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Assessment of vibratory stimulation on neuromuscular system

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Chapter 1 - Introduction

INTRODUCTION

Human reactions to vibration have been extensively investigated in the past. [Dickmann, 1958; Dennis, 1965; Griffin, 1975; Griffin and Whitham 1976]

Vibration, as well as whole-body vibration, was commonly considered as an occupational hazard and it has been highlighted for its detrimental effects on human condition and comfort. It is normally associated with lower back disorders [Bovenzi and Hulshof, 1999], muscle and nerve tissue damage [Necking et al 1992], Raynaud's Disease (vibration white finger) [Herrick, 2005] and interference with cognitive processes such as that required for short-term memory. [Sherwood and Griffin, 1990]

Although vibration may produce undesirable side-effects, different studies have shown the positive impacts of vibration upon the bone density of postmenopausal women and disabled children [Rubin et al, 2004; Verschueren et al, 2004; Ward et al, 2004], back pain [Rittweger et al, 2002b], stroke [van Nes et al, 2004], multiple sclerosis [Schuhfried et al, 2005] and muscle spasticity of cerebral palsy sufferers [Ahlborg et al, 2006]. Physiologists and physiotherapists have also been reported to use vibration as a therapeutic intervention such as for clearing the lungs and improving joint mobility.

A great part of the literature is however dedicated to the positive effects of vibration when used as method for muscular stimulation and as an exercise intervention (muscular training).

The aim of research has been the investigation on the positive effects that the use of vibrations, in particular the effects of specific whole body vibrations, may have on muscular activity.

THE EFFECTS OF VIBRATION

Vibration effects were initially investigated to study the actions of muscle spindles [De Gail et al, 1966; Desmedt and Godaux, 1978; Marsden et al, 1969]. Indeed, localized, direct applications of vibratory stimuli to a single muscle or a tendon where found to produce reactions of muscle spindles.[De Gail et al, 1966; Marsden et al, 1969; Desmedt and Godaux, 1975 and 1978]

Local tendon vibrations induce activity of the muscle spindle la fibers, mediated by monosynaptic and polysynaptic pathways and a reflex muscle contraction known as the Tonic Vibration Reflex (TVR) arises in response to such vibratory stimulus.[Roll et al, 1989; Bongiovanni and Hagbart, 1990; Romaiguére et al, 1991; Person and Kozina, 1992; Martin and Park, 1997].

Whole body vibration training aims to mechanically activate muscles by eliciting stretch reflexes and was initially proposed as a possible application of the TVR to the entire body. [Torvinen et al, 2002]

The impact of whole body vibration (WBV) treatments on muscular activity, neuromuscular, and postural control has been widely studied. The first application of vibration in this field was conducted by Nazarov, which demonstrated the efficacy of WBV in increasing muscle strength [Nazarov and Spivak, 1885]. Then, the effect of WBV treatments has been evaluated on subjects with different athletic conditions, age, sex, and according to different exercise protocols [Abercromby et al, 2007; Cardinale et al, 2003, Cesarelli et al, 2010; Hazel et al, 2007; Martin and Park, 1997; Petit et al, 2010; Torvinen et al, 2002].

Other research activities showed that the vibration stimulus produced positive effects on bone mineral density [Belavý el al, 2011; Von Stengel et al, 2011a,b] and human hormones [Cardinale et al, 2010a,b; Erskine et al, 2007; Kvorning et al, 2006]; whereas, its positive effect on patients with Parkinson's disease is still doubtful [Arias et al, 2009; King et al, 2009; Turbanski et al, 2005]. Roelants [Roelants et al., 2006] studied the electromyographic (EMG) responses of the rectus femoris, vastus lateralis, and vastus medialis during static squat. They showed that EMG activity was higher in the presence of vibration in all the muscle groups and in all exercises. In agreement, Abercromby and colleagues [Abercromby et al, 2007] analyzed electromyographic signals on subjects performing static and dynamic squat while on a vibration platform. They reported an increase in the neuromuscular activation of the muscles during WBV exercises.

Other works have analyzed the rise in specific oxygen consumption (sV_{O2}) in the last seconds of the exercise [Rittweger et al, 2001 and 2002], when a steady-state condition is reached, to provide an estimation of the cardiorespiratory system activity. These studies are based on the assumption that the sV_{O2} response is due to the increased number of muscle fibers (and thus the increased muscle activity) activated by the vibrations [Martin et al, 1997; Person and Kozhina, 1992; Roll et al, 1989; Romaiguére et al, 1991]. In fact, Rittweger et al. [Rittweger et al, 2001] reported that simple standing and dynamic squats performed on a WBV platform increased sV_{O2} compared to the same exercise without vibration. Later, Rittweger et al. [Rittweger et al, 2002] showed that the sV_{O2} was increased when vibration frequency and amplitude were increased. Similarly, after monitoring sV_{O2} and heart rate (HR) during and 24 hrs after a WBV exercise session and a second session without vibration (NoV), Hazell and Lemon [Hazell and Lemon, 2011] reported that sV_{O2} was 23% higher during WBV training session.

MOTIVATIONS

Despite many studies on the effects of the vibrations applied to the whole body (i.e. WBV), the findings in literature are not yet coherent. It is important to point out that the studies presented in literature investigated WBV effects only on muscular activity by recording electromyographic signal [Abercromby et al, 2007; Roelants et al, 2006] or on metabolic power by monitoring the sV_{O2} [Hazell and Lemon, 2011; Rittweger et al, 2001 and 2002] without standard protocol and using different exercise parameters.

The purpose of this study was to monitor simultaneously both signals in a novel approach. We investigated the differences due to WBV effects on V_{O2} and EMG between static and dynamic squat exercises. This was done to identify the better exercise characteristics for improving neuromuscular activation and progress in training efficacy. Monitoring V_{O2} throughout the exercise and not just during the last seconds (sV_{O2}) of the exercise (Rittweger et al, 2001 and 2002) allows for analyzing the curves from the beginning of the exercise in order to find out possible differences in the sV_{O2} trend and differences in how it is reached at steady-state.

CHAPTER 2 - WHOLE BODY VIBRATIONS

WHOLE BODY VIBRATIONS

Vibratory stimulations were investigated for their positive action in eliciting muscle activity. Localized vibrations applied to tendons have been used for studying the tonic vibration reflex (TVR), a reflex muscle response induced by stretching action of the applied vibration. The change produced in the length of the muscle is detected by muscle spindles and induces reflex and adaptive responses. [Bongiovanni and Hagbarth, 1990]

Training with vibration extended to the whole body, that is Whole Body Vibration (WBV), was initially proposed as a possible application of the Tonic vibration reflex occurrence to the entire body. [Bosco et al, 1999b] Indeed, if a localized vibratory stimulus produced elicited muscle activity, then whole body vibration, if properly delivered, could obtain similar muscular activity in all the body muscles.

