the present randomized, controlled, single-blind pilot study. Participants were chosen on the basis of the following inclusion criteria: (a) age between 40 and 65 years; (b) clinical diagnosis with knee OA according to the American College of Rheumatology criteria (Altman *et al.*, 1986); (c) no contraindications to execute maximal knee extension tests (e.g. cardiorespiratory complications); (e) no previous musculoskeletal surgery or joint injuries besides knee OA; and (f) no neurological problems. Data of patients are reported in Table 1.

Ethical issue

The study was approved by the Ethical Committee of the Principal Investigator Institution (no. 0021573), and it followed the Helsinki recommendations on nontherapeutic biomedical research involving humans. All participants were given careful explanation of the aim and methods used and consent was obtained to participate in the study. Before their enrollment they signed an informed consent form. Participants were free to withdraw from the study at any time.

Table 1 **Patient data**

		Whole group			Electromyography subgroup		
	Groups	*N*	Mean	SD	*N*	Mean	SD
Age*	Vibra	15	61.8	5.8	10	61.2	7.1
	NMES	15	55.7	9.1	10	56.7	7.9
BMI	Vibra	15	26.1	2.9	10	23.3	4.0
	NMES	15	26.0	2.8	10	26.6	2.8

		Whole group			Electromyography subgroup		
		N	Male (*n*)	Female (*n*)	*N*	Male (*n*)	Female (*n*)
Sex	Vibra	15	9	6	10	6	4
	NMES	15	5	10	10	2	8

NMES, neuromuscular electrical stimulation.
$^*P = 0.004$.

Intervention

Participants were randomly assigned to two groups using a random number generator: a study group, which was treated with LMV (150 Hz), and a control group treated with NMES. All patients were treated by the same physical therapist (L.C.) in an outpatient setting. No other physiotherapy was carried out in the timeframe of the study. Only paracetamol (maximum 3 g/die) was allowed as rescue therapy for pain.

In addition, 20 patients out of the 30 made themselves available to participate voluntarily in the sEMG study of the quadriceps muscle.

Vibration

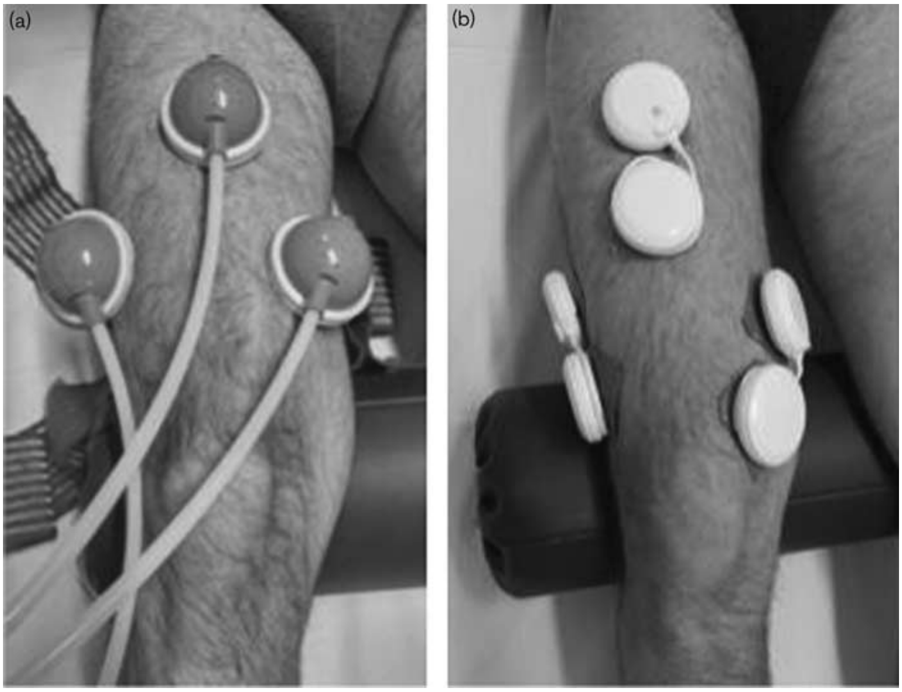
LMV at 150 Hz vibration frequency was chosen because high-frequency low-amplitude vibration was found able to selectively activate primary spindle endings in animals (Brown *et al.*, 1967) and in humans (Roland and Nielsen, 1980). A pneumatic vibrator powered by compressed air (Vibra Plus; A Circle s.p.a. Company, San Pietro in Casale, Bologna, Italy) with a range of utilization spanning between frequencies below 10 Hz to frequencies up to 300 Hz and more was used. The 150 Hz vibration was applied over the rectus femoris, vastus medialis, and vastus lateralis muscle bellies of the quadriceps by means of a cup-shaped transducer with a contact surface of 5 cm for 20 min. The transducer was kept in place with a nonelastic band wrapped around the limb with a constant contact force of 20–25 N.

Neuromuscular electrical stimulation

A commercial device (Compex wireless professional, DJO Italia, SRL, Trezzano sul Naviglio, Milano, Italy) was used on the quadriceps muscle of the control group. According to the most recent pieces of evidence for muscle strengthening (de Oliveira Melo *et al.*, 2013), a muscular reinforcement pattern was chosen, including (a) a ‘heating phase’ [low-frequency impulses (6Hz) for 2 min], (b) a ‘working phase’ [high-frequency impulses (85 Hz) for 4 s alternated with low-frequency impulses of 4 Hz for 8 s for a total of 15 min], and a ‘recovery phase’ [low frequency (3 Hz) for 3 min]. Pulse intensity was regulated at patient tolerance; pulse width was 350 μs. Three independent channels were used for rectus femoris, vastus medialis, and vastus lateralis using a constant rectangular current with pulse compensation to eliminate any direct current component to prevent residual polarization at skin level. Three independent channels were used for rectus femoris, vastus medialis, and vastus lateralis using a constant rectangular current with pulse compensation to eliminate any direct current component to prevent residual polarization at skin level.

Both LMV and NMES sessions, respectively, were administrated for 5 days a week for 2 weeks approximately at the same time of the day (morning) with the patient lying relaxed supine on a bed (Fig. 1). The lower

Fig. 1



Sketch of the muscular training setting: (a) localized muscle vibration transducer and (b) neuromuscular electrical stimulation electrodes on the quadriceps belly.

limb with the most painful knee OA was considered for treatment.

Clinical outcome measures

The Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) (Salaffi *et al.*, 2003) for the assessment of pain, stiffness, and functional limitation was used as primary clinical outcome measure. Furthermore, Visual Analogue Scale score for pain, knee flexion–extension range of motion (ROM), Timed Up and Go test (TUG) (Podsiadlo and Richardson, 1991), and Stair Climbing Test (ST -stair measure test) (Dobson *et al.*, 2013) were assessed.

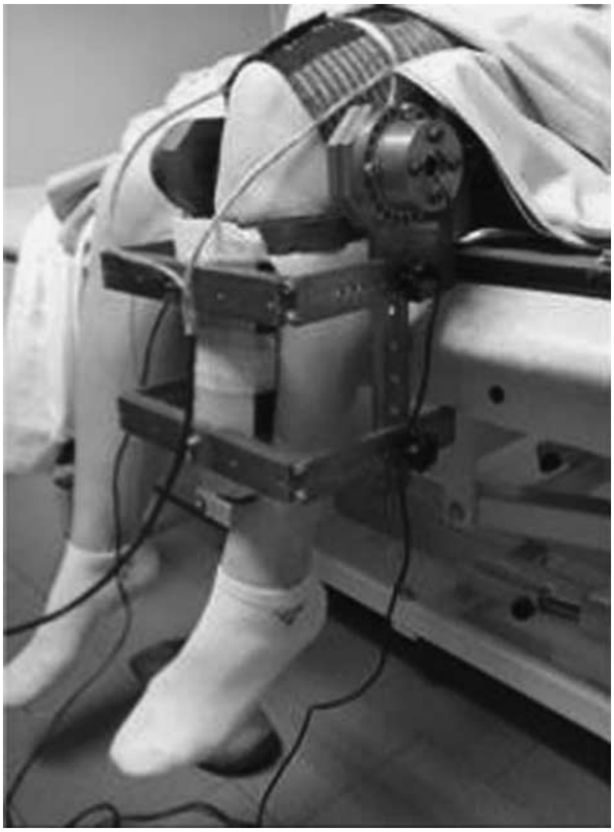
Surface electromyography measures

Each participant was seated in a comfortable chair with the lower limb intended for the treatment placed in an isometric brace (MISO1; LISiN Bioengineering Centre, Turin Polytechnic, Turin, Italy), which was equipped with two torque transducers (one on each side of the arm) connected to a display that provided the participant with visual feedback concerning the produced level of torque (Fig. 2).

The participants were asked to perform a brief (3–5 s) isometric extension contraction that allowed the quality of the myoelectric signals to match the criteria described in detail by Rainoldi *et al.* (1999), and then performed three 3 s maximum voluntary contractions (MVCs) under isometric conditions, separated by intervals of five minutes. The contraction with the highest force value was selected as the reference MVC, thus allowing submaximal targets to be set on the visual feedback display. After a further 5 min rest, the participants were asked to perform 30 s of voluntary contractions at 80% of MVC.

Electromyography (EMG) signals were recorded in a single differential configuration using linear electrode arrays composed of 16 electrodes [silver bars, 10 × 1 mm in size, 10 mm interelectrode distance; OT Bioelettronica, Turin, Italy (Merletti *et al.*, 2003)]. The skin was slightly abraded with abrasive paste and cleaned with water in accordance with SENIAM recommendations for skin preparation (Hermens *et al.*, 2000) before placement of the electrode arrays. Optimal position and orientation of the array was sought for each muscle by visual inspection of the EMG signals (Rainoldi *et al.*, 2004). The sites with clear muscle fiber action potential propagation and the main innervation zones were identified. The electrode arrays were then placed parallel to the muscle fibers where unidirectional propagation of the motor unit action potentials was detected. The EMG signals were amplified, sampled at 2048 Hz, bandpass filtered (3 dB bandwidth, 20–450 Hz, 12 dB/oct slope on each side), and converted to digital data with a 12-bit A/D converter (EMG-USB; OT Bioelettronica). Samples were visualized

Fig. 2



The isometric brace equipped with two torque transducers connected to a display used for surface electromyography during isometric contraction.

during acquisition and then stored on a personal computer using OT BioLab software, version 1.8 (OT Bioelettronica), for further analysis.

The EMG signals were visually inspected to select the best channels for estimating variables. The mean frequency of the power spectrum (MNF) and muscle fiber conduction velocity (CV) were computed off-line for each epoch of EMG signal, by means of numerical algorithms (Rainoldi *et al.*, 1999). We adopted non-overlapping signal epochs of 0.5 s, thus generating 60 estimates of each variable during the 30-s contraction. The CV was estimated among all accepted channels and computed as *e*/*d*, where *e* is the interelectrode distance and *d* is the delay time between the signals obtained from the two double differential arrays spaced 5 mm apart. The correlation coefficient between two adjacent double differential signals was calculated; if the correlation coefficient was less than 0.8, the recorded signals were excluded from the analysis. MNF estimates were averaged from the accepted channels.

Linear regression analysis was applied to the time course of the EMG variables as it has been demonstrated to be the best model to fit EMG data acquired during fatiguing contractions (Rainoldi *et al.*, 1999). The initial value of each EMG variable was calculated as the intercept of the regression line at time = 0 s, which is the first instant of muscle contraction when the exerted torque reaches the target level. The rate of change in the EMG variable was calculated as the ratio between the change in EMG estimate in each epoch and the initial value (expressed as %/s). The rate of changes in EMG estimates was used as indices of EMG manifestations of fatigue (for detail see Rainoldi *et al.*, 1999).

Statistical analysis

Sample size was calculated according to the minimal clinically important difference, mean score, and SD of WOMAC function subscale reported in Tubach *et al.*, 2005. A sample size of 15 cases per treatment arm was determined using an a priori model of power analysis and a two-sided alternative hypothesis, given $\alpha = 0.05$ and power $(1-\beta) = 0.80$. Clinical and sEMG measures were taken before initiating the treatment (T0) and 2 days after the end of the treatment (T1) (Table 2).

All continuous variables were expressed as mean ± SD. Delta scores were calculated for each participant and each continuous variable as follows: (T1–T0)/T0. Categorical variables (sex) were summarized in terms of frequency and contingency tables and the Fisher exact test was used to assess the difference between the two groups.

Two-way repeated-measure analysis of variance (two group × two time) was performed to test the effects of the treatments on continuous variables. Post-hoc analysis was conducted using *t*-test with Bonferroni correction to test differences between groups and between T0 versus T1.

As the sEMG measurements were performed on a subgroup of 20 out of 30 patients (10 patients for each group), we tested whether the sEMG group differed with respect to the whole sample using the belonging to the sEMG group as a covariate in the clinical analysis.

Statistical analyses were considered significant for *P* value of less than 0.05 and were performed using SAS/Stat software (version 9.3; SAS Institute, Cary, North Carolina, USA).

Table 2 **Time table of the session of treatments and measurements**

Days	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
LMV	■	■	■	■	■			■	■	■	■	■			
NMES	■	■	■	■	■			■	■	■	■	■			
Outcome measures	■														■
sEMG	■														■

LMV, localized muscle vibration; NMES, neuromuscular electrical stimulation; sEMG, surface electromyography.

Results

Clinical outcome

Patients in group NMES were relatively younger compared with patients in the group LMV ($P=0.004$). Sex distribution and BMI were not significantly different between the two groups. When the interaction time× group resulted significant, the LMV group showed better improvements compared with the NMES group (Fig. 3). In particular, LMV showed a significant decrease in WOMAC score ($P<0.001$), Visual Analogue Scale score ($P=0.004$), TUG ($P<0.001$), and stair climbing time ($P=0.001$) and an increase in knee flexion ($P=0.001$) (Table 3). These improvements were not significant in patients treated with NMES. No differences were found for the muscle force exerted in the isometric knee extension between the two groups and before and after the treatment. The group of 20 patients that underwent EMG measurements were not different in terms of age and BMI (Table 1) and showed similar outcome changes with respect to the whole sample (all $P>0.05$). No patient assumed paracetamol for pain throughout the duration of the treatment.

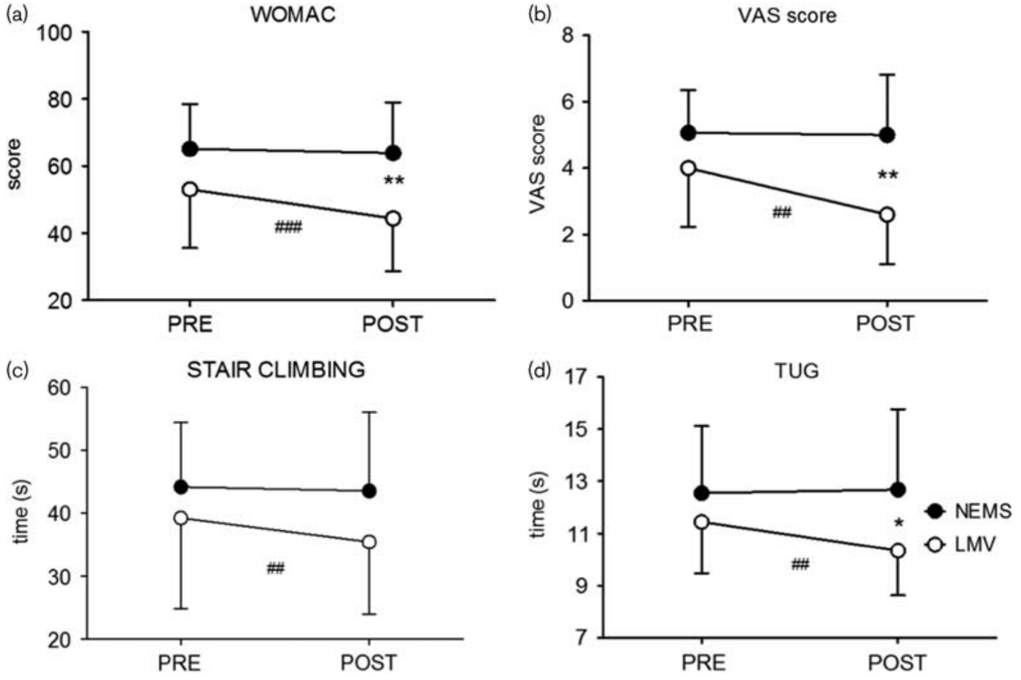
Electromyography outcome

The two-way repeated measure analysis of variance showed significant treatment×time interaction ($F=3.2$, $P=0.04$) for the rate of change in CV, but not for the rate of change in MNF ($F=2.4$, $P=0.12$). The rate of change in CV was not different between the two groups before treatment ($P>0.05$), whereas it was more negative ($P=0.03$) in LMV than in NEMS after treatment (Fig. 4a). Similarly, the rate of change in MNF was not different between the two groups before treatment ($P>0.05$), whereas it was more negative ($P<0.001$) in LMV than in NEMS after treatment (Fig. 4b). No significant treatment×time interaction was detected for the initial value of CV ($F=0.05$, $P=0.81$) (Fig. 4c), and for initial value of MNF ($F=2.4$, $P=0.2$) (Fig. 4d).

Discussion

Quadriceps weakness and reductions in function are commonly reported in knee OA patients (Bennell *et al.*, 2013; Øiestad *et al.*, 2015) and persists after knee surgery (Moon *et al.*, 2016). Land-based exercise have been recognized to be effective in lower limb muscle strengthening in OA, but the presence of pain often limits active exercise (Fransen *et al.*, 2015; Bennell *et al.*, 2016). Physical modalities, such as NMES, are considered a standard treatment in traditional muscle strengthening programs, although recent reviews have warned of a high risk for bias (Monaghan *et al.*, 2010). Vibration therapy has been introduced as alternative with the aim of providing muscle strengthening.

Fig. 3



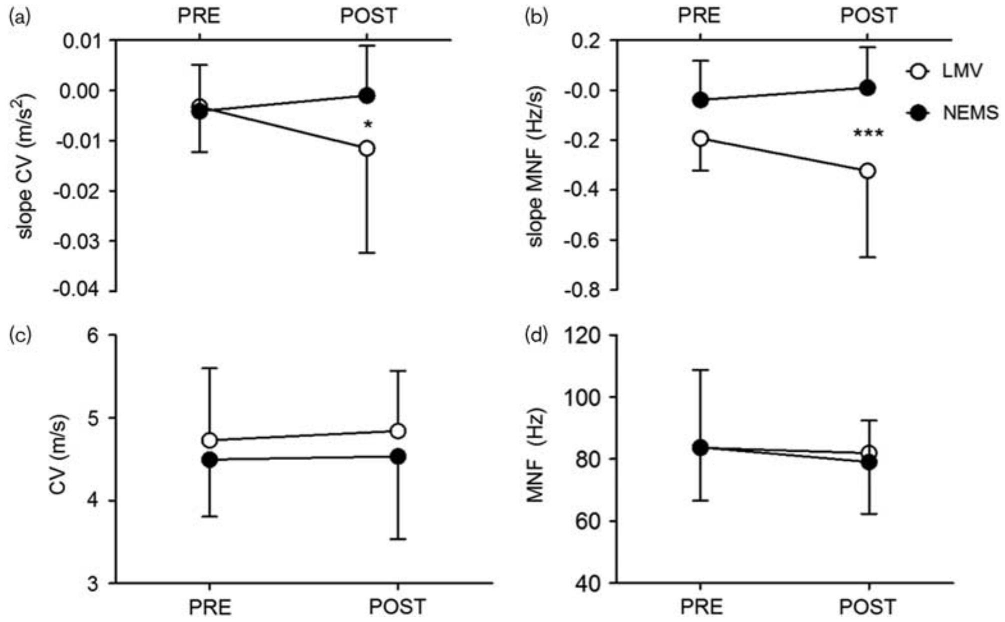
The Mean (SD) of clinical outcome measures at before and after treatment are ported for (a) WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index, (b) VAS, Visual Analogue Scale score, (c) Stair climbing, (d) TUG, Timed Up and Go test. Statistically significant differences between pre-treatment and post-treatment are reported as follow: $^{\#\#}P<0.01$, $^{\#\#\#}P<0.01$. Statistically significant differences between electromyostimulation (NEMS) and local muscle vibration (LMV) groups are reported as follow: $^{*}P<0.05$, $^{**}P<0.01$.

Table 3 **Values of the tests performed before (T0) and after (T1) the treatment**

Variables	Group	*N*	T0 [mean (SD)]	T1 [mean (SD)]	T1 − T0/T0 [Δ (SD)]	*P* value of T0 vs. T1	Time × group interaction
WOMAC	LMV	15	53.1 (17.5)	44.4 (15.7)	−8.7 (6.9)	**< 0.001**	*F* = 9.8, *P* = 0.004
	NMES	15	65.1 (13.3)	63.9 (15.1)**	−1.3 (6)	0.42	
VAS	LMV	15	4.0 (1.8)	2.6 (1.5)**	−1.4 (1.6)	**0.004**	*F* = 7.1, *P* = 0.01
	NMES	15	5.1 (1.3)	5.0 (1.8)	−0.1 (1.1)	0.81	
Knee extension force (a.u.)	LMV	10	3.0 (0.4)	3.2 (0.8)	0.2 (0.3)	0.40	*F* = 0.2, *P* = 0.62
	NMES	10	2.9 (0.5)	3.0 (0.7)	0.1 (0.3)	0.77	
Knee flexion (deg.)	LMV	15	129.7 (8.5)	134.0 (7.1)	4.3 (4.2)	**0.001**	*F* = 9.8, *P* = 0.004
	NMES	15	129.3 (9.0)	130.0 (8.0)	0.7 (1.7)	0.16	
Knee extension (deg.)	LMV	15	−1.7 (7.5)	−1.3 (4.8)	0.3 (4.0)	0.75	*F* = 0.5, *P* = 0.45
	NMES	15	−2.7 (4.9)	−1.3 (4.0)	1.3 (3.0)	0.10	
TUG	LMV	15	11.4 (2.0)	10.3 (1.7)*	−1.1 (1)	**< 0.001**	*F* = 16.5, *P* < 0.001
	NMES	15	12.5 (2.6)	12.7 (3.1)	0.1 (0.7)	0.60	
SCT	LMV	15	39.2 (14.4)	35.5 (11.4)	−3.7 (5.5)	**0.001**	*F* = 3.4, *P* = 0.07
	NMES	15	44.2 (10.2)	43.5 (12.4)	−0.7 (3.6)	0.66	

Mean (SD) of primary outcome WOMAC, and secondary outcomes Visual Analogue Scale (VAS) score for pain; knee extension force; knee flexion; knee extension; Timed Up and Go (TUG); stair climbing time (SCT); are reported. Statistically significant differences between T0 versus T1 are highlighted in bold. Statistically significant differences between the local muscle vibration (LMV) and the electromyostimulation [neuromuscular electrical stimulation (NEMS)] group are reported as follows:
*$P < 0.05$.
**$P < 0.01$.

Fig. 4



The mean (SD) of rate of changes (a, b) and initial values (c, d) in muscle fiber conduction velocity (CV) and mean power spectral frequency (MNF) of electromyography (EMG) signal are reported. The EMG indices were calculated from the vastus lateralis muscle over a 30 s knee extensors voluntary isometric contraction at the 80% of the maximal voluntary contraction (MVC). Statistically significant differences between the electromyostimulation (NEMS) and local muscle vibration (LMV) groups are reported as follow: *$P < 0.05$, ***$P < 0.001$. NMES, neuromuscular electrical stimulation.

In the literature there are some apparently conflicting results related to the application of LMV; although a study (Couto *et al.*, 2013) found that maximal voluntary contraction of the quadriceps improved after 4 weeks of 8 and 26 Hz LMV, other studies indicated that LMV causes a reduction in force output (Mottram *et al.*, 2006). These discrepancies have been related to the different parameters of stimulation used in terms of frequency and duration of the application (Casale *et al.*, 2009). In a laboratory setting, localized LMV was found to improve muscle functions since the late 80s (Casale *et al.*, 2009); however, only recently LMV has been introduced as a clinical tool to improve muscle force and reduce fatigue onset in healthy participants (Pamukoff *et al.*, 2016a, 2016b) as well as in the rehabilitation settings (Gusi *et al.*, 2006; Casale *et al.*, 2014; Constantino *et al.*, 2014; Murillo *et al.*, 2014; Sadeghi and Sawatzky, 2014). For these reasons, in this study the frequency of 150 Hz was chosen because high LMV has been shown to induce a reduction in muscle fatigue and an improvement in muscle contraction properties. When applied locally to the quadriceps muscle of a group of participants affected by knee

OA, high-frequency LMV showed a better efficacy compared with NMES enhancing physical function and improving neurophysiological parameters.

Accordingly to the research questions of the study, the overall meaning of the results and of the underlying mechanism of the improvement so far obtained in the LMV group will be discussed for each of the clinical functional and neurophysiological studied parameters.

Clinical outcome measures

Our data show an improvement in WOMAC index in the treated group, in agreement with the literature (Rabini *et al.*, 2015). Standing up from a sitting position and walking (TUG), and climbing stairs are two of the most used bed-side functional tests to assess participants with pain due to OA of the lower limb. They both are classified as activity indexes in the ICF domain. Although considered quite rough on stand-alone evaluation (Dobson *et al.*, 2012), when they are administered in a battery of evaluation they significantly correlate with the WOMAC Index: lower scores on the activity domain are associated with lower scores on the WOMAC Index (Lin *et al.*, 2001; Schoene *et al.*, 2013).

The improvements in the activity indexes is the functional results of the amelioration of the other clinical as well as sEMG parameters. In particular, it is not surprising that the application of a vibration provides a significant reduction in pain in the LMV group Actually, vibration is indicated for pain control with a much more specific mechanism of activation of the gate control compared with TENS because of its specificity in activating highly myelinated fibers (Lundeberg *et al.*, 1984; Salter and Henry, 1990a, 1990b), and therefore with a strong homotopic gating effect (Staud *et al.*, 2011).

Electrophysiological outcomes

During the isometric contraction EMG variables showed a decrement in CV and MNF over time, which are typical trends referred to as electrophysiological manifestations of fatigue (Rainoldi *et al.*, 1999).

Data pointed out that in the LMV group a larger decrease in CV over time (i.e. greater electrophysiological manifestations of fatigue) was observed compared with the NMES group. This finding is usually explained as a consequence of a larger recruitment (either in number or in firing rate) of type II muscle fibers (Kupa *et al.*, 1995). A previous work (Casale *et al.*, 2009) suggested that this adaptive response to the vibratory conditioning was more neuromediated compared with a direct effect on the muscle fiber composition. Notwithstanding, several previous studies interpreted differences in the rate of change in CV as alterations in muscle fiber composition due to physical training (Casale *et al.*, 2008), pathologies (Melchiorri and Rainoldi, 2008; Boccia *et al.*, 2016), and aging (Boccia *et al.*, 2015). Although the adopted protocol cannot disambiguate between neural and/or histological changes, an overall larger activation of type II fibers during the contraction can be speculated. In other terms a congruous vibratory stimulus applied for a reasonable length of time and during several days seems able to induce plastic rearrangement in the sensory motor system. From a neurophysiologic point of view the experimental protocol seems to indicate a long-lasting effect of vibration as the effects were statistically observable 2 days after the end of the vibration sessions. This is due to a functional variation in the sensory-motor coupling more than a morphological rearrangement (Casale *et al.*, 2009). This information, although limited in time, is relevant in the clinical setting in planning conservative as well as presurgery and postsurgery rehabilitation. These mechanisms could also explain the limited results obtained with NMES. Despite the large use of NMES alone or combined with other therapies in quadriceps strengthening in knee OA, its effectiveness is still debated, and experimental studies to include morphological and neural variables have been suggested to understand its action (de Oliveira Melo *et al.*, 2013).

Some limitations of the present study need to be discussed. The design of the study was basically that of a pilot study that aimed at originally exploring the mechanism of effectiveness of LMV on muscle from a neurophysiological point of view. Previous studies (Rabini *et al.*, 2015) demonstrated the effectiveness of local vibration in patients with knee OA only looking at physical functioning; sEMG used in the present study originally allowed disentangling the underlying mechanism of the clinical effectiveness of LMV. However, as the setup to correctly pick up the sEMG signal and to obtain the mean spectral frequency and the muscle fiber conduction velocity is quite complex, it was realistically decided to test it in a small sample of patients before extending its application to a wider population of knee OA patients. Moreover, age of patients was not homogenous in the two groups and it could represent a bias. For example, sEMG parameters might be affected by the age (Boccia *et al.*, 2015). However, as we calculated within-subject changes, this potential bias is mitigated.

Conclusion

Findings of the present pilot paper corroborate the hypothesis of neurophysiological central effects of local vibration, which reflect in clinical improvement of patients with knee OA. This effect was not seen for NMES. On the basis of the findings of the present study, further research in a wider sample of knee OA patients is guaranteed.

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Conflicts of interest

There are no conflicts of interest.

References

Altman R, Asch E, Bloch D, Bole G, Borenstein D, Brandt K, *et al.* (1986). Development of criteria for the classification and reporting of osteoarthritis. *Arthritis Rheum* **29**:1039–1049.

Bennell KL, Wrigley TV, Hunt MA, Lim BW, Hinman RS (2013). Update on the role of muscle in the genesis and management of knee osteoarthritis. *Rheum Dis Clin North Am* **39**:145–176.

Bennell KL, Hall M, Hinman RS (2016). Osteoarthritis year in review 2015: rehabilitation and outcomes. *Osteoarthr Cart* **24**:58–70.

Boccia G, Dardanello D, Rosso V, Pizzigalli L, Rainoldi A (2015). The application of sEMG in aging: a mini review. *Gerontology* **61**:477–484.

Boccia G, Coratella G, Dardanello D, Rinaldo N, Lanza M, Schena F, Rainoldi A (2016). Severe COPD alters muscle fiber conduction velocity during knee extensors fatiguing contraction. *COPD* **13**:583–588.

Bongiovanni LG, Hagbarth KE (1990). Tonic vibration reflexes elicited during fatigue from maximal voluntary contractions in man. *J Physiol* **423**:1–14.

Brown MC, Engberg I, Matthews PBC (1967). The relative sensitivity to vibration of muscle receptors of the cat. *J Physiol* **192**:773–800.

Cardinale M, Bosco C (2003). The use of vibration as an exercise intervention. *Exerc Sport Sci Rev* **31**:3–7.

Casale R (2015). Focal, local or segmental vibration? *Eur J Phys Rehabil Med* **51**:507–508.

Casale R, Rainoldi A, Nilsson J, Bellotti P (2008). Can continuous physical training counteract aging effect on myoelectric fatigue? A surface electromyography study application. *Arch Phys Med Rehabil* **84**:513–517.

Casale R, Ring H, Rainoldi A (2009). High frequency vibration conditioning stimulation centrally reduces myoelectrical manifestation of fatigue in healthy subjects. *J Electromyogr Kinesiol* **19**:998–1004.

Casale R, Damiani C, Maestri R, Fundarò C, Chimento P, Foti C (2014). Localized 100 Hz vibration improves function and reduces upper limb spasticity: a double-blind controlled study. *Eur J Phys Rehabil Med* **50**:495–504.

Constantino C, Galuppo L, Romiti D (2014). Efficacy of mechano-acoustic vibration on strength, pain, and function in poststroke rehabilitation: a pilot study. *Top Stroke Rehabil* **21**:391–399.

Couto BP, Silva HR, Filho AG, da Silveira Neves SR, Ramos MG, Szmuchrowski LA, Barbosa MP (2013). Acute effects of resistance training with local vibration. *Int J Sports Med* **34**:814–819.

De Gail P, Lance JW, Neilson PD (1966). Differential effects on tonic and phasic reflex mechanisms produced by vibration of muscles in man. *J Neurol Neurosurg Psychiatry* **29**:1–11.

De Oliveira Melo M, Aragão FA, Vaz MA (2013). Neuromuscular electrical stimulation for muscle strengthening in elderly with knee osteoarthritis – a systematic review. *Compl Ther Clin Pract* **19**:27–31.

Dobson F, Hinman RS, Hall M, Terwee CB, Roos EM, Bennell KL (2012). Measurement properties of performance-based measures to assess physical function in hip and knee osteoarthritis: a systematic review. *Osteoarthritis Cartilage* **20**:1548–1562.

Dobson F, Hinman RS, Roos EM, Abbott JH, Stratford P, Davis AM, *et al.* (2013). OARSI recommended performance-based tests to assess physical function in people diagnosed with hip or knee osteoarthritis. *Osteoarthr Cart* **21**:1042–1052.

Eklund G, Hagbarth KE, Torebjörk E (1978). Exteroceptive vibration-induced finger flexion reflex in man. *J Neurol Neurosurg Psychiatry* **41**:438–443.

Forner-Cordero A, Steyvers M, Levin O, Alaerts K, Swinnen SP (2008). Changes in corticomotor excitability following prolonged muscle tendon vibration. *Behav Brain Res* **190**:41–49.

Fransen M, McConnell S, Harmer AR, Van der Esch M, Simic M, Bennell KL (2015). Exercise for osteoarthritis of the knee: a Cochrane systematic review. *Br J Sports Med* **49**:1554–1557.

Gusi N, Raimundo A, Leal A (2006). Low-frequency vibratory exercise reduces the risk of bone fracture more than walking: a randomized controlled trial. *BMC Musculoskelet Disord* **7**:92.

Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol* **10**:361–374.

Kupa EJ, Roy SH, Kandarian SC, De Luca CJ (1995). Effects of muscle fiber type and size on EMG median frequency and conduction velocity. *J Appl Physiol* **79**:23–32.

Lin YC, Davey RC, Cochrane T (2001). Tests for physical function of the elderly with knee and hip osteoarthritis. *Scand J Med Sci Sports* **11**:280–286.

Lundeberg T, Nordemar R, Ottoson D (1984). Pain alleviation by vibratory stimulation. *Pain* **20**:25–44.

Melchiorri G, Rainoldi A (2008). Mechanical and myoelectric manifestations of fatigue in subjects with anorexia nervosa. *J Electromyogr Kinesiol* **18**:291–297.

Merletti R, Farina D, Gazzoni M (2003). The linear electrode array: a useful tool with many applications. *J Electromyogr Kinesiol* **13**:37–47.

Monaghan B, Caulfield B, O'Mathúna DP (2010). Surface neuromuscular electrical stimulation for quadriceps strengthening pre and post total knee replacement. *Cochrane Database Syst Rev* **1**:CD007177.

Moon YW, Kim HJ, Ahn HS, Lee DH (2016). Serial changes of quadriceps and hamstring muscle strength following total knee arthroplasty: a meta-analysis. *PLoS One* **11**:e0148193.

Mottram CJ, Maluf KS, Stephenson JL, Anderson MK, Enoka RM (2006). Prolonged vibration of the biceps brachii tendon reduces time to failure when maintaining arm position with a sub-maximal load. *J Neurophysiol* **95**:1185–1193.

Murillo N, Valls-Sole J, Vidal J, Opisso E, Medina J, Kumru H (2014). Focal vibration in neurorehabilitation. *Eur J Phys Rehabil Med* **50**:231–242.

Øiestad BE, Juhl CB, Eitzen I, Thorlund JB (2015). Knee extensor muscle weakness is a risk factor for development of knee osteoarthritis. A systematic review and meta-analysis. *Osteoarthr Cart* **23**:171–177.

Pamukoff DN, Pietrosimone B, Lewek MD, Ryan ED, Weinhold PS, Lee DR, Blackburn JT (2016a). Immediate effect of vibratory stimuli on quadriceps function in healthy adults. *Muscle Nerve* **54**:469–478.

Pamukoff DN, Pietrosimone B, Lewek MD, Ryan ED, Weinhold PS, Lee DR, Blackburn JT (2016b). Whole-body and local muscle vibration immediately improve quadriceps function in individuals with anterior cruciate ligament reconstruction. *Arch Phys Med Rehabil* **97**:1121–1129.

Podsiadlo D, Richardson S (1991). The timed Up & Go: a test of basic functional mobility for frail elderly persons. *J Am Geriatr Soc* **39**:142–148.

Rabini A, De Sire A, Marzetti E, Gimigliano R, Ferriero G, Piazzini DB, *et al.* (2015). Effects of focal muscle vibration on physical functioning in patients with knee osteoarthritis: a randomized controlled trial. *Eur J Phys Rehabil Med* **51**:3–20.

Rainoldi A, Galardi G, Maderna L, Comi G, Lo Conte L, Merletti R (1999). Repeatability of surface EMG variables during voluntary isometric contractions of the biceps brachii muscle. *J Electromyogr Kinesiol* **9**:105–119.

Rainoldi A, Melchiorri G, Caruso I (2004). A method for positioning electrodes during surface EMG recordings in lower limb muscles. *J Neur Meth* **134**:37–43.

Roelants M, Delecluse C, Goris M, Verschueren S (2004). Effects of 24 weeks of whole body vibration training on body composition and muscle strength in untrained females. *Int J Sports Med* **25**:1–5.

Roland PE, Nielsen VK (1980). Vibratory thresholds in the hands: comparison of patients with suprathalamic lesions with normal subjects. *Arch Neurol* **37**:775–779.

Sadeghi M, Sawatzky B (2014). Effects of vibration on spasticity in individuals with spinal cord injury: a scoping systematic review. *Am J Phys Med Rehabil* **93**:995–1007.

Salaffi F, Leardini G, Canesi B, Mannoni A, Fioravanti A, Caporali R, *et al.* (2003). Gonarthrosis and Quality Of Life Assessment (GOQOLA). Reliability and validity of the Western Ontario and McMaster Universities (WOMAC) Osteoarthritis Index in Italian patients with osteoarthritis of the knee. *Osteoarthr Cart* **11**:551–560.

Salter MW, Henry JL (1990a). Differential responses of nociceptive vs non-nociceptive spinal dorsal horn neurons to cutaneously applied vibration in the cat. *Pain* **40**:311–322.

Salter MW, Henry JL (1990b). Physiological characteristics of responses of wide dynamic range spinal neurons to cutaneously applied vibration in the cat. *Brain Res* **507**:69–84.

Schoene D, Wu SM, Mikolaizak AS, Menant JC, Smith ST, Delbaere K, Lord SR (2013). Discriminative ability and predictive validity of the timed up and go test in identifying older people who fall: systematic review and meta-analysis. *J Am Geriatr Soc* **61**:202–208.

Staud R, Robinson ME, Goldman CT, Price DD (2011). Attenuation of experimental pain by vibro-tactile stimulation in patients with chronic local or widespread musculoskeletal pain. *Eur J Pain* **15**:836–842.

Tubach F, Ravaud P, Baron G, Falissard B, Logeart I, Bellamy N, *et al.* (2005). Evaluation of clinically relevant changes in patient reported outcomes in knee and hip osteoarthritis: the minimal clinically important improvement. *Ann Rheum Dis* **64**:29–33.

Vaz MA, Baroni BM, Geremia JM, Lanferdini FJ, Mayer A, Arampatzis A, Herzog W (2013). Neuromuscular electrical stimulation (NMES) reduces structural and functional losses of quadriceps muscle and improves health status in patients with knee osteoarthritis. *J Orthop Res* **31**:511–516.