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Potentiation of muscle strength by focal vibratory stimulation on quadriceps femoris

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ABSTRACT. **Introduction:** ***Several studies have investigated the effects of focal vibration on muscle strength. Non-univocal results have been found.***
The aim of this study was to evaluate the effect of prolonged focal vibratory stimulation on quadriceps muscle strength at two different frequencies (80 and 300 Hz). The evaluation of muscle strength was performed at different intervals of time after the end of the vibratory stimulation in order to quantify the long-term effects and their trends over time.
Methods: ***Twenty-seven healthy volunteers were divided into three groups, a control group (no treatment) and two groups treated with vibratory stimulation (80 or 300 Hz) of relaxed quadriceps femoris bilaterally, once a day (30 min) for 5 consecutive days. The quadriceps' strength was measured through an isokinetic dynamometer, before and at three time intervals after the treatment, with a follow-up period of 4 weeks. The outcome measure was the Peak Torque (PT, Nm) of the quadriceps femoris produced by extension movement at three defined angular velocities and during isometric contraction.***
Results: ***No changes in PT were observed in the control group over time, while PT increased in the treated groups. No significant difference in PT behavior was observed between these two groups. PTs recorded before and after the treatment were markedly different ($p < 0.05$), and the increase in the PT persisted until the follow-up at 4 weeks, for all angular velocities tested.***
Conclusion: ***Prolonged vibratory stimulation of the quadriceps femoris, both at 80 and at 300 Hz, leads to an increase in muscle strength. The vibration effect does not appear to fade at the end of treatment, but persists at the follow up, suggesting a likely underlying plastic process.***
The results of the current study suggest that 30-min per day, 5 day focal vibratory treatment can be helpful during the clinical practice to regain muscular strength. It does not require patient's effort during the treatment, requires a little time, its effects are long-lasting, and there are no known adverse effects.

Key words: *vibration, healthy volunteers, quadriceps muscle, muscle strength, rehabilitation.*

RIASSUNTO. POTENZIAMENTO DELLA FORZA MUSCOLARE ATTRAVERSO LA STIMOLAZIONE VIBRATORIA FOCALE SUL QUADRICIPITE FEMORALE. ***Introduzione:*** **Molti studi hanno ricercato gli effetti della vibrazione focale sulla forza muscolare. I risultati ottenuti non sono univoci.**
Lo scopo di questo studio è quello di valutare gli effetti della stimolazione con vibrazione focale sulla forza muscolare del quadricipite femorale a due differenti frequenze (80 e 300 Hz). La valutazione della forza muscolare è stata effettuata in tempi diversi dopo la fine del trattamento con vibrazione al fine di quantificare gli effetti e verificare l'andamento nel tempo degli stessi.

Introduction

Vibration of muscle tendon or muscle belly elicits consistent firing in the afferent fibres from muscle receptors (1). The afferent discharge from the spindles, particularly from the large diameter Ia fibres, elicits a plethora of effects. A slowly developing tonic vibration reflex (TVR) is often observed in the vibrated muscle (2,3). This is accompanied by decreased excitability of the monosynaptic reflex elicited in the vibrated muscle by electrical stimulation or tendon tap (4,5), likely due to enhancement of presynaptic inhibition of the reflex arc (6-8). Interestingly, trains of low-intensity electrical stimulation of the muscle nerve, targeting large diameter fibres, elicits a tonic activity similar to TVR that is accompanied instead by an increase in the motoneurone reflex excitability (9).

Not unexpectedly, vibratory stimulation of the spindles, normally signalling muscle stretch, also elicits illusions of movement (10,11). These are associated with activation of the cortical motor and parietal areas (12,13). The perception of force and the sense of effort are also modulated by vibration (14-16). Vibration therefore exerts powerful effects both at spinal and supraspinal level, targeting circuits most relevant for the control of muscle action.

Several studies investigated the effect of focal vibration on muscle strength. The results are tightly constrained by the experimental conditions. During vibration, muscles produce less force than without vibration, both in the cat and man (80 Hz) (17,18). However, Warman et al. found improvement in quadriceps strength for concentric contractions during vibration (19). Low-frequency vibration (20 Hz) may decrease the endurance of maximal and sustained isometric muscular contraction (20,21). Others have shown that vibration (150 Hz) can indeed increase muscle force, but this is dependent on duration of vibration period and fatigue status of muscle (22,23), and may depend on inhibitory effects at spinal level interfering with the efficacy of the descending command. Maximal voluntary contraction and rate of force production decreased immediately after 30 min vibration (30 Hz) of the rectus femoris (24). In the same line, Jackson and Turner (25) found reductions in maximal force and maximum rate of force generation in quadriceps following 30 minutes of

Metodi: **Ventisette soggetti sani sono stati divisi in 3 gruppi, un gruppo di controllo (nessun trattamento) e due grupppi trattati con stimolazione vibratoria (80 o 300 Hz) su quadricipite femorale rilassato bilateralmente, una volta al giorno (30 minuti) per 5 giorni consecutivi. La forza muscolare è stata misurata con dinamometro isocinetico prima e a tre intervalli di tempo dopo il trattamento, con un periodo di follow up di 4 settimane complessivamente. La misura di outcome è il Peak Torque (PT, Nm) del quadricipite prodotto dal movimento di estensione di ginocchio a tre differenti velocità angolati e durante la contrazione isometrica.**
Risultati: **Nessuna variazione del PT è stata evidenziata nel gruppo di controllo nel corso del tempo, mentre il PT è aumentato nei gruppi di soggetti trattati. Non è stata osservata nessuna differenza significativa nel comportamento del PT in questi due gruppi. Il PT registato prima e dopo il trattamento è marcatamente differente ($p < 0.05$) e l'incremento del PT si mantiene al follow up a 4 settimane, per tutte le velocità angolari testate.**
Conclusioni: **La stimolazione vibratoria prolungata sul quadricipite femorale, sia a 80 che a 300 Hz determina un incremento della forza muscolare. Gli effetti della vibrazione non sembrano svanire al termine del trattamento, ma persistono al follow up, sottolineando un probabile sottostante processo di plasticità.**
I risultati del presente studio suggeriscono che un trattamento di 30 minuti al giorno per 5 giorni con vibrazione focale possono essere utili nella pratica clinica per il recupero della forza muscolare. Il trattamento non richiede sforzo da parte del paziente, impiega poco tempo, i suoi effetti sono di lunga durata e non si conoscono effetti avversi.

Parole chiave: vibrazione, volontari sani, muscolo quadricipite, forza muscolare, riabilitazione.

continuous vibration at 30 Hz and 120 Hz (30 Hz causing the greatest effect). Non-significant effects of vibration (50 Hz) superimposed to voluntary contraction have been found on peak isometric force, peak rate of force development, rate of force development of quadriceps (26).

Significant post-training effects were found when subjects were trained three times a week for 3 weeks with voluntary contraction upon which vibration (44 Hz) was superimposed (27). Others noted that vibration (30 Hz) superimposed upon resistance training did not enhance the increase in strength induced by resistance training alone (28). On the other hand, prolonged vibration (60 Hz) superposed to tonic contraction induced lasting (30 min) plastic changes, as assessed by motor potentials (MEPs) evoked by single or paired-pulse transcranial magnetic stimulation, whereas contraction alone caused no outlasting effects (29).

Filippi et al. (30) assessed the effects of prolonged (100 Hz, three 10-min sessions a day for 3 consecutive days) vibration treatment of the quadriceps in a group of sedentary young-elderly women, and showed that treatment improved stance control and lower limb muscle strength. Interestingly, their effects also persisted for a prolonged period of time after the end of the treatment. Brunetti et al. (31) used the same vibratory stimulation protocol in female volleyball players, and showed that treatment improved persistently muscle performance. The same authors tested the vibratory treatment in a group of postmenopausal osteoporotic women and confirmed that three administrations per day of mechanical vibration of quadriceps (100 Hz) improved muscle performance and counteracted demineralization (32). Significant, long-lasting improvement of muscle performance and hormonal responses has been reported by Iodice et al. after 300 Hz vibration treatment (33).

There are thus several reports attesting positive effects of focal muscle vibration on the force produced by voluntary contraction of the vibrated muscle. While vibration can be detrimental when applied during contraction, after-effects of prolonged vibration treatment certainly improve force-producing capacity. However, the exploited vibration protocols differed significantly, in terms of duration, repetition rate and frequency of the vibratory trains, and status of the vibrated muscle.

Hence, the present study aimed to evaluate the effects of the vibratory stimulation on quadriceps muscle strength in healthy volunteers at two different frequencies (80 and 300 Hz). The former is the optimal frequency for spindle activation, with greater effect on firing of large afferent fibres, the latter has been less frequently administered, possibly in the absence of a strong motivating hypothesis, but seems to produce effects (33). We have therefore compared the effects of both frequencies, delivered by such vibratory apparatus in two groups of healthy young subjects. Further, the strength of the quadriceps was assessed at different time intervals after treatment to quantify long term effects and the time-course of their development.

Materials and Methods

Subjects

The study was performed on 27 healthy volunteers, 15 males and 12 females aged between 20 and 28 years (mean: 22.25; DS: 2.69). No subject had disorders of the nervous, cardiovascular or musculoskeletal systems, either past or present. All the subjects enrolled gave their informed consent for participation in this research study according to the Declaration of Helsinki. The 27 subjects were divided into 3 groups each composed by 9 subjects (4 females for each group): non-treated subjects (controls); subjects who received bilateral vibration of the quadriceps femoris muscles at a frequency of 80 Hz; and subjects who received bilateral quadriceps vibration at 300 Hz. The three groups are matched for age, sex and bodyweight.

Vibration treatment

The conditioning procedure consisted in the application of local high-intensity vibrations using the Vibra Plus apparatus (a-circle, San Pietro in Casale, Italy). This device is a tool consisting of a compressor delivering mechanical-sound waves at frequencies from 30 to 300 Hz at pressure up to 540 millibar and in a series of applicators (up to n = 28) to be placed on the skin above the muscle transferring locally the acoustic waves. In this investigation, three applicators were placed on the thigh, bilaterally, in correspondence with the bellies of the vastus medialis, vastus lateralis and rectus femoris muscles, and kept adherent to the skin with elastic bands to ensure optimal conduction of the vibratory stimulus. Each applicator delivered a continuous train of vibration, lasting 30 min, at a peak oscillation pressure of 240 millibar. The two groups of subjects received this treatment on the same three heads of the quadriceps muscles of both legs, for the same time interval, the only difference being the frequency of vibration (80 or 300 Hz). Vibration amplitude did not change with the modification in frequency. Subjects were treated once a day for 5 consecutive days. During vibration, subjects were lying on an examination bed and their muscles were kept fully relaxed.

Examination

The tests were performed using the Cybex dynamometer (CSMi-Medical Solution, Stoughton, USA).

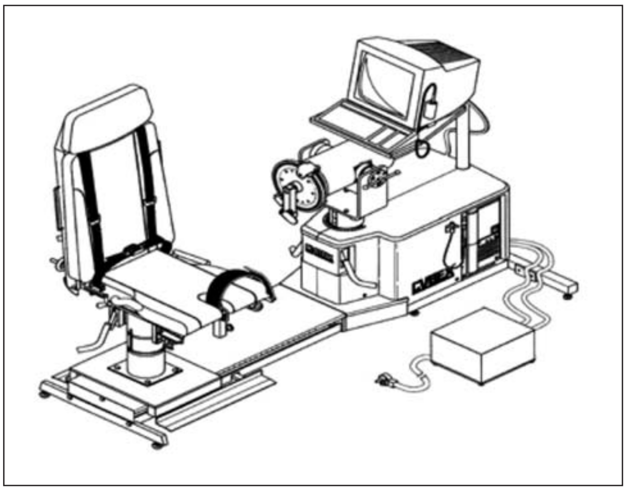

Figure 1. *Cybex dynamometer*

Prior to each test, all the subjects of the three groups carried out a warming-up series of stretching exercises of the femoral quadriceps for 10 minutes. Then, participants sat on the dynamometer seat with the trunk-thigh and the knee joint angles at 90°. The seat of the dynamometer was adjusted to match the center of rotation of the knee with that of the arm of the dynamometer. The length of the arm was adjusted to leg length, and set at the tibia's lower end. After placement of the subjects, the angle of excursion of the dynamometer arm was adjusted between full leg extension (0 deg) and maximum flexion (90 deg). Then, subjects were asked to perform 20 movements of flexion-extension of the knee to familiarize with the procedure. The recording session was divided into four successive stages, separated by two min rest. The first 3 epochs were characterized by 5 unilateral successive flexion-extension movements knee at maximum strength at angular velocities of 60 deg/s, 120 deg/s and 180 deg/s, respectively. Tests were separated by time intervals ranging from 30s to one minute. The fourth examination consisted in a series of 5 quadriceps isometric contractions producing maximal voluntary knee extensor efforts, each lasting about three seconds. At the end of the right-leg test, we proceeded in a similar way for the left leg. Overall, the evaluation session lasted about 1 hour. The highest value of torque attained among the five repeated tests per condition was taken as index of the contraction strength. Hence, the outcome measure was the maximal Peak Torque (PT) (in Nm) of the quadriceps femoris among those produced by each extension movement and by the isometric contractions.

The Peak Torque of the quadriceps femoris muscles was assessed in all subjects at different time-periods with respect to vibration treatment. The two treated groups underwent 2 evaluations pre-treatment (T0 & T1) and 3 evaluations post-treatment (T2 to T4). The pre-treatment assessments were carried out at T0 and after 2 weeks from T0 (T1). The post-treatment evaluations were made 2-3 h after the last application of vibration (T2) and 2 and 4 weeks thereafter (T3 and T4 respectively). This is explained in the scheme of Figure 1. The subjects of the control group were evaluated at the same time as the treated subjects.

Statistics

Mean PT values and standard error of the mean (SEM) are reported in the text. Statistical analysis was performed by means of repeated-measures ANOVA on different measures of the highest single value of peak torque (PT) for each limb, subject, time-interval of assessment, and angular velocity (60-120-180°/sec of knee extension or 0°s for isometric effort). When the main effects or the interactions were significant, post-hoc analysis was performed using the Turkey's HSD Test. The level of significance was set at $p < 0.05$ for both ANOVA and post hoc comparisons. Statistics were performed by means of the software Statistica (Statsoft, Tulsa, OK, USA).

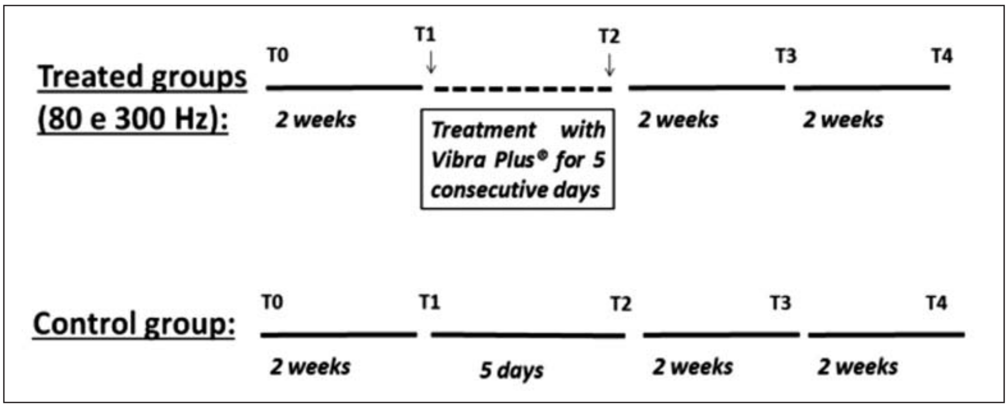

Figure 2. *A display of the protocol is sketched. The timing of the evaluation periods is reported for each group. Two distinct groups received the vibration (at 80 Hz and 300 Hz, respectively). The vibration administration lasted 30 min per day*

Results

The graphs in Figure 3 show a summary of the results. There was no statistical difference in the PT values of right and left leg for all angular velocities (F (1) 0.98, p = 0.33), so we took into account, for the analysis, the mean value of PT between the right and left leg.

Figure 3 shows that PTs were constant in the control group, regardless of the assessment times, but were different, as expected, as a function of the velocity of contraction. From the fastest extension to the isometric effort (0 deg/s), PT almost doubled. This pattern was stable at all assessment times. Moreover, in the two treated groups (80 and 300 Hz vibration frequency), PTs were not significantly different at T0 and T1 for all four velocities, while they increased at T2, T3 and T4.

Overall, PTs clearly increased in the treated groups all along the assessment times, with the same trend in both groups. Indeed, ANOVA for repeated measures showed a significant difference between the four angular velocities (F(3) 191.73, $p < 0.001$) and between times of evaluation (F (4) 22.59, $p < 0.001$) in both treated groups. There were also significant interactions between the time of evaluation and group (F (8, 96) 7.06, $p < 0.001$), between angular velocity and time of evaluation (F (12,288) 8.47, $p < 0.001$) and between angular velocity, time of evaluation and group (F (24, 288) 2.02, p = 0.004). The comparison between the two tested groups (80 and 300 Hz vibration frequency) revealed no significant difference (F(1,16) 0.38, p = 0.54).

In the 80 Hz group, the post-hoc test showed a difference in the PTs recorded at T2, T3 and T4 assessment times with respect to T0 and T1, for all angular velocities ($p < 0.05$ for all paired comparison). Within the 300 Hz tested group, the post-hoc test showed a difference between the PTs recorded at T3 and T4 assessment time with respect to T0 and T1 for 120°/s and 180°/s, and for PTs recorded at T2, T3 and T4 assessment times with respect to T0 and T1 for the other angular velocity 0°/s and 120°/s).

Notably, there was a mean improvement of PTs of about 30Nm between the T1 and T3 assessment times. Interestingly, in the two tested groups, at the T4 assessment time, there was a further improvement of PTs value with respect to T3 ($p < 0.05$) for all the angular velocity except for 120 °/s in the 80 Hz group. In this case, PT value remained stable.

Discussion

In the present study we showed that the peak torque (PT) produced by maximal voluntary contraction (MVC) under three isokinetic and one isometric contractions decreased linearly with increasing angular velocity. This was expected based on old and recent papers (34,35). Since there was no difference (p = 0.33) between the PT data collected for the right and left leg, we did not consider the side variable in the assessment of the treatment effects. Importantly, there was no difference in the PT of the control group (no treatment) across the five testing periods (falling in a range of seven weeks). On the one hand, this suggests a good repeatability of the isokinetic measurements (36), on the other, it bears witness to the absence of peak force enhancement solely due (no vibration) to the repetition of the isokinetic and isometric efforts (five trials per day per 5 testing sessions) or to improved motor skill coordination (37). These mechanisms might be responsible just for the inconstant increase in peak torque observed at the second testing session with respect to the first one, in all three subject groups, prior to any treatment.

Investigation of the mechanisms responsible for the increased muscle strength after vibratory stimulation was warranted, because of the controversial findings in the literature. Firstly, the aftereffects of prolonged proprioceptive stimulation on contraction force appear to be as diverse and complex and capable to affect many nervous functions, as those found during stimulation (38,39). A recent review paper attempts to list and discuss several of these effects, which include illusions of motion, postural imbalance, and disorders of orientation, and alteration in self-motion perception (40). Of major interest is that aftereffects can last well beyond the end of the vibratory stimulation. When it comes to contraction force, a recent animal investigation has shown that vibration (45 Hz) improves muscle contractility and force in mice with no ad-

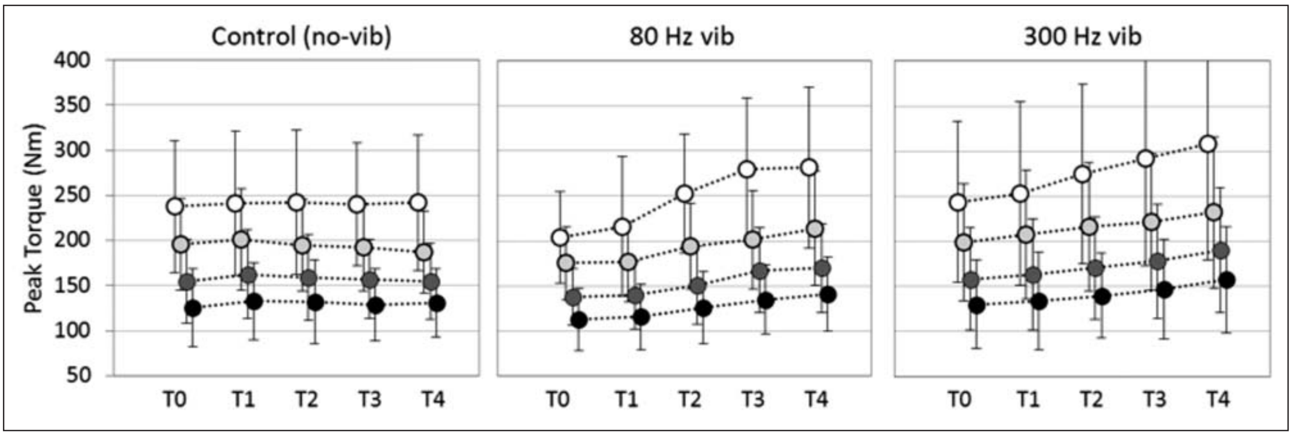

Figure 3. *Mean and SD of the PTs recorded during the extension phase of the knee for all groups of subjects and contraction velocities, and for all assessment times. White spot: 0 °/s; light grey spot: 60 °/s; grey spot: 120°/s; black spot: 180°/s*

verse effects to muscle function or cellular adaptations (41). In man, immediately after one bout (30 s) of 100 Hz vibration, maximal voluntary contraction may be reduced (42). However, repeating the vibratory stimulation in successive days can produce definite effects on muscle strength (43-45).

In our study the linear decrease of PT with increasing angular velocity was common to the three subject groups (no vibration treatment, 80 Hz vibration, 300 Hz vibration) and to the time-intervals of testing. Since there was no interaction ($p = 0.75$) between velocity and group, one can safely conclude that a vibration treatment of 30 minutes for 5 consecutive days (both frequencies) did not alter the fundamental force-velocity relationship of the quadriceps muscle.

Most interestingly, the vibration treatment increased the peak-torque value by about 30 Nm, computed as the average of the increment of the final values measured at T4 of the two treated groups. This increment is close to that observed as a consequence of electrical stimulation or short-term isokinetic and isotonic training in athletes, and is much larger than that observed after a single training session of two bouts of 5-maximal isokinetic contractions (46-48). Of note, this sizeable increase in force was obtained in spite of the vibrated muscles being fully relaxed during vibration.

Relevant to the working hypothesis is the absence of significant difference in the vibration effects between the two treated groups. The use of both 80 Hz and 300 Hz induced similar increments in peak torque, regardless of the leg, velocity or time of testing after the end of the vibratory treatment. The percent increment of peak torque as assessed at T4 (four weeks after the end of the treatment) was similar for the 80 Hz and 300 Hz group, ranging from 5 to 10 percent of the pre-treatment values, generally smaller for the 60 deg/s and larger for the isometric contraction. This similar effect of the two vibration frequencies may be not unexpected. A one-to-one firing of the Ia spindle afferent fibres can be elicited in response to up to 200 Hz vibration frequency according to diverse animal and human studies (49,50). Beyond that frequency, failure of some spindles to regularly follow the one-to-one ratio could be anticipated, due to the refractory period of the action potential when frequency increases above the optimal value (49). However, the ensemble volley originating from the muscle as a whole (from the entire population of the activated spindles) may overall not decrease, because the trough in the afferent train of a spindle may be well compensated by peaks, though short-lasting, of high frequency discharge of some other spindles. As a corollary, it would seem that, in order to produce the force-enhancing effect, the afferent discharge need not be steady, as it should be with frequencies around 80-100 Hz, because it is unlikely that 300 Hz induces a steady frequency of 300 Hz discharge in the spindle afferent fibres. As a non-alternative explanation, even in the case that the total spindle firing elicited by 300 Hz could eventually be stronger (higher discharge frequency and higher number of vibration-sensitive spindles) than that elicited by 80 Hz, one could speculate that sort of a ceiling effect ensues in the increment of force production, and justifies the non-superior outcome of the 300-Hz over 80-Hz vibration treatment. In fact, post-treatment peak torques reached, in our physically unfit subjects, values as high as 300 Nm, namely values not much below those recorded in athletes (51).

Also when considering the duration of the muscle potentiation after treatment, 80 Hz or 300 Hz showed a substantial similarity. We did not assess the persistence of the potentiation beyond four weeks, though. This would be advisable, because after four weeks potentiation was still on the rise, although the rate of change was weaker, in spite of our subjects being not involved in any maintenance scheme. Of course, we do not know the potential effect of the testing session at the 2nd week *per se* onto the measurements at the 4th week, but we would presume that only one recording session per week should be ineffective in augmenting prior strength gains (52). Of note, Pietrangelo et al. (53) evaluated the effects of focal vibration (300 Hz) on skeletal muscle trophism in a group of elderly volunteers diagnosed with sarcopenia, and showed that vibration was effective in reducing the loss of muscle mass in these persons. They revealed consistently high values of muscle strength in follow-up measurements until 16 weeks after the end of training. The intensity of their vibration treatment was lower, but its overall duration longer than that used in our study, so that the two studies might be reasonably compared. They found that vibration training induced several changes at the muscle molecular level, including up-regulation of genes encoding sarcomeric proteins. This might explain our slow build-up of strength and the persistence of the effects.

A recent study compared two different frequencies of focal vibration and showed an increase in upper limb motor performance, in terms of number of repetitions, mean velocity, peak velocity, in two groups of healthy subjects treated with focal vibration at 100 and 200 Hz; however, significant levels were reached only in the group receiving the higher frequency (54). We would not claim that 80 Hz and 300 Hz are completely equivalent and can equally be employed when muscle potentiation is searched. The effects found here have been obtained with vibration applied to relaxed muscles, but it is known that voluntary contraction enhances the response to vibration and that vibration treatment is more effective when the vibration train is superimposed to a contracted muscle (30,32,55,56). It would be appropriate to repeat the present experiments searching for differences between low and high vibration frequency and for interaction between frequency and muscle state.

Conclusion

In conclusion, we have shown that a vibration treatment, applied by means of three applicators put onto three heads of the quadriceps, and featuring a 80 Hz or 300 Hz vibration train lasting 30 min every day for 5 days, induces remarkable gains in quadriceps strength during maximal isometric or isokinetic contractions. The entity of the effect is comparable to that reported in the literature on other types of force training. The steady increase in muscle force in the three subsequent measurements after the vibration administration suggests a complex underlying plastic process. We would conclude that this mechanical treatment is useful to regain muscular strength. Current standard treatment for reducing structural and functional losses of muscle mass for immobilized patients is neuromuscular electric stimulation, although evidence of its efficacy is inconclusive (57-60). The focal vibration stimulation does not require patient's collaboration, it requires a reasonably short period, its effects are long-lasting, and there is no known or conceivable adverse effect. This treatment can be significant in the clinical practice, in particular for patients with prolonged bed rest. Focal vibration stimulation might become a potent supplement or alternative for neuromuscular electric stimulation, if the results of this study on healthy volunteers could be reproducible in patients as well; so further studies are necessary to investigate the effects on patients. Not unlikely, positive effects could be achieved with treatments of even shorter duration, but further studies are required.

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