The aim of WBV training (WBVT) is to mechanically activate muscles by eliciting similar stretch reflexes that occurred for localized application of vibration.

Nasarov, a Russian coach, was one of the first to apply vibratory stimulation to help athletes in physical training. Vibrations were applied to the distal muscles and then transmitted through the body chain to the proximal muscles. He used a special device to generate vibrations at a frequency of about 23Hz. Nasarov experiments highlighted the potential benefits of training with vibration to muscular development and peripheral circulation improvement. [Nazarov and Spivak, 1987]

Although literature has largely analyzed and documented the effects of WBV in electing neuromuscular, metabolic and hormonal responses, the exact mechanisms that are accountable for those effects are still unclear.

WBV training is clearly different from localized vibratory stimulation; rarely studies on WBVT monitored the local muscle stimulation (acceleration and displacement) and accounted for motion artifacts presence on EMG recordings.

However, it is important to understand the neuro-physiological mechanisms involved in muscle activation under vibration stimulation in order to prescribe safe and effective WBVT programs. [Cardinale and Wakeling, 2005]

PRODUCTION AND DELIVERY OF VIBRATION

Several methods of vibratory stimulation have been reported within the literature, they can be divided by the nature of the vibratory stimulus: local applied stimulus or whole body extended vibration.

Whole body vibration is the most common used method of delivering vibration in the fields of exercise physiology and sport medicine for enhancing human performance.

For this type of vibration stimulation, subjects stand on an oscillating plate and vibratory stimulation can be applied by using vibrating platform with a vertical or a rotational (side-to-side alternating) direction (Figure 1). These two ways of applying the stimulus generate dissimilar mechanical behaviors and hence they lead to a different neuromuscular response [Pel et al, 2009].

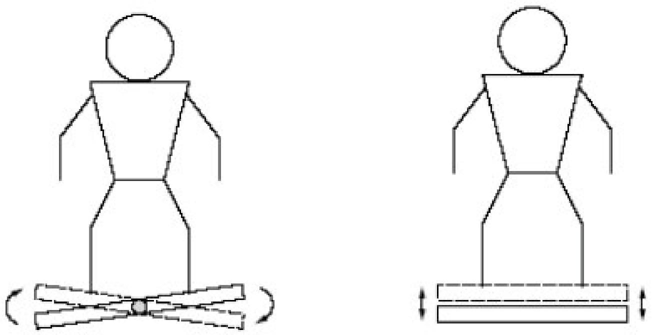


Figure 1: Methods of whole body vibration stimulation: alternating rotation (left) and vertical oscillation (right) (Cardinale and Wakeling, 2005)

HUMAN RESPONSE TO WHOLE BODY VIBRATION

WBVT has been proposed in addition with classical resistance training for its ability to increase the strength in the lower limbs.

Recent studies recommend WBVT as a possible therapeutic approach of sarcopenia and osteoporosis. Although in the past, vibrations have been studied largely for their possible harmful effects, recently it was highlighted that WBVT may achieve safe and effective outcomes on the musculoskeletal, endocrine-hormonal and cardiovascular system.

However, the results depend strictly on the stimulation protocol, which is related to different parameters: the frequency and amplitude of the stimulus, the duration of WBVT session, the physical conditions of the subjects involved and the posture assumed on the platform.

In the next paragraphs the main aspects on the mechanism and hypothesis on which these treatment are based are presented.

TONIC VIBRATION REFLEX

Within WBV literature, tonic vibration response and/or the tonic vibration reflex (TVR) are acronyms used to describe the neuromuscular effects of localized vibration.

TVR is a sustained contraction of a muscle subjected to vibration. The application of mechanical vibration to the muscle or tendon elicits a reflexive contraction and the reciprocal inhibition of its antagonists [Eklund and Hagbarth, 1966]

The TVR occurred when vibration is applied to the muscle belly or tendons and is closely related to the stretch reflex (figure 2); 30-100 Hz vibration activates receptors of the skin, tendons and, most importantly, muscle spindles. [Cardinale and Lim, 2003; lssurin et al, 1996; Lebdev and Polyakov, 1992]

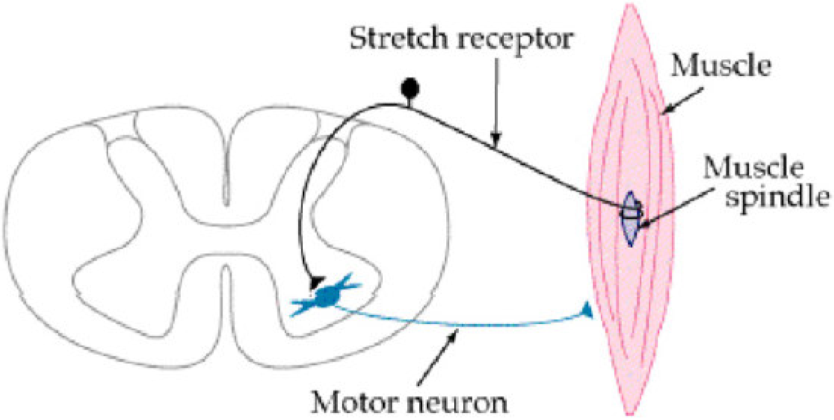


Figure 2: Illustration of the stretch reflex

Muscle spindle discharges are sent to the spinal cord through afferent nerve fibers, where they activate monosynaptic and polysynaptic reflex arcs (stretch reflex), causing the muscle to contract.

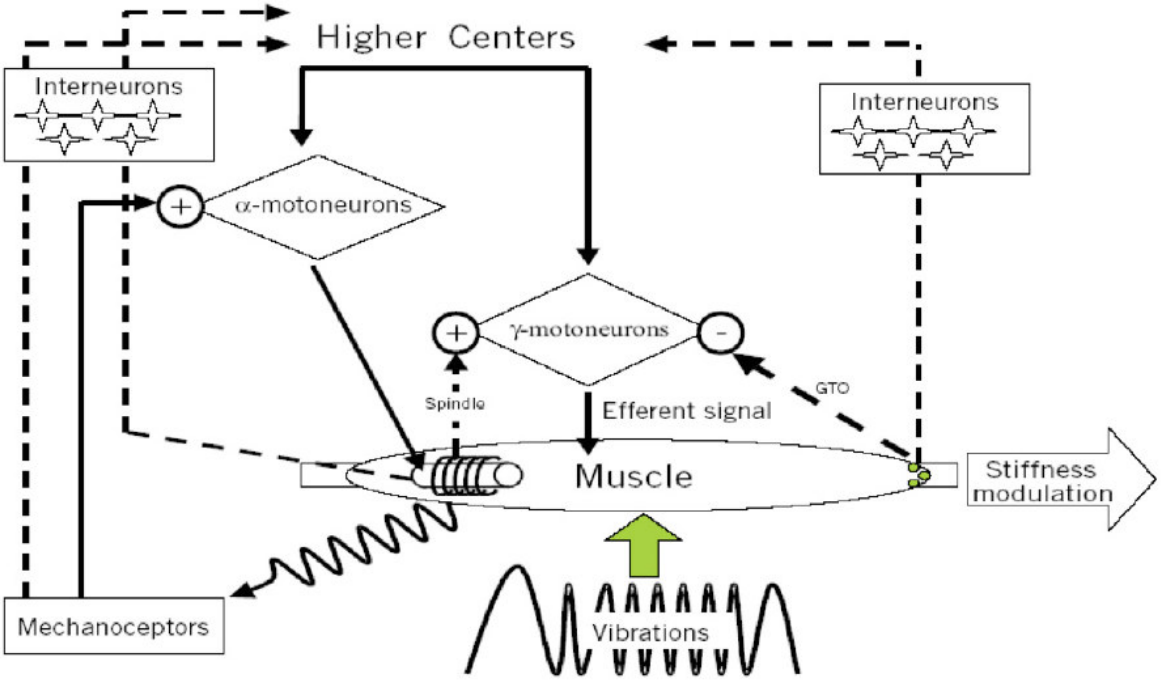


Figure 3: Potential mechanisms for vibration-induced neuromuscular effects (adopted from Cardinale and Bosco, 2003)

In WBV other receptors are stimulated. In addition to the neuromuscular spindles and the Golgi tendon organs, skin, joints and ligaments receptors are also stimulated (Pacinian and Meissner corpuscles, type lll and IV nerve endings). (Figure 3)

THE MUSCLE TUNING HYPOTHESIS

There is evidence to suggest that the body is capable of tuning its muscle activity in order to reduce the vibrations that are passing through the soft tissue that may produce a detrimental effect [Nigg, 1997].

The amount of muscle activity required is dependent on the level of vibration, where maximal muscle activation can reduce or purge oscillations within the tissues.

Everyday activities such as walking, running and jumping result in impact forces, from the collision of the heel with the ground, producing vibrations of 10–20 Hz to the lower limbs [Wakeling and Nigg, 2001], where an input signal from the impact force produces muscle activity or ‘tuning’ response to reduce soft tissue vibrations.

This activation or tuning supposedly occurs shortly before the heel strikes the ground [Nigg, 1997]. Consequently, muscle tuning relies on three components: i) the frequency and amplitude of the input force, ii) the vibration resonance of the soft tissue and iii) the level of muscle activity.

Therefore, damping vibration will depend on the individual's neuromuscular (muscle spindle) response, the sensitivity of joint and skin receptors, the proportion of muscle fiber types and viscoelastic (stiffness) elements [Bazzett-Jones et al., 2008].

In summary, impact forces create vibrations in the foot where the vibrations travel through the lower limb musculature. To prevent resonance, soft tissues damp the vibrations, which cause sensory organs to send impulses to the central nervous system to increase muscle activity and adjust joint stiffness.

Evidence for muscle tuning was presented by increased gastrocnemius and biceps femoris activity along with corresponding muscle damping. [Wakeling et al., 2003]

Vibration damping has also been highlighted during human walking. [Wakeling et al, 2003]

ACUTE AND CHRONIC EFFECTS OF VIBRATIONS

The effects of whole body vibration can be divided in two main categories: Acute and Chronic. Acute are named the effects that appear during the treatment (e.g. EMG increase) and after a short period of time (few days). Chronic effects are generally intended the outcomes of prolonged WBV exposures.

Acute Effects

The acute beneficial effects of WBV (that is, following a single session of WBV) are less convincing than long-term effects.

It appears that strength, power and balance may be increased [Bosco et al., 1999 and 2000; Torvinen et al., 2002a], decreased [deRuiter et al., 2003] or remain unchanged [deRuiter et al., 2003; Gerodimos et al., 2010; Torvinen et al., 2002b] depending on the exercise volume and intensity while flexibility may be improved [Gerodimos et al., 2010].

Surface EMG analyses in different studies demonstrate a significant increase in muscular activity; some study reports that the EMG increase is frequency dependent. [Bosco et al, 1999; Cardinale and Lim, 2003]

Acute effects on muscular activity are also supported by increased metabolic activity, and even an improved circulation in the target muscles. [Bosco et al, 2000; Rittweger et al, 2001]

Even if metabolic activity is increased it appears to have little effect on fat mass.[Roelants et al, 2004] A study, combining squatting exercise with additional load of 35-40% of bodyweight and WBV stimulation, reported the oxygen consumption to increase up to 50% of maximal oxygen uptake [Rittweger et al., 2002a]

Variation of frequency and/or amplitude have been found to vary oxygen consumption and in turn energy expenditure. [Rittwegeret al, 2001]

These findings, however, have been contradicted by other work that exposed untrained individuals to five times one minute WBV exposures (30 Hz; 8mm; 284.3 m s^{-2}) and two minute rest periods.[de Ruiter et al, 2003]. This study also showed the knee extensors to have a reduced ability to perform maximal voluntary contractions up to 60 minutes after static squat WBV.[de Ruiter et al, 2003] Similarly, participants described as non-elite, failed to show acute improvements in vertical jump height after experiencing five times two minute exposures, separated by 40 second rest periods, at a frequency of 26 Hz and amplitude of 5.5 mm (maximum acceleration = 146.8 m s^{-2}) [Cochrane et al, 2004]. It is unclear why these differences occurred.

As demonstrated, several studies have analyzed the acute effects of WBVT on neuromuscular performance; however it is difficult to find agreement in findings. EMG analysis, indeed, were often made only by the use of concise parameters (i.e. root mean square) a rarely accounted for the presence of motion artifact on surface electrodes. WBV amplitude also impacts upon the acute response.

Chronic Effects

As well as research on WBV acute effects, research on prolonged WBV treatments has shown opposite or inconsistent results. A repeated exposure to WBVT over 10 days produced increases in power output and vertical jump height, 6% and 12% respectively.[Bosco et al, 1998]

Nevertheless, in another group of physically active individuals, six WBV sessions over two weeks do not have revealed improvements in knee extensor strength. [de Ruiter et al, 2003]

Performing two months of static and light dynamic exercises while exposed to WBV, an untrained group, improved knee extensor strength and counter movement jump height by 7.8% and 2.5% respectively. However, the further two months of treatments, did not revealed differences between the WBV and control group for either performance measure [Torvinen et al, 2002a].

WBVT effects have been also incongruous in longer term research.

A comparison between the combination of WBV with dynamic exercise and traditional resistance training alone was completed, in untrained individual groups, after a 12-week period. Results have shown similar improvements in knee extensor strength occurred for both groups but countermovement jump improved in the WBV group only. [Delecluse et al, 2003]

In a study lasting eight-month period using the same exercise protocol, untrained individuals improved vertical jump height by 7.8% more than a control group, but failed to show any change in knee extensor strength. [Torvinen et al, 2003].

WBV exercise in the static squat position over 11-weeks has demonstrated no change in knee extensor strength and counter movement jump height. [de Ruiter et al, 2003]

HORMONAL RESPONSE

Among acute and chronic effects of training with WBV, some studies have also suggested significant effects on endocrine system.

Applications of vibration to the whole body indeed have been found to change the production of testosterone, cortisol and growth hormone. [Bosco et al, 2000]

Vibratory stimulation, making quick changes in the length of muscle and tendon leads to a complex reflex response. The activation of specific afferents has proved able to modulate growth hormone production. Experiments on rats have also shown how vibrations may be able to elevate serotonin levels (5HT) and 5-HIAA in the brain.

NOMENCLATURE

As evidenced in the text, although the consistent number of study on WVBT the effectiveness of vibration as a method for muscular stimulation seems to be still unclear.

Among others, one possible reason has also been found in the lack of nomenclature standardization. [Lorentzen et al, 2008] The lack of standardization makes difficult to replicate experiments among researchers leading to misinterpretation of the phenomena.

The main aspects on which the literature shows higher discrepancy are: nomenclature used for reporting vibration magnitude and the methods to compute the maximum acceleration impressed by the platform. Vibration frequency appears instead to be accurately and clearly reported in literature, measured in oscillation per second (Hz).

Magnitude of Vibration

Magnitude is one of the variables of the WBV treatment.

As well as the other parameters it has to be reported clearly. Magnitude has been associated with displacement, amplitude, peak to peak displacement. [Lorentzen et al, 2008] As a paradox, in one study only the vibration frequency was reported making it impossible to replicate [Rønnestad, 2004].

In the case of vibration, amplitude is the maximum displacement of a vibrating point from a mean position, while peak-to-peak displacement is used to describe the total vibration excursion of a point between its positive and negative extremes (see Figure 4).

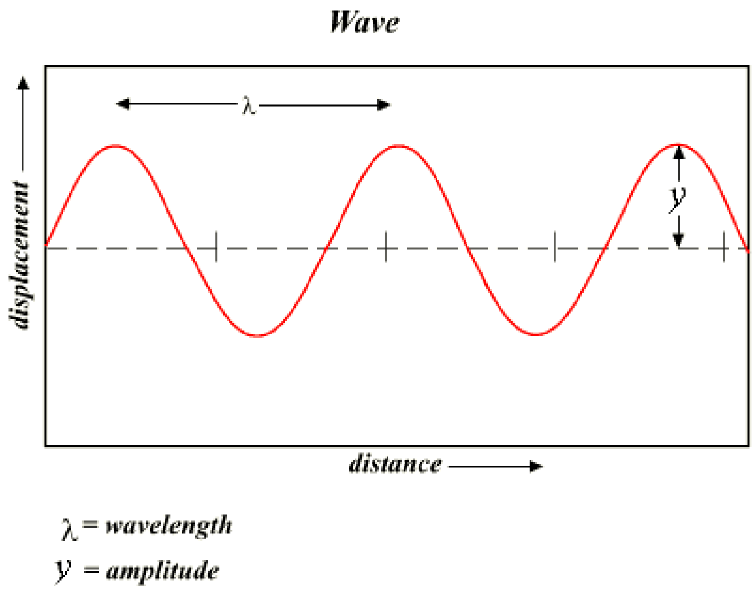


Figure 4: Frequency, amplitude and peak to peak displacement of a vibrating object (adopted from CCOHS)

The movement of tilting and vertical oscillating platform can be assumed sinusoidal:

$$s(t) = A \sin(2\pi f t)$$

where f is vibratory frequency, A is the amplitude.

In vertical oscillating platforms all the points will move approximately at the same way; they will have the same peak to peak displacement and the same maximal amplitude.

However, in tilting oscillating platform it is difficult to deduce the real acceleration or displacement to which the subject undergoes. As shown in figure 5 feet distance from the rotation axis vary the magnitude of the stimulus delivered to the patient as well as the acceleration. It can be computed as the double derivatives of s(t):

$$a(t) = \frac{d^2 s(t)}{dt^2} = A(2\pi f)^2 \sin(2\pi ft)$$

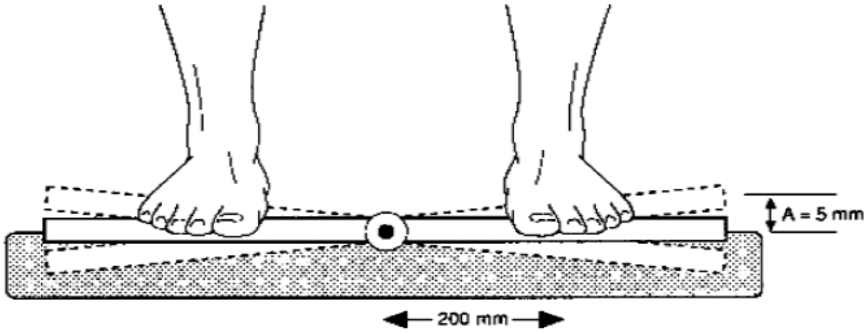


Figure 5: Explanation of the variation in peak to peak displacement of fixed points of the platform depending on their distance from the axis

Practices in reporting amplitude, displacement and peak-to-peak displacement vary so widely that it is really important to establish specific guidelines in an attempt to gain consistency across studies. [Lorentzen et al, 2008]

Acceleration

As previously mentioned, in WBV literature the methods to report acceleration impressed by the platform have shown a similar range of inconsistency as that reported for amplitude. [Lorentz et al, 2008]

Acceleration in not always reported as peak (maximal) acceleration.

Acceleration depends on frequency and amplitude of the vibration (formula 2) and the maximal value (peak) can be easily computed by:

$a_{max} = A(2\pi f)^2$

Gravitational forces then, can be obtained by dividing the maximal acceleration by gravity g (9,81[m][s^{-2}]).

Therefore, an amplitude of 2 mm and a frequency of 20 Hz will produce a peak acceleration of a_{max} = 31.55 [m][s^{-2}].

Table 1 shows some example of estimated maximal accelerations as a function of frequency and amplitude.

Amplitude [mm]	**Frequency [Hz]**	**Acceleration [m][s]$^{-2}$**
1	10	3.94
2	10	7.89
1	20	15.78
2	20	31.55
1	30	35.49
2	30	70.99
1	40	63.10
2	40	126.20

Acceleration (maximum), amplitude and frequency are therefore the basic parameters to be reported in vibration studies. The use of the maximal acceleration will demonstrate to the reader the real vibration intensities that are applied to the individuals, making similarity in results to be accurately made.

NOMENCLATURE RECOMMENDATION

After a concise analysis of the terminology used to report all the variables characterizing vibratory treatment, Lorentzen et al. 2008 proposed a nomenclature recommendation.

Recommendations suggest the amplitude to be reported as the maximum displacement from the plate's horizontal position (peak to peak displacement).

In case of using tilting platforms precise position of anatomical landmark of the foot, such as the middle toe, should be measured.

Clearly, each of the studies should report the amplitude, frequency and maximal acceleration.

”Acceleration max or gravity more accurately indicate the forces being imposed on the human body during whole body vibration and should therefore be reported by all studies" [Lorentzen et al, 2008]

HEALTH RISKS ASSOCIATED WITH WHOLE BODY VIBRATION EXPOSURE

Whole body vibration exposure has often been associated with health risks. Prolonged exposure to vibration, increases the risk of cognitive changes, acrophobia, low back trouble, visual limitations and epilepsy, among other things. [Mester et al, 1999]

Vibration is believed to be an occupational risk factor that may induce adverse effects in trucks drivers , fork-lift trucks, tractors, cranes, helicopter pilots [Bovenzi and Hulshof, 1999] and subjects who operate hand held machinery. [Bovenzi et al, 2000] Amplitude and frequency of the vibration also play a key role in the possible risks of prolonged exposure to vibration. The body's strategy in response to such vibration frequencies is to attenuate the vibration as much as possible to prevent discomfort. ISO 2631 establishes the discomfort level for vibration exposure of less than 30 minutes, at 0.4 g at 30 Hz. It is worth mentioning that the resonance frequencies of vital organs range from 5 to 20 Hz.

Nevertheless, whole body vibration research has typically used accelerative forces exceeding these loads (see table 1).

The literature has documented some minor side-effects in response to WBV exposure. Erythema and edema of lower limbs were reported as common side-effects probably due to the occurrence of vessels vasodilatation.[Crewther et al, 2004; Rittweger et al, 2000; Kerschan-Schindl et al., 2001] Hip and knee pain, discomfort from the vibration induced head motion have also been reported. High amplitudes, such as 5-6 mm may induce severe accident to the participants. [Crewther et al, 2004; Roelants et al, 2004; Russo et al., 2003]

We here remember that for such amplitude (5-6 mm) and a frequency of 30 Hz stimulation the accelerations can reach values around 200 m s^{-2}.

Although, not only these studies utilized these intensities with untrained individuals, it was concluded that frequency and amplitude combinations that produce large g-forces should be cautiously applied. [Crewther et al, 2004].

Other studies reported the effects at specific frequencies, such as faintness at 27 Hz and "sea-sickness" feeling at 17 Hz. [Rubin et al, 2004]

In older adults, the most typical side effect has been transient itching, tingling and erythema of the feet and lower legs. [Bruyere et al, 2005; Russo et al, 2003]

Reports of back and groin pain that has precluded participants from continuing the treatment. [Roelants et al, 2004; Bautmans et al, 2005]

Knee pain has also been reported in participants with pre-existing osteoarthritis, subsiding after several days of rest. [Roelants et al, 2004; Russo et al, 2003]

HUMAN RESONANCE

When considering the adverse effects of WBV, human resonance should be considered. The complexity of the human structure, and the anthropometric human characteristics, implies that there are different resonant frequencies [Randall et al, 1997].

Studies have reported varying resonant frequencies during standing posture ranging between 5.5 to 15.7 Hz [Matsumoto and Griffin, 1998; Randall et al, 1997). Individuals may have one main resonant frequency [Harazin and Grzeik, 1998] but may also have resonant peaks at other frequencies [Matsumoto and Griffin, 1998]. Height, weight and gender have been demonstrated to bear no relationship with resonance [Randall et al, 1997].

Exposure to frequencies at human resonance increases the transmissibility of vibration, increasing the forces transmitted through some body parts and potentially causing a pathogenic response. In the erect and relaxed standing postures, transmissibility at the hip has been demonstrated to exceed 100% at frequencies lower than 20 Hz [Rubin et al, 2003]. Research with the elderly has been performed within the reported ranges of human resonance, without causing detrimental effects [Bruyere et al, 2005].

NATIONAL AND INTERNATIONAL GUIDELINES

It is now widely accepted that prolonged and regular exposure to vibration can have a detrimental effect on an operator's health.

Regulation and guidelines on vibration exposure have been therefore issued during years in a converging way among different countries. The main aims on which law concentrate are “Whole Body Vibration” and “Hand-Arm Vibration Syndrome”.

As reported by Legislative Decree 187/05 we can define:

- *Whole body vibration*: "the mechanical vibration that, when transmitted to the whole body, entails risks to the health and safety of workers, in particular lower- back morbiditiy and trauma of the spine"
- *Hand-arm vibration*: "the mechanical vibration that, when transmitted to the human hand-arm system, entails risks to the health and safety of workers, in particular vascular, bone or joint, neurological or muscular disorders".

Hand-arm vibration syndrome (HAV or vibration white finger) is a widespread hazard for employees in many industries and occupations. HAV exposure at work can arise from the use of hand-held power tools (such as grinders or hammer drills), hand-guided machinery (such as lawnmowers and plate compactors) and hand-fed machines (such as pedestal grinders).

Since the risks of pathologies emerging from vibration exposure are evident, individuals can be reasonably protected from the health effects caused by vibration by reducing time to exposure.

The ISO 2631 guidelines on the vibration exposure limit values suggest for hand-arm vibrations a maximal daily exposure value of about A(8) = 5 m/s^2, while for whole-body vibration the daily exposure limit value is A(8) = 0.9 m/s^2.

Where A(8) is also an indicator of risk assessment and is computed as follows:

Hand-arm vibration

The assessment of the level of exposure to hand-arm vibration is based on the calculation of the daily exposure value normalized to an eight-hour reference period, A(8) (m/s^2), expressed as the square root of the sum of the squares ($A_{(wsum)}$) of the R.M.S values of the frequency-weighted accelerations, determined on the orthogonal axes x, y, z, as defined in the ISO standard 5349-1: 2001. The mathematical formula to calculate A(8) is shown below.

$A(8) = A_{(wsum)} (Te/8)^{1/2}$

where Te represents the Total daily duration of vibration exposure (hours); $A_{(wsum)}$ is equal to $(a^2_{wx}+ a^2_{wy}+ a^2_{wz})^{1/2}$ and a_{wx}, a_{wy}, a_{wz} are the R.M.S values of frequency-weighted acceleration (in m/s^2) on the orthogonal axes x, y, z (ISO 5349-1: 2001)

Whole-body vibration

The assessment of the level of exposure to whole-body vibration is based on the calculation of the daily exposure over an eight-hour period, A(8) (m/s^2), calculated as the highest R.M.S. value of the frequency-weighted accelerations, determined on three orthogonal axes:

$1.4\ a_{wx}$, $1.4\ a_{wy}$, a_{wz}

using the formula shown below:

$$A(8) = A_{(wmax)}\,(Te/8)^{1/2}$$

where Te represents the total daily duration of vibration exposure (hours); $A_{(wmax)}$ is the highest value between $1.4\ a_{wx}$, $1.4\ a_{wy}$, a_{wz} (individual into a seated position) and a_{wx}; a_{wv}; a_{wz}, are the R.M.S. values of the frequency-weighted acceleration (in m/s^2) on the orthogonal axes x, y, z (ISO 2631-1: 1997)

CHAPTER 3 - NEUROMUSCULAR SYSTEM

NEUROMUSCULAR SYSTEM

Muscular system is the biological system of humans that produces movement. The combination of the nervous system and muscles, working together to permit movement, is known as the neuromuscular system.

The muscular system, in vertebrates, is controlled through the nervous system, although some muscles, like cardiac muscle, can be completely autonomous. The brain controls the movements of skeletal (voluntary) muscles via specialized nerves. The electrical signal from the brain travels down the nerves and prompts the release of the chemical acetylcholine from the pre-synaptic terminals. This chemical is picked up by special receptors in the muscle tissue. If enough receptors are stimulated by acetylcholine, the result is muscular contraction.

Muscle is contractile tissue and is derived from the mesodermal layer of embryonic germ cells. Its function is to produce force and cause motion, either locomotion or movement within internal organs. Much of muscle contraction occurs without conscious thought and is necessary for survival, like the contraction of the heart or peristalsis, which pushes food through the digestive system. Voluntary muscle contraction is used to move the body and can be finely controlled, such as movements of the finger or gross movements that of the biceps and triceps.

Depending on their function, therefore, we can characterize three muscle types

- smooth or "involuntary": it consists of spindle shaped muscle cells found within the walls of organs and structures such as the esophagus, stomach, intestines, bronchi, uterus, ureters, bladder, and blood vessels. Smooth muscle cells contains only one nucleus and no striations;
- cardiac muscle: as well as smooth muscle it is also an "involuntary muscle" but it is striated in structure and appearance. Like smooth muscle, cardiac muscle cells contains only one nucleus. Cardiac muscle is found only within the heart;
- skeletal or "voluntary muscle": it is anchored by tendons to the bone and is used to effect skeletal movement such as locomotion. Skeletal muscle cells are multinucleated with the nuclei peripherally located. Skeletal muscle is called ‘striated‘ because of the longitudinally striped appearance under light microscopy.

Skeletal and cardiac muscle are types of striated muscle. Striations don't give the muscle its characteristics, but are the physical result of the overlapping patterns of actin and myosin filaments in those muscles. Although smooth muscle has actin and myosin filaments, it does not appear to be striated as these filaments are not arranged as orderly as they are in the other two types of muscle. Striated muscle is often used in short, intense bursts, whereas smooth muscle sustains longer or even near-permanent contractions.

ANATOMY AND PHYSIOLOGY OF SKELETAL MUSCLES

Body skeletal muscles consists of muscle tissue, connective tissue, nerves and blood vessels. A fibrous fascia called the epimysium covers each muscle and tendon. Tendons connect the muscle belly to bone and they attach to the bone periosteum – more connective tissue that covers all bones. Contraction of the muscle belly pulls on the tendon and in turn, the bone it is attached to.

Limb muscles (such as the biceps brachii in the upper arm) have two attachments to bone. The proximal or origin is the attachment closest to the trunk. Distal or insertion is the attachment furthest from the trunk. Trunk muscles (such as the rectus abdominus in the stomach) also have two attachments: superior (closer to the head) and inferior (further from the head).

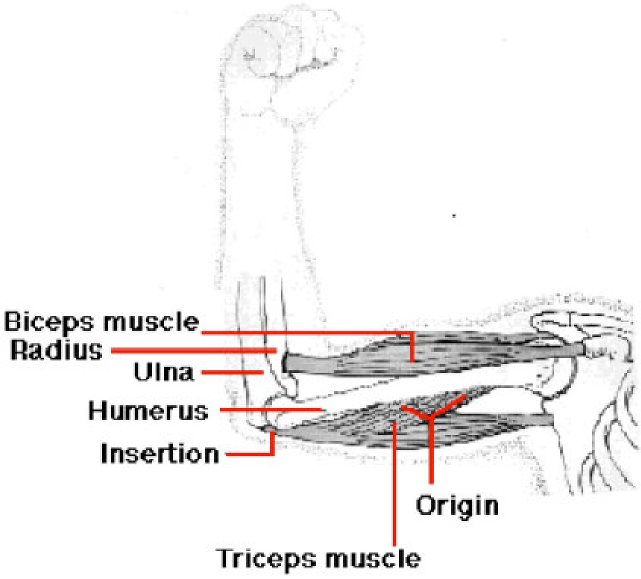


Figure 6: Muscles of upper limb. in figure it is depicted the origin and insertion of biceps and triceps brachi muscle

Muscles are composed by a great number of muscle cells or fibers. Muscle fibers are grouped into bundles (of up to 150 fibers) called fasciculi.

Each fasiculus or bundle is surrounded by connective tissue called perimysium.

Fibers within each bundle are surrounded by more connective tissue called endomysium.

Each individual fiber consists of a membrane (sarcolemma) and can be further broken down into hundreds or even thousands of myofibrils. Myofibrils are surrounded by sarcoplasm and together they make up the contractile components of a muscle. See the diagram below:

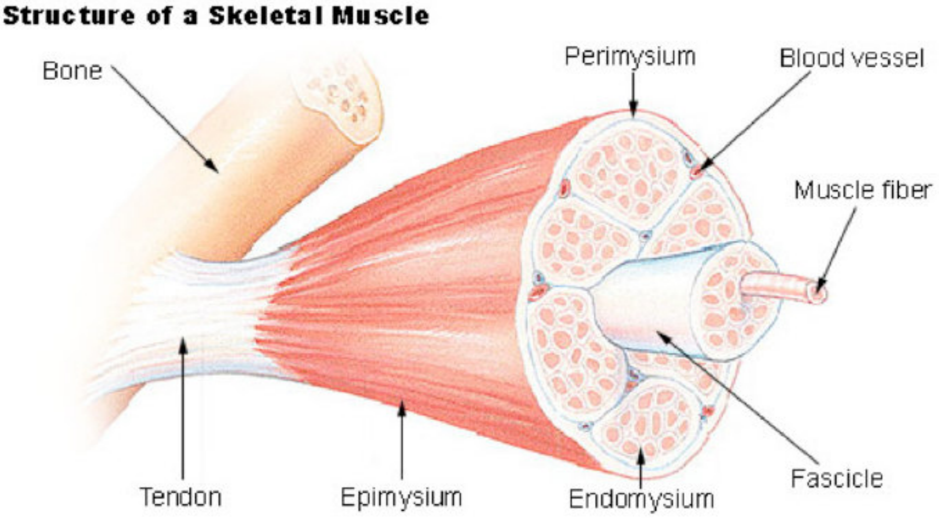


Figure 7:Muscle anatomy representation (Adopted from Wikimedia Commons)

Sarcoplasm contains glycogen, fat particles, enzymes and the mitochondria. The myofibrils consist of two types of protein filaments or myofilaments, actin and myosin.

Myosin and actin filaments run in parallel to each other along the length of the muscle fiber. Myosin has tiny globular heads protruding from it at regular intervals. These are named cross bridges and play a pivotal role in muscle action.

Each myofibril is organized into sections along its length. Each section is called a sarcomere and they are repeated right along the length of a muscle fiber. It's similar to how a meter ruler is split into centimeters and millimeters. Just as the millimeter is the smallest function of a ruler, the sarcomere is the smallest contractile portion of a muscle fiber.

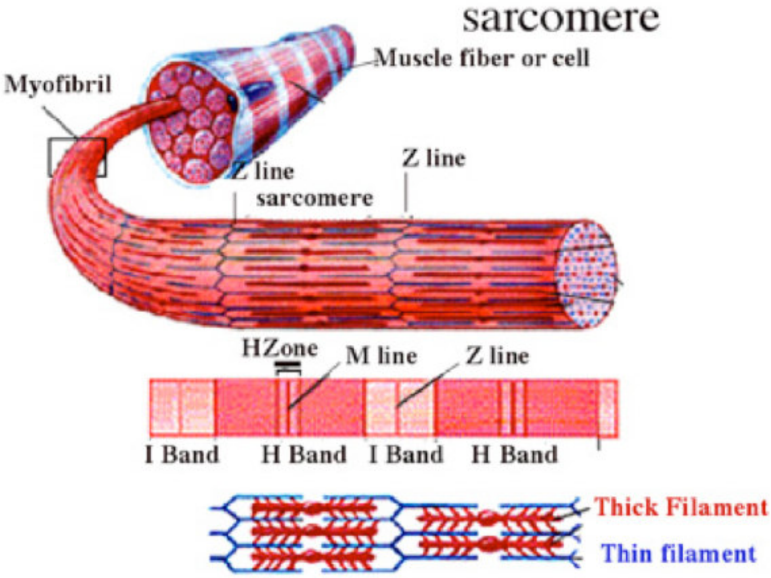


Figura 8 :Sarcomere (Adopted from MCAT)

The sarcomere is divided into different zones to show how it behaves during muscle action (figure 8). The Z-line separates each sarcomere. The H-zone is the center of the sarcomere and the M-line is where adjacent myosin filaments anchor on to each other.

Skeletal muscle fibers

Skeletal muscle fiber types can be characterized into two main types: slow twitch (Type I) muscle fibers and fast twitch (Type ll) muscle fibers. Fast twitch fibers can be further categorized:

- Type I, slow oxidative, slow twitch, or "red" muscle is dense with capillaries and is rich in mitochondria and myoglobin, giving the muscle tissue its characteristic red color. It can carry more oxygen and sustain aerobic activity.

- Type II,fast twitch, muscle has three major kinds that are, in order of increasing contractile speed:
  a) Type IIa, which, like slow muscle, is aerobic, rich in mitochondria and capillaries and appears red;
  b) Type IIx (also known as type lld), which is less dense in mitochondria and myoglobin. This is the fastest muscle type in humans. It can contract more quickly and with a greater amount of force than oxidative muscle, but can sustain only short, anaerobic bursts of activity before muscle contraction becomes painful (often attributed to a build-up of lactic acid). N.B. in some books and articles this muscle in humans was, confusingly, called type IIB;
  c) Type IIb, which is anaerobic, glycolytic, "white" muscle that is even less dense in mitochondria and myoglobin. In small animals like rodents or rabbits this is the major fast muscle type, explaining the pale color of their meat.

For most muscles, contraction occurs as a result of conscious effort originating in the brain. The brain sends signals, in the form of action potentials, through the nervous system to the motor neuron that innervates the muscle fiber. However, some muscles (such as the heart) do not contract as a result of conscious effort. These are said to be autonomic. Also, it is not always necessary for the signals to originate from the brain.

Reflexes are fast, unconscious muscular reactions that occur due to unexpected physical stimuli. The action potentials for reflexes originate in the spinal cord instead of the brain.

The functions of the skeletal muscle include support of the body, aids in bone movement, helps maintain a constant temperature throughout the body, assists with the movement of cardiovascular and lymphatic vessels through contractions, protection of internal organs and contributing to joint stability

ORGANIZATION OF SKELETAL MUSCLE FIBERS

The muscle fibers in a single fasciculus are parallel, but the organization of fasciculi in the skeletal muscle can vary, as can the relationship between the fasciculi and the associated tendon. Four patterns of fasciculi organization form parallel muscles, convergent muscles, pennate muscles, and circular muscles.

Parallel Muscles

In a parallel muscle, the fasciculi are parallel to the long axis of the muscle. Most of the skeletal muscles in the body are parallel muscles. Some are flat bands with broad attachments (aponeuroses) at each end; others are plump and cylindrical with tendons at one or both ends. In the latter case, the muscle is spindle-shaped, with a central body, also known as the belly, or gaster. The biceps brachii muscle of the arm is a parallel muscle with a central body. When a parallel muscle contracts, it gets shorter and larger in diameter. You can see the bulge of the contracting biceps brachii on the anterior surface of your arm when you flex your elbow.

A skeletal muscle cell can contract until it has shortened by roughly 30 percent. Because the fibers in a parallel muscle are parallel to the long axis of the muscle, when the fibers contract together, the entire muscle shortens by the same amount. If the muscle is 10 cm long, the end of the tendon will move 3 cm when the muscle contracts. The tension developed during this contraction depends on the total number of myofibrils the muscle contains. Because the myofibrils are distributed evenly through the sarcoplasm of each cell, we can use the cross-sectional area of the resting muscle to estimate the tension. A parallel muscle 6.25 cm^2 in cross-sectional area can develop approximately 23 kg of tension.

Convergent Muscles

In a convergent muscle, the muscle fibers are spread over a broad area, but all the fibers converge at one common attachment site. They may pull on a tendon, an aponeurosis (tendinous sheet), or a slender band of collagen fibers known as a raph. The muscle fibers typically spread out, like a fan or a broad triangle, with a tendon at the apex. The prominent chest muscles of the pectoralis group have this shape. A convergent muscle has versatility, because the stimulation of only one portion of the muscle can change the direction of pull. However, when the entire muscle contracts, the muscle fibers do not pull as hard on the attachment site as would a parallel muscle of the same size. The reason is that the convergent muscle fibers pull in different directions rather than all pulling in the same direction.

Pennate Muscles

In a pennate muscle, the fascicles form a common angle with the tendon. Because the muscle cells pull at an angle, contracting pennate muscles do not move their tendons as far as parallel muscles do. But a pennate muscle contains more muscle fibers and, as a result, produces more tension than does a parallel muscle of the same size. Tension production is proportional to the number of contracting sarcomeres; the more muscle fibers, the more myofibrils and sarcomeres.

If all the muscle fibers are on the same side of the tendon, the pennate muscle is unipennate. The extensor digitorum muscle, a forearm muscle that extends the finger joints, is unipennate. More commonly, a pennate muscle has fibers on both sides of the tendon. Such a muscle is called bipennate. The rectusfemoris muscle, a prominent muscle that extends the knee, is bipennate If the tendon branches within a pennate muscle, the muscle is said to be multipennate. The triangular deltoid muscle of the shoulder is multipennate.

Circular Muscles

In a circular muscle, or sphincter, the fibers are concentrically arranged around an opening or a recess. When the muscle contracts, the diameter of the opening decreases. Circular muscles guard entrances and exits of internal passageways such as the digestive and urinary tracts. An example is the orbicularis oris muscle of the mouth.

MUSCLE REFLEXES

A stretch reflex is a muscle contraction in response to stretching within the muscle. It is a monosynaptic reflex which provides automatic regulation of skeletal muscle length.

When muscle lengthens, the spindle is stretched and the activity increases. This increases alpha motoneuron activity. Therefore the muscle contracts and the length decrease as a result. The gamma co-activation is important in this reflex because this allows spindles in the muscles to remain taut, therefore sensitive, even during contraction.

Function of this reflex is to maintain a constant length and has the shortest latency of all spinal reflexes including 'Reflex mediated by the GTO (Golgi Tendon Organ)' and 'Reflex mediated by pain and cutaneous receptors'.

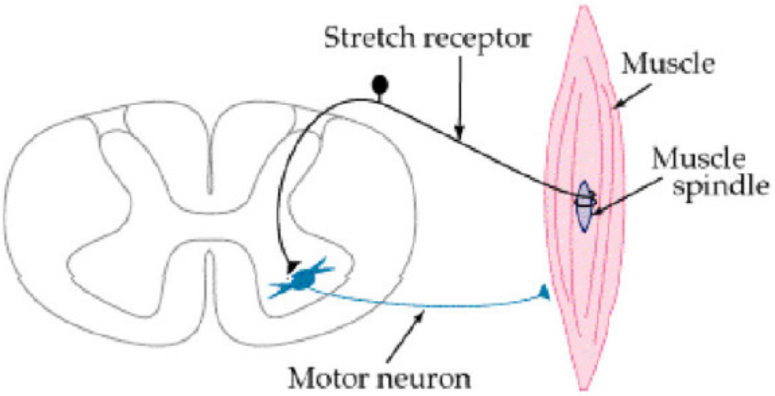


Figure 9: Illustration of the stretch reflex

The mechanical action of vibrations produces short fast deformation of the muscle and tendon, stimulating the primary Ia afferents of muscle spindles

[Burke et al, 1976a and 1976b]. Secondary muscle spindle endings and Golgi tendon organs also respond to vibration [Burke et al, 1976a and 1976b], but these receptors are not as responsive to vibration as the primary afferent endings [Brown et al, 1967; Trott, 1976]. Upon stimulation of the primary la afferents, afferent neurons transmit impulses to the spinal cord. From the spinal cord the sensory neurons synapse with the alpha motor neuron of the stretched muscle, exciting the muscle's extra-fusal fibers producing a contraction. At the same time, the afferent neurons also connect with inhibitory motor neurons of the antagonist muscle inhibiting contraction of this muscle.

Vibration stimulates both monosynaptic and polysynaptic reflex pathways [Burke and Schiller, 1976]. Monosynaptic reflex pathways are the simplest reflex pathways consisting of an afferent neuron, one synapse, and an efferent neuron.

MUSCLE OF LOWER LIMBS

Since, for our purpose we are focused on lower limb muscles, a brief description of quadriceps muscles will be provided to the reader.

The quadriceps femoris, also called simply the quadriceps, is one of the largest muscle group in the body.

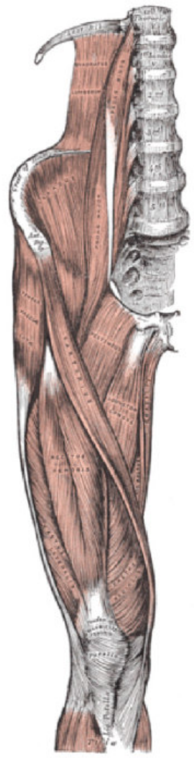


Figure 2: Quadriceps muscle anatomy representation (Adopted from Wikimedia Commons)

It includes the four prevailing muscles on the front of the thigh. Quadriceps femoris is the biggest extensor muscle of the knee, forming a large mass which covers the front and sides of the femur.

Quadriceps muscle is divided into four separate portions or ‘heads’ (from the latin quadri-ceps four-head), which have received distinctive names:

- Rectus femoris has a fusiform shape; its superficial fibers are disposed in a bipenniform arrangement, the deep fibers running straight down to the deep aponeurosis. It occupies the middle of the thigh, covering most of the other three quadriceps muscles. It originates on the ilium;

- The other three lie deep to rectus femoris and originate from the femur body:
    a. Vastus Lateralis is on the lateral side of the femur (i.e. on the outer side of the thigh);
    b. Vastus Medialis is on the medial side of the femur (i.e. on the inner part thigh);
    c. Vastus intermedius lies between vastus lateralis and vastus medialis on the front of the femur (i.e. on the top or front of the thigh).

All four parts of the quadriceps muscle attach to the patella (knee cap) via the quadriceps Tendon

Quadriceps Femoris	**ORIGIN**	**INSERTION**	**NERVE SUPPLY**	**ACTION(S)**
Rectus Femoris	Anterior inferior iliac spine. Ilium superior to acetabulum	Bass of patella and by patellar ligament to tibial tuberosity	Femoral nerve	Extends leg at knee joint. Rectus Femoris also steadies hip joint and helps iliopsoas to flex thigh
Vastus Lateralis	Greater trochanter. Lateral lip linea aspera			
Vastus Medius	Intertrochanteric line. Medial lip linea aspera			
Vastus Intermedius	Anterior and lateral surfaces of body femur			

Figure 11 : Short explanation of muscle origin, insertion innervation and action of quadriceps

The action of quadriceps muscle is to extend the knee joint. Its four components are crucial in walking, running, jumping and squatting.

Rectus Femoris attaches to the ilium, