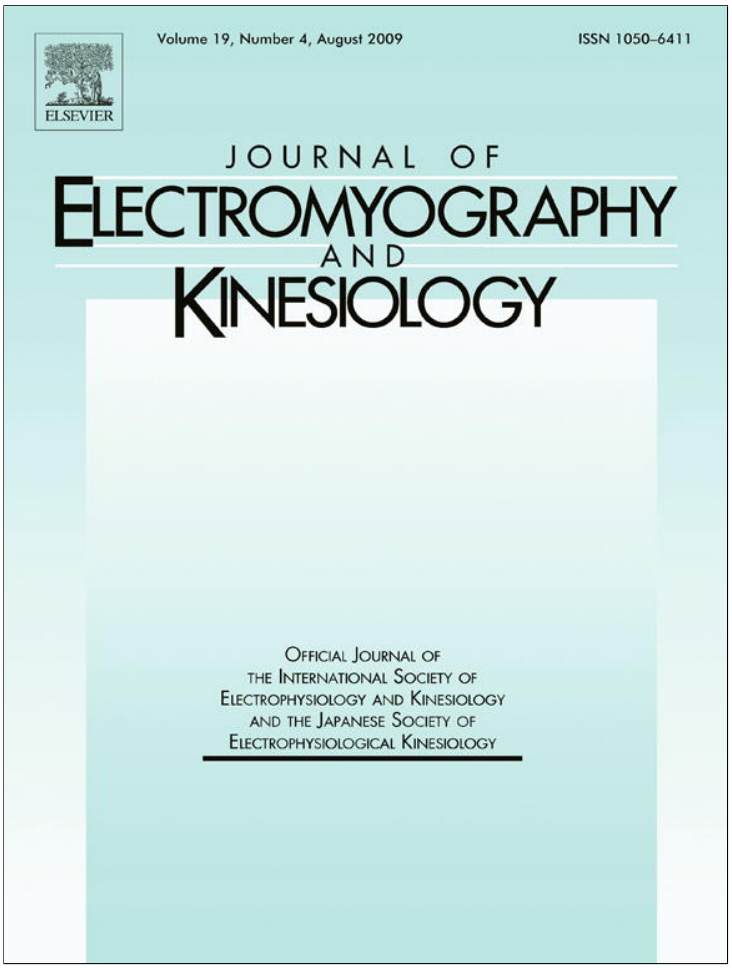

Available online at www.sciencedirect.com
ScienceDirect
Journal of Electromyography and Kinesiology 19 (2009) 710–718
JOURNAL OF ELECTROMYOGRAPHY AND KINESIOLOGY
www.elsevier.com/locate/jelekin

Relevance of motion artifact in electromyography recordings during vibration treatment

Antonio Fratini, Mario Cesarelli *, Paolo Bifulco, Maria Romano

Department of Electronic and Telecommunication Engineering, University "Federico II" of Naples, Via Claudio, 21, 80125 Naples, Italy

Received 31 October 2007; received in revised form 8 April 2008; accepted 8 April 2008

Abstract

Electromyography readings (EMGs) from quadriceps of fifteen subjects were recorded during whole body vibration treatment at different frequencies (10–50 Hz). Additional electrodes were placed on the patella to monitor the occurrence of motion artifact, triaxial accelerometers were placed onto quadriceps to monitor motion. Signal spectra revealed sharp peaks corresponding to vibration frequency and its harmonics, in accordance with the accelerometer data. EMG total power was compared to that associated with vibration harmonics narrow bands, before and during vibration. On average, vibration associated power resulted in only 3% (±0.9%) of the total power prior to vibration and 29% (±13.4%) during vibration. Often, studies employ surface EMG to quantitatively evaluate vibration evoked muscular activity and to set stimulation frequency. However, previous research has not accounted for motion artifacts. The data presented in this study emphasize the need for the removal of motion artifacts, as they consistently affect RMS estimation, which is often used as a concise muscle activity index during vibrations. Such artifacts, rather unpredictable in amplitude, might be the cause of large inter-study differences and must be eliminated before analysis. Motion artifact filtering will contribute to thorough and precise interpretation of neuromuscular response to vibration treatment.

Keywords: Vibration treatment; Electromyography; Motion artifact; Whole body vibration

1. Introduction

Whole body vibration treatment (WBV), or vibration treatment via the use of vibrating platforms, has recently begun to generate interest in the fields of exercise physiology and bone research. Recent studies indicate that mechanical and metabolic responses arise within the neuromuscular system when vibration loads are applied (Bosco et al., 1999, 2000; Mester et al., 1999). Many researchers have investigated the effect of vibration treatment and its possible clinical applications (Bautmans et al., 2005; Bosco et al., 1998, 1999; Homma et al., 1981; Issurin et al., 1994 and Kerschan-Schindl et al., 2001; Burke et al., 1996; Delecluse et al., 2003). In general, vibration treatment devices deliver vertical sinusoidal oscillations from 1 to 10 mm to a subject over a frequency range from 10 to 80 Hz (Mester et al., 2006; Cardinale and Wakeling, 2005). Throughout the treatment, the patient's body sustains vibrations transferred to various muscles or tendons, which may results in a reflex muscle contraction similar to the tonic vibration reflex (Verschueren et al., 2003). Vibrations may induce activity of the muscle spindle Ia fibers, mediated by monosynaptic and polysynaptic pathways (Roll et al., 1989; Romaiguère et al., 1991). WBV treatments subject vibrations to the patient's entire body, which generates mechanical stresses to muscle groups and soft tissues throughout the body. While soft tissues act as wobbling masses, vibrating in a damped manner in response to mechanical excitation, the neuromuscular system acts to dampen this soft tissue resonance that occurs in response to pulsed and continuous vibrations (Wakeling et al., 2001, 2002). Muscle response depends on muscle-tension, muscle or segment-stiffness, amplitude and frequency of the mechanical vibra-

* Corresponding author. Tel.: +39 081 768 3788; fax: +39 081 768 3804.
E-mail address: cesarell@unina.it (M. Cesarelli).

1050-6411/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jelekin.2008.04.005

tion (Wakeling and Liphardt, 2006; Wakeling and Nigg, 2001). However, it is very difficult to predict the actual stress delivered to a specific muscle due to the complex kinematics chain involved in this process.

Surface electromyography (SEMG) is a technique largely utilized to assess muscular response elicited by vibrations. As a concise quantitative index of muscle activity, the electromyography devices often report the root mean square (RMS) of the EMG signal. Many studies report a significant increase of EMG RMS values in the lower body muscles during vibration training, which often suggests an increase in neuromuscular activity (Cardinale and Lim, 2003; Verschueren et al., 2003). Further, specific WBV frequencies seem to produce a higher EMG RMS signal than others (Cardinale and Lim, 2003), while the frequency that maximizes the RMS corresponds to the highest muscular response (Bosco, 2001; Cardinale and Lim, 2003). A preliminary session can be dedicated to find the best vibration frequency for each subject (commonly a range of 10–50 Hz is explored at increasing steps of a few Hz). Nevertheless, it is well known that during surface biopotential recording, motion artifacts arise from the relative motion between electrodes and skin, between skin layers, and during skin stretching, which modifies the internal charge distribution, resulting in a variation of electrode potential (Turker, 1993; De Talhouet and Webster, 1996; Ödman and Åke Öberg, 1982; Searle and Kirkup, 2000; Tam and Webster, 1977).

Currently, literature focuses on the motion artifact as it pertains to clinical recording, such as ECG, EEG, EMG, electrical impedance pneumography, etc. In electrocardiography (ECG), motion artifact voltage amplitude can result in values ten times larger than the measured signal, which can be particularly troublesome either in ambulatory ECG recordings and or during exercise ECG testing (Holter monitoring or stress tests) (Clancy et al., 2001). Fortunately, as the typical power density of these types of artifacts is confined at very low frequencies, they can be largely attenuated using a high-pass filter (Clancy et al., 2002) with limited loss of signal content. Generally, these filters prevent motion artifacts from causing saturation of the recording apparatus. In classical clinical EMG recordings (isokinetic, isotonic, gait, etc.), the frequency content of motion artifact is also considered to be below 10–20 Hz; therefore, a high-pass filter is often applied (e.g. with a cut-off frequency of 20 Hz), resulting in minimal loss of the EMG signal power while rejecting most of the motion artifact (Hermens et al., 1999). However, in particular situations such as vibration treatment, the power of motion artifacts is not confined below 10–20 Hz and standard high-pass filters are not suitable for filtering out this artifact.

The aim of this study is to highlight the contribution of motion artifact in SEMG recordings during vibration treatment, focused precisely on leg quadriceps muscles. Presence of large motion artifacts, related to vibration frequency (clearly visible on SEMG signal), affects computation of the SEMG–RMS, which is often used as a quantitative index of muscle activity during vibration treatment. The introduction of motion artifact in SEMG recordings leads to errors in estimation of muscular activity elicited by vibration treatment.

2. Materials and methods

2.1. Subjects

Fifteen healthy males (age 24.6 ± 4.9 years, height 175.17 ± 5.83 cm, weight 74.17 ± 9.09 kg), not affected by any known neurological or musculoskeletal disorders, voluntarily participated in the study and gave their informed, written consent to participate. All of the subjects were not athletically trained, while nine of them were lean and the remaining participants were muscular.

2.2. System set-up

A vibrating platform (TSEM S.p.A., Padova – Italy) was used to deliver vibration to the patients. The platform used was modified, for our purposes, by the manufacturer to allow remote control of the principal parameters (i.e. vibration frequency and intensity) from an external PC. Vibrations impressed by the platform were exclusively vertical (there was neither a horizontal shift, nor pitch, roll or yaw) and the platform displacement was sinusoidal with an intensity (peak-to-peak displacement) set to 1.2 mm and a frequency ranging from 10 to 80 Hz. With the peak-to-peak displacement constant, the maximum acceleration impressed upon the patients was proportional to the square of the pulsation.

2.3. Data recording and processing

Before recording, the subjects were instructed about proper positioning on the platform (hack squat with a 100° knee flexion), and they were familiarized with the device. No constraint was used during testing. Signals from the vastus medialis (VM), rectus femoris (RF) and vastus lateralis (VL) of the dominant leg were collected. In addition, two supplementary electrodes were mounted on the patient's patella to assess the nature and magnitude of motion artifact on recordings, under the hypothesis that no EMG contribution would be measured at this site (see Fig. 1). Signals were recorded using small disc Ag/AgCl electrodes (5 mm in diameter, inter-electrode distance of 20 mm arranged in the direction of the muscle fibres). The areas of skin exposed to the electrodes were shaved and cleaned before the placement of electrodes and conductive paste was used. In accordance with the guidelines of SENIAM project (Hermens et al., 1999) two electrodes were placed at 80% on the line between the anterior spina iliaca superior and the joint space in front of the anterior border of the medial ligament, perpendicular to the same line to record VM signal. Further, two electrodes were placed at 50% on the line from the anterior spina iliaca superior to the superior part of the patella, in the direction of the same line to record the RF signal. Finally, the VL activity was collected using two electrodes placed at 2/3 on the line from the anterior spina iliaca superior to the lateral side of the patella in the direction of the muscle fibres. Patellar electrodes were arranged vertically using the same inter-electrode distance (see Fig. 1). All the electrodes and cables were secured by adhesive tape to prevent the cables from swinging and from causing induced artifact. A reference electrode was placed

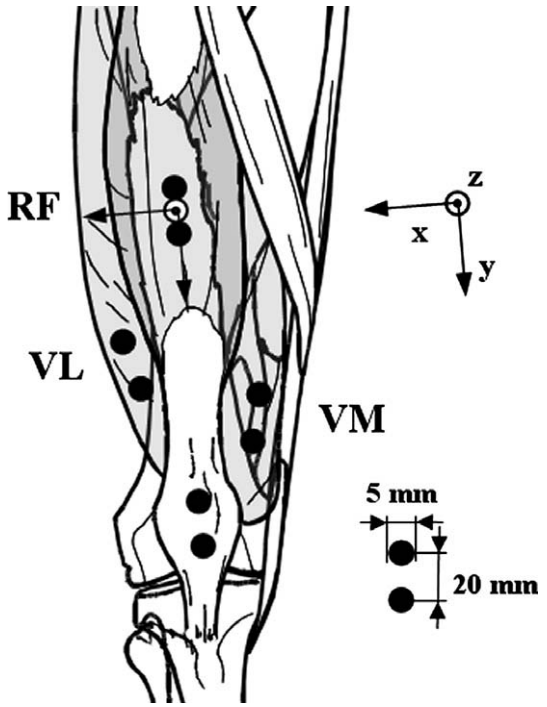

Fig. 1. Electrodes and accelerometer arrangement; EMG signals from the vastus medialis (VM), rectus femoris (RF), vastus lateralis (VL), and signal from the patellar tendon were recorded before and during vibration treatment. Couples of skin Ag/AgCl electrodes for biopotential, with an inter-electrodes distance of 20 mm, positioned as in the figure, were utilized for the acquisition. Three-axial accelerometer (the axes were positioned as described in figure) was used to measure accelerations and discover their relationship with the vibration frequency and the motion artifacts.

on the ankle of the same leg being measured. EMG signals were amplified using a multi-channel, isolated biomedical signal amplifier (Biomedica Mangoni, Pisa, Italy – model. BM623; input impedance > 10 MΩ; CMRR > 100 dB). The gain was set to 1000 V/V and a band pass filter (−3 dB frequency 10–500 Hz) was applied; no notch filters were used to further suppress line interference.

A tiny and lightweight (less than 10 g) three-axial MEMS accelerometer (Freescale semiconductors) was placed on the patient's skin, as close as possible to the electrodes, in order to measure accelerations on the skin at the RF EMG electrodes level (Fig. 1). The sensor was set to measure accelerations within a ±6 g range and the signal was pre-processed in order to exclude the influence of gravity in this study. Acceleration signals provide information related to the patient's RF muscle belly oscillation. A PC multi-channel 16-bit data acquisition card (National Instruments DAQCard 6251) was used to acquire SEMG and acceleration signals and to drive the vibrating plate. Specific software was designed using the Lab-Windows/CVI (National Instruments) environment to collect and analyze all the data. All signals were sampled at 1536 Hz, while a set of consecutive 20-second vibrations at different frequencies: 12.8, 17.9, 23.3, 28.5, 33.9, 39.2, and 44.5 Hz, spaced with 60 s rest intervals, was delivered to patient. During rest intervals, the patient stood and resumed the hack squat position ten seconds prior to application of the stimulus. In minimizing fatigue-related effects, the vibration frequencies order was randomized.

To quantify motion artifact influence on EMG RMS (the most reported concise parameter), RMS values were computed before and after artifact suppression. Running RMS was estimated using a 500 ms time window. Motion artifact components on recorded EMG signals were filtered out using a set of standard notch filters (Matlab iirnotch.m was used with a −3 dB band of 1.5 Hz) centred on the applied vibration stimulus frequency and its harmonics.

In order to estimate power contribution of the noise (motion artifact) with respect to the total power of the recorded signal, the power associated with the motion harmonic components and the total signal power before and after vibration onset was calculated. The EMG power spectrum was computed on the 20 s signal segments (in which the vibratory stimulation was present) using a standard PSD MATLAB® algorithm. The algorithm estimates the power spectral density of a discrete-time signal using Welch's averaged, modified periodogram method. EMGs were divided into overlapping sections, each of which was de-trended and windowed with a Hamming window; the length of each signal section was set to 5 s and the overlap was set to 50%.

Noise power was calculated considering only three narrow bands (1.5 Hz wide) centred at f_0, $2f_0$, $3f_0$ where f_0 is the applied vibration frequency. Defining the power in the three mentioned narrow bands as *noise power* and the remaining power (out of them) as an estimation of the *signal power*, we developed a signal to noise ratio as:

$$\mathrm{SNR} = \frac{Ps - Pa}{Pa}$$

where *Ps* represents the *signal power* and *Pa* the *noise power*. In the absence of vibration stimuli, it was assumed that noise was a small part of the total EMG power. As shown in Table 1, the

Table 1
SNR of the surface electromyography recordings (see text)

Muscle	Frequency (Hz)	Mean (±SD)	Minimum values	Maximum values
VM				
	12.8	20.33 (±13.22)	3.79	44.90
	17.9	13.00 (±14.05)	0.89	44.63
	23.3	9.06 (±14.15)	0.69	43.89
	28.5	4.14 (±4.73)	0.55	18.05
	33.9	4.16 (±4.67)	0.47	12.84
	39.2	3.16 (±2.57)	0.52	7.89
	44.5	3.55 (±3.35)	0.23	9.91
RF				
	12.8	17.47 (±10.28)	3.66	37.92
	17.9	25.87 (±39.89)	0.33	143.85
	23.3	13.93 (±16.62)	0.08	58.88
	28.5	7.58 (±9.36)	0.18	31.50
	33.9	6.71 (±7.71)	0.23	27.34
	39.2	5.13 (±5.42)	0.25	14.11
	44.5	4.81 (±5.83)	0.07	14.88
VL				
	12.8	25.93 (±18.41)	3.26	75.48
	17.9	15.38 (±8.47)	3.08	37.14
	23.3	7.06 (±3.49)	1.15	12.68
	28.5	4.76 (±4.19)	0.67	16.82
	33.9	3.79 (±3.79)	0.46	15.25
	39.2	2.96 (±2.97)	0.28	10.95
	44.5	3.65 (±3.13)	0.42	9.65

Subjects held hack squat position.

noise power consistently resulted as less than 5% of the total power. In the presence of vibration, the artifact power was slightly overestimated. Standard mean (MNF) and median (MDF) frequency of EMG spectra were also computed to assess variations associated with vibration.

3. Results

Fig. 2 represents a typical example of the recorded signals during a vibration onset test. Biopotential signals were recorded from VM, RF, VL and the patella, as described above, by the three acceleration components (for x, y and z axes orientation see Fig. 1). When subjects assumed the hack squat position, EMG signals increased with muscular activity due to the maintenance of the position, while the patella signal remained almost negligible. After the onset of vibration, EMG and patellar signals increased in amplitude. The power spectrum densities showed, within the selected narrow bands, similar behaviour to that of the accelerometer signals. The first harmonic exactly corresponded to the mechanical vibration frequency of the platform. These data suggest that the electrical signal recorded by the skin electrodes was directly related to the mechanical vibration. Important to note, the detected acceleration on the patient's leg always displayed superior harmonics. Hypothetically, the presence of higher harmonic components is an effect of the non-linear mechanical behaviour of soft tissues. However, in our study, only the first three harmonics are visible. Vibration-induced artifact clearly appeared in SEMG recordings (especially on VM, in the Fig. 2) after the onset of the stimulus. Before vibration, when the subject was holding the hack squat position, the recorded signal amplitude was relatively small and showed a typical surface EMG interference pattern. During vibration, the power spectra clearly showed sharp peaks in correspondence to the mechanical frequency and its harmonics, similar to those recorded on the patella.

Interestingly, the artifacts related to the vibration frequency and its harmonics fell within the standard surface EMG frequency band (a standard high-pass filter would be not suitable). In our study, only the first three harmonics were significant; therefore, noise power was calculated in those narrow bands (1.5 Hz wide) centred at f_0, $2f_0$, $3f_0$ where f_0 is the applied vibration frequency. Fig. 3 reports the percentage of the total signal power contained in the mentioned bands, computed before and during the stimulus. When the subject held the hack squat position, the signal only contained the spontaneous surface EMG while a negligible contribution was also recorded at the site of the patella. It was determined that the percentage of power content in those bands statistically represented less than 4% of the total power (on average). Furthermore, the standard deviation between subjects, in regard to the percentage of

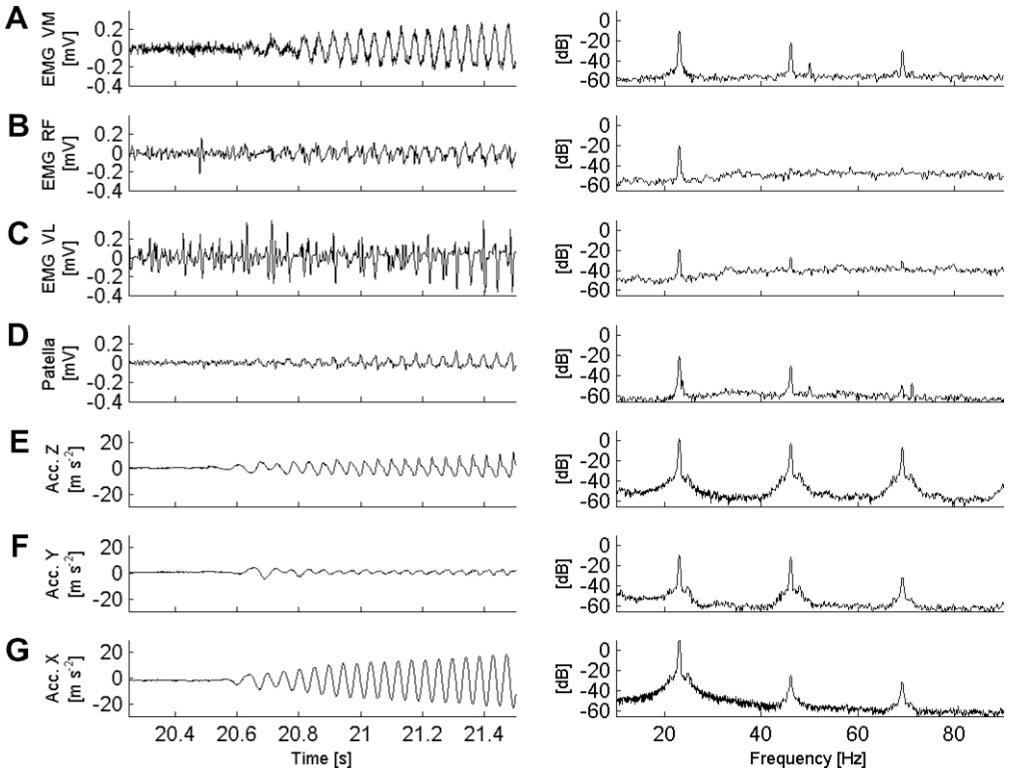

Fig. 2. Example of surface biopotential and acceleration recordings during vibration treatment. Biopotentials are recorded from vastus medialis (A), rectus femoris (B), vastus lateralis (C). Additionally, biopotential signal from patella (D) was recorded. Acceleration signals come from the MEMS accelerometer (x, y and z direction) placed onto rectus femoris belly (E–F–G). They are shown for the direction normal to the skin surface (G), parallel to the femur (F), and mediolateral (E). Power spectral density of the signals is also presented on the right in $dB^2_{mV/Hz}$. Here the excitation frequency was 23.3 Hz. Spectra were computed on a time interval of a 20 s after the vibration onset (relative only to the vibration period).

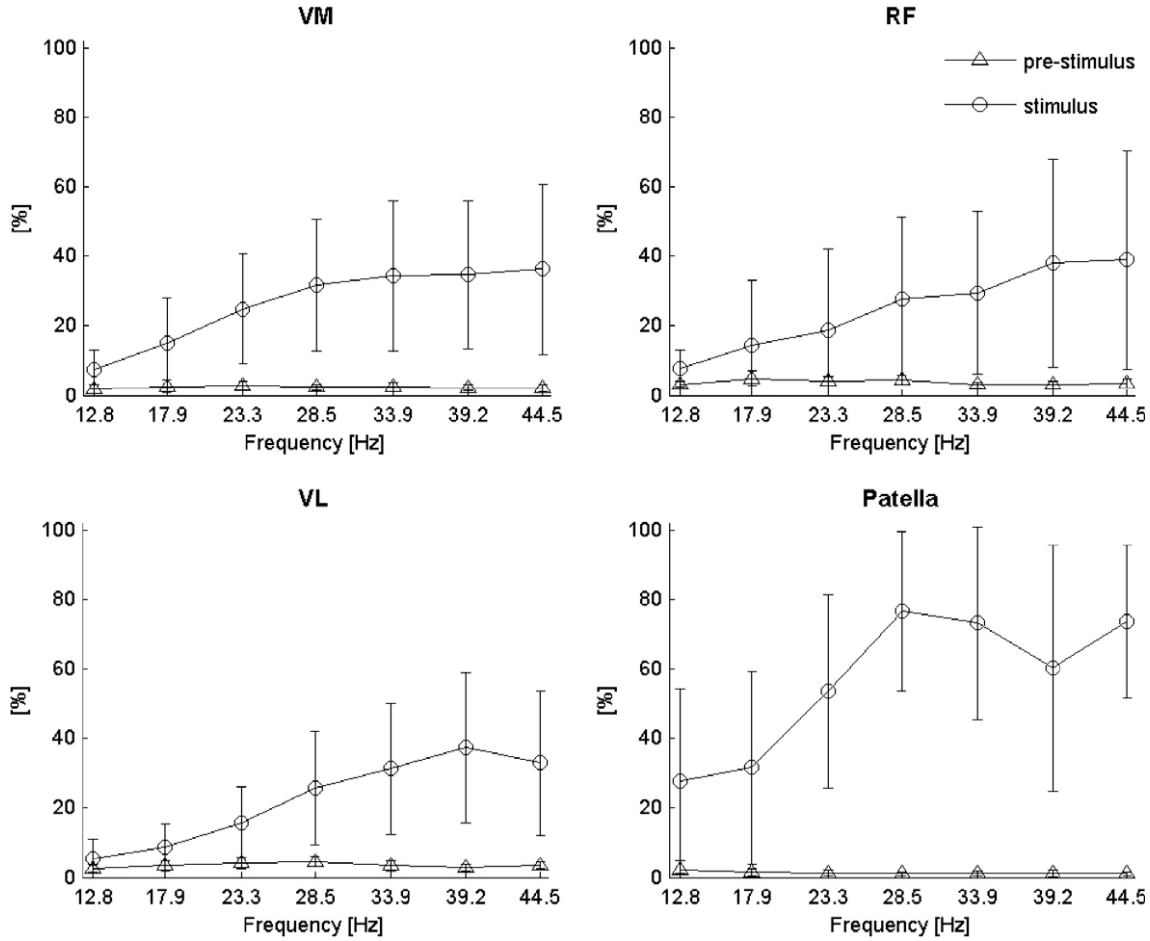

Fig. 3. Power percentage contained in the three narrow bands (1.5 Hz wide) centred at f_0, $2f_0$, $3f_0$ before and during vibratory stimulation. Signals from vastus medialis (VM), rectus femoris (RF), vastus lateralis (VL) and patellar (Patella) electrodes are analyzed.

power content in the measured bands only, ranged from 0.7% to 2.2% (on average).

After the onset of vibration, power related to the three considered bands increased significantly. Fig. 3 displays the measured increase. Percentage of power content in the three bands resulted in 24.7% on average, reaching a maximum of 81.9%. Moreover, inter-subject standard deviation increased, ranging from 5.3% to 31.4%. Further, the variability between subjects was found to be minimal at lower frequencies and was noted to increase with increasing stimulation frequency. In order to provide a quantitative comparison of the power content amongst the measurements during vibration, the power relative to the three narrow bands of EMGs and the patellar signal was compared, as shown in Fig. 4. Average power values and standard deviations were computed for all subjects over the entire frequency range of the vibration stimulus. EMG power amounts result comparable with that of the patella. Both the EMG and patella power were seen to increase with increasing frequency. As previously reported, power in the three mentioned narrow bands is referred to as *noise power* and the remaining power as an estimation of *signal power*.

Unfortunately, the SNR values measured were extremely variable and resulted in measurements at or below the value of one, as displayed in Table 1. With this unreliable data, the fidelity of the SEMG (Roy et al., 2007) could not be ensured. RMS values of surface EMG during vibration testing were seen to differ significantly between filtered and unfiltered signals. A paired *t*-test was performed to examine the statistical significance of the RMS values before and after artifact filtering. The test confirmed separation of the two RMS classes with a significance $p < 0.01$.

Results showed that the EMG RMS value computed from the filtered signal (once the motion artifact was suppressed) can be reduced by up to 30%, on average (up to 45% in some cases), which indicated that the power of motion artifact was not negligible with respect to SEMG activity (Fig. 5). The analysis of MNF and MDF did not show considerable variation (less than 5%) with respect to stimulation frequency either for the filtered signal or the unfiltered signal.

4. Discussion and conclusion

While the vibration treatment has recently grown in the areas of sports and rehabilitation medicine (Flieger et al., 1998; Rubin et al., 2001, 2004; Issurin and Tenenbaum, 1999; Torvinen et al., 2002), there are significant caveats

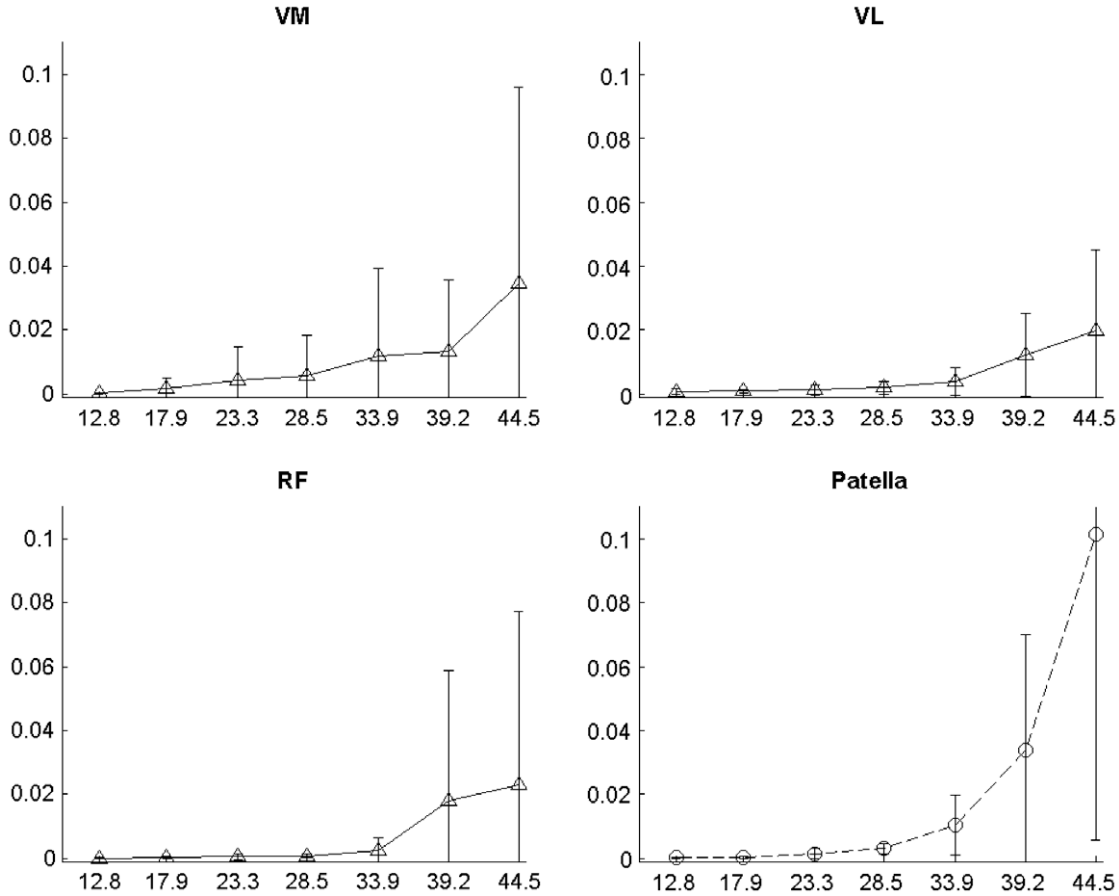

Fig. 4. Power contained in the three narrow bands (1.5 Hz wide) centred at f_0, $2f_0$, $3f_0$ during vibratory stimulation. Signals from vastus medialis (VM), rectus femoris (RF), vastus lateralis (VL) and patellar (Patella) electrodes are analyzed.

to this technique and its effectiveness is questionable. Interaction of the human body with applied vibrations is extremely complex and is a function of multiple variables. The actual kinematics chain, through which mechanical vibration propagates in the body, strongly depends on subject anatomy, positioning and physiological condition; in addition, individual muscle conformation and soft tissue properties also alter mechanical characteristics (e.g. resonance and dumping). In order to customize vibration treatments, the patient's EMG signal is often considered as an estimation of specific muscle activity. Use of concise EMG parameters (e.g. RMS) is a common practice to dictate the proper stimulation frequency as well as the vibration effectiveness during the treatment. However, motion artifacts consistently hamper the collection of raw SEMGs. The measured EMGs power spectra clearly showed sharp peaks in correspondence to the mechanical frequency and its harmonics, similarly to those recorded on the patella.

Previous studies about tonic vibration reflex focused on the observation of single motor unit behaviour during vibratory stimuli (Romaiguère et al., 1991; Person and Kozhina, 1992). A certain synchronization with tendon taps of some specific motor units, presumably due to a monosinaptic reflex, was found in these studies. Other researchers reported that surface EMG power spectrum contains characteristic peaks at the vibration frequency and its harmonics, which may depend on motor unit synchronization (Lebedev and Polyakov, 1992; Martin and Park, 1997). Nevertheless, our results demonstrated that the power spectrum of the considered narrow bands of the patella was comparable to that of the EMG, suggesting a significant presence of motion artifact on the EMG. This data provides evidence that analysis of muscular activity during vibration, based on unprocessed EMG RMS signal, may significantly overestimate muscle response. Therefore, filtering out the motion artifact would possibly prevent misinterpretation of experimental results. Analysis of the results also suggested the need for specific filtering before any other parameter estimation (Cutmore and James, 1999). As demonstrated by our results, vibrations generated variable motion artifact on skin electrodes in all the quadriceps muscles analysed (vastus medialis, rectus femoris and vastus lateralis). Interestingly, the motion artifacts were measured at different amounts in the quadriceps muscles, which could be indicative of interference by local skin layers or electrode motion. Furthermore, the SNR measurements, one of the required parameters in EMG data reporting as mentioned in "standards for reporting EMG data" (Merletti, 1996), resulted in low values. Theoretically, high SNR values should correspond to the ability to use unprocessed data.

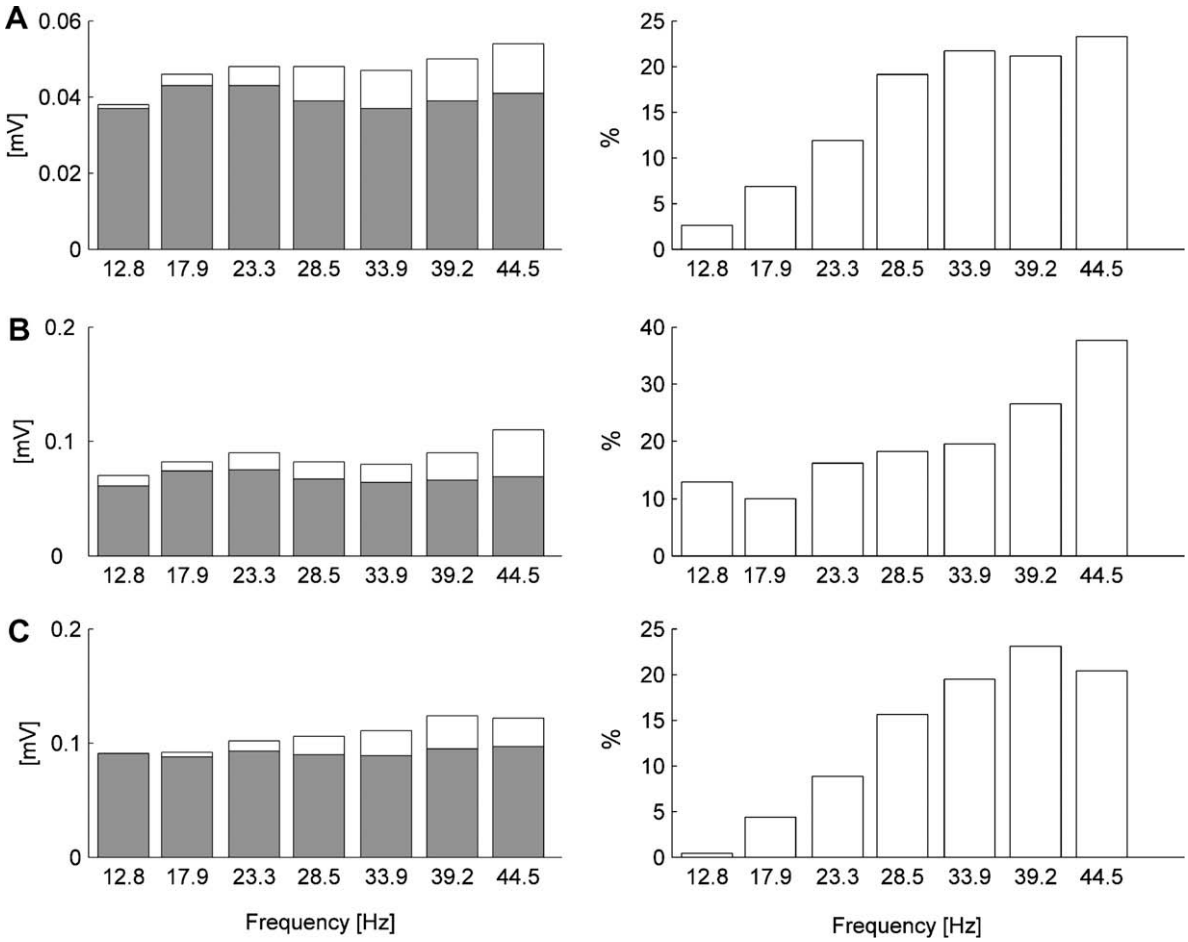

Fig. 5. Average RMS values of surface EMG during vibration on all subjects for each of the explored muscles: vastus medialis (A), rectus femoris (B) and vastus lateralis (C). The diagrams on the left show the difference of values between filtered (grey bars) and unfiltered signals (white bars). Signals were filtered using multiple notch to eliminate the artifact contribution (see text). The diagrams on the right show the average percentage of reduction of the EMG RMS values on filtered signal (once motion artifact was suppressed).

Moreover our experience suggests that the possibility of reducing motion artifact by using particular electrodes and accurately preparing skin is limited. Although the data indicates that some improvements were made in reducing the artifact through careful preparation of the skin, complete elimination of the effect was not achieved. It was also hypothesized that as the spectrum of the accelerometer signal only consisted of the vibration frequency and its higher harmonics, the spectrum of the motion artifact would also show the same frequency components. Indeed, the spectrum of the motion artifact (see Patella spectrum) consisted only of the vibration frequency and its higher harmonics.

Artifact amplitude was found to be unpredictable and dependent upon skin properties, electrode type and preparation, etc. Presence of motion artifact led to overestimation of EMG power, EMG–RMS and consequently muscle activity during vibration. Artifact harmonics extended within the EMG spectrum, making classic high-pass filters unusable. However, the raw EMG signal can be easily filtered with a series of sharp notch filters centred at the vibration frequency and its superior harmonics. In the use of sharp notch filters, some true EMG signal is lost, yet the use of this simple filter hides possible variation of EMG power in those bands due to mechanical activated synchronisation of muscles during vibration. However, the additional pair of electrodes placed onto patient's patella certainly demonstrates that a considerable part of the signal depends exclusively on motion.

The accelerometer provided useful information about skin motion at the site of the electrodes. Acceleration signals showed the same characteristics as the artifact signal (oscillation at platform frequency and its harmonics). Presence of higher harmonics suggested a non-linear behaviour of the mechanical system. Mechanical response depends on vibration intensity and frequency. Moreover, it was determined that vibration effects varied between subjects as well. Motion artifacts were present (in different amounts) on all of the EMGs collected. The duration of each vibratory stimulus was restricted to 20 s with a rest interval of 60 s. Vibration frequency was randomized, to minimize fatigue-related effects during the trials. MDF and MNF did not vary significantly (within 5%) for either the raw signals or for the filtered version.

To further understand the effects of vibration testing on the occurrence of motion artifact, studies with female subjects should be performed to compare with the results

obtained for male subjects. Moreover, extensive testing will aim to better predict accelerations of different muscles and body parts during vibration treatment. In conclusion, this study highlights the relevance of EMG motion artifact during vibrations. Consequently, EMG RMS signals measured by devices currently used in the sports and rehabilitation medicine fields are inadequate. The data presented here directly links increased motion artifact to increased frequencies, which can have deleterious effects on the measurement and application of vibration testing.

Variability of motion artifact intensity may be one of the reasons for the inhomogeneous findings reported in literature (Mester et al., 2006); therefore, appropriate filtering should help to reduce uncertainty concerning neuromuscular response to vibrations.

Acknowledgement

Authors are grateful to TSEM S.p.A. for providing the vibration training device and customer hardware modifications. Authors are also particularly grateful to Ing. Antonio La Gatta for helpful discussions and suggestions and Ing. Gulio Pasquariello for his kind and precious collaboration.

References

Bautmans I, Van Hees E, Lemper JC, Mets T. The feasibility of whole body vibration in institutionalised elderly persons and its influence on muscle performance, balance and mobility: a randomised controlled trial. BMC Geriatrics 2005;5:17.

Bosco C. Automatic device for optimized muscular stimulation. US Patent No. WO01/56650. United States 2001.

Bosco C, Colli R, Introini E. Adaptive responses of human skeletal muscle to vibration exposure. Clin Physiol 1999;19(2):183–7.

Bosco C, Cardinale M, Tsarpela O. Influence of vibration on mechanical power and electromyogram activity in human arm flexor muscles. Eur J Appl Physiol Occupat Physiol 1999;79(4):306–11.

Bosco C, Iacovelli M, Tsarpela O, Cardinale M, Bonifazi M, Tihanyi J, et al.. Hormonal responses to whole-body vibration in men. Eur J Appl Physiol 2000;81(6):449–54.

Bosco C, Cardinale M, Tsarpela O, Colli R, Tihanyi J, von Duvillard SP, et al.. The influence of whole body vibration on jumping performance. Biol Sport 1998;15(3):157–64.

Burke JR, Schutten MC, Koceja DM, Kamen G. Age-dependent effects of muscle vibration and the jendrassik maneuver on the patellar tendon reflex response. Arch Phys Med Rehab 1996;77(6):600–4.

Cardinale M, Lim J. Electromyography activity of vastus lateralis muscle during whole-body vibrations of different frequencies. J Strength Condition Res 2003;17(3):621–4.

Cardinale M, Wakeling J. Whole body vibration exercise: are vibrations good for you?. Br J Sports Med 2005;39:585–9.

Clancy EA, Morin EL, Merletti R. Sampling, noise-reduction and amplitude estimation issues in surface electromyography. J Electromyogr Kinesiol 2002;12(1):1–16.

Clancy EA, Bouchard S, Rancourt D. Estimation and application of EMG amplitude during dynamic contractions. IEEE Eng Med Biol Mag 2001;20(6):47–54.

Cutmore TRH, James DA. Identifying and reducing noise in psychophysiological recordings. Int J Psychophysiol 1999;32(2):129–50.

De Talhouet H, Webster JG. The origin of skin-stretch-caused motion artifact under electrodes. Physiol Measure 1996;17(2):81–93.

Delecluse C, Roelants M, Verschueren S. Strength increase after whole-body vibration compared with resistance training. Med Sci Sports Exercise 2003;35(6):1033–41.

Flieger J, Karachalios Th, Khaldi L, Raptou P, Lyritis G. Mechanical stimulation in the form of vibration prevents postmenopausal bone loss in ovariectomized rats. Calcified Tissue Int 1998;63(6):510–4.

Hermens HJ, Freriks B, Merletti R, Stegeman D, Blok J, Rau G, Disselhorst-Klug C, Hägg G. European recommendations for surface electromyography, results of SENIAM project. 8th ed. Enschede: Roessingh Research and Development; 1999.

Homma I, Nagai T, Sakai T, Ohashi M, Beppu M, Yonemoto K. Effect of chest wall vibration on ventilation in patients with spinal cord lesion. J Appl Physiol 1981;50(1):107–11.

Issurin VB, Liebermann DG, Tenenbaum G. Effect of vibratory stimulation training on maximal force and flexibility. J Sports Sci 1994;12(6):561–6.

Issurin VB, Tenenbaum G. Acute and residual effects of vibratory stimulation on explosive strength in elite and amateur athletes. J Sports Sci 1999;17:177–82.

Lebedev MA, Polyakov AV. Analysis of surface EMG of human soleus muscle subjected to vibration. J Electromyogr Kinesiol 1992;2(1):26–35.

Kerschan-Schindl K, Grampp S, Henk C, Resch H, Preisinger E, Fialka-Moser E, et al.. Whole-body vibration exercise leads to alterations in muscle blood volume. Clin Physiol 2001;21(3):377–82.

Martin BJ, Park HS. Analysis of the tonic vibration reflex: influence of vibration variables on motor unit synchronization and fatigue. Eur J Appl Physiol 1997;75(6):504–11.

Merletti R. Standards for reporting EMG data. J Electromyogr Kinesiol 1996;6(4):III–IV.

Mester J, Spitzenfeil P, Schwarzer J, Seifriz F. Biological reaction to vibration-implications for sport. J Sci Med Sport 1999;2(3):211–26.

Mester J, Kleinoder H, Yue Z. Vibration training: benefits and risks. J Biomech 2006;39:1056–65.

Ödman S, Åke Öberg P. Movement-induced potentials in surface electrodes. Med Biol Eng Comput 1982;20(2):159–66.

Person R, Kozhina G. Tonic vibration reflex of human limb muscles: discharge pattern of motor units. J Electromyogr Kinesiol 1992;2(1):1–9.

Roll JP, Vedel JP, Ribot E. Alteration of proprioceptive messages induced by tendon vibration in man: a microneurographic study. Exp Brain Res 1989;76(1):213–22.

Romaiguère P, Vedel JP, Azulay JP, Pagni S. Differential activation of motor units in the wrist extensor muscles during the tonic vibration reflex in man. J Physiol 1991;444(1):645–67.

Roy SH, De Luca G, Cheng MS, Johansson A, Gilmore LD, De Luca CJ. Electro-mechanical stability of surface EMG sensors. Med Biol Eng Comput 2007;45(5):447–57.

Rubin CT, Turner SA, Bain S, Mallinckrodt C, McLeod K. Low mechanical signals strengthen long bones. Nature 2001;412:603–4.

Rubin CT, Recker R, Cullen D, Ryaby J, McCabe J, McLeod K. Prevention of postmenopausal bone loss by a low-magnitude, high-frequency, mechanical stimuli: a clinical trial assessing compliance, efficacy, and safety. J Bone Mineral Res 2004;19(3): 343–51.

Searle A, Kirkup L. A direct comparison of wet, dry and insulating bioelectric recording electrodes. Physiol Measure 2000;21:271–83.

Tam H, Webster JG. Minimizing electrode motion artifact by skin abrasion. IEEE Trans Biomed Eng 1977;24(2):134–9.

Torvinen S, Kannu P, Sievänen H, Järvinen TA, Pasanen M, Kontulainen S, et al.. Effect of a vibration exposure on muscular performance and body balance. Randomized cross-over study. Clin Physiol Funct Imag 2002;22(2):145–52.

Turker KS. Electromyography: some methodological problems and issues. Phys Therapy 1993;73(10):698–710.

Verschueren S, Roelants M, Delecluse C, Swinnen S, Vanderschueren D, Boonen S. Effect of 6-month whole body vibration training on hip density, muscle strength, and postural control in postmenopausal women: a randomized controlled pilot study. J Bone Mineral Res 2003;19(3):352–9.

Wakeling JM, Liphardt A. Task-specific recruitment of motor units for vibration damping. J Biomech 2006;39(7):1342–6.
Wakeling JM, Nigg BM. Modification of soft tissue vibrations in the leg by muscular activity. J Appl Physiol 2001;90(2):412–20.
Wakeling JM, Nigg BM, Rozitis AI. Muscle activity damps the soft tissue resonance that occurs in response to pulsed and continuous vibrations. J Appl Physiol 2002;93(3):1093–103.
Wakeling JM, von Tscharner V, Nigg BM, Stergiou P. Muscle activity in the leg is tuned in response to ground reaction forces. J Appl Physiol 2001;91(3):1307–17.

Antonio Fratini received the Laurea degree in Electronic Engineering at the University of Naples in 2005 discussing the degree thesis "Wireless medical telemetry via Bluetooth". He has attended the 2002–2003 program of the "European Post-graduate Course in Biomedical Engineering", at the Department of Medical Physics, University of Patras, Greece. At present, he is Ph.D. student in Biomedical Engineering. His main research activities are in the field of biomedical signal processing, sport and rehabilitation medicine, biomedical instrumentation and medical wireless telemetry. At present he is author and co-author of publications on these topics.

Mario Cesarelli received the Laurea degree in Electronic Engineering at the University of Naples in 1979 and post-graduate specialisation in Biomedical Technologies from the University of Naples. In 1995 visiting Professor at the Institute for Rehabilitation Research in Hoensbroek, The Netherlands. He is Associate Professor in Biomedical Engineering and teaches Biomedical Signal Processing at the University of "Federico II" of Naples. He also teaches Biomedical topics in under-graduate courses and in post-graduate schools of the Faculties of Medicine and Surgery at the Universities of Naples. He is member of the Teaching Board of the Ph.D. in Biomedical Engineering at the University of Bologna. His main fields of scientific interests are biosignal and image analysis, biomedical instrumentation, health care information system. He is member of the "Associazione Italiana di Ingegneria Medica e Biologica" (AIIMB) affiliated with the International Federation for Medical and Biological Engineering (IFMBE). At present he is author and co-author of many publications.

Paolo Bifulco received the Laurea degree in Electronic Engineering at the University of Naples. In 1994, he was a research assistant at the University of Southampton, UK. He got the Ph.D. in Biomedical Engineering in 1998. He conducts research at the Department of Electronic Engineering and Telecommunications of the University of Naples "Federico II", where he teaches Biomedical Instrumentation and Clinical Engineering. His main research activities are in the field of biomedical signal and image processing, biomedical instrumentation and telemedicine. He has been a speaker in many scientific national and international conferences, as documented by scientific publications.

Maria Romano received the Laurea in Electronic Engineering at the University "Federico II" of Naples, with grades 110/110, discussing the degree thesis "Cardiotocographic signal processing in frequency domain". She got the Ph.D. in Biomedical Engineering in 2003. In 2005, she received a post-doctorate grant from the University of Napoli "Federico II". Her research fields are biomedical signal processing, in particular prenatal monitoring, and biomedical imaging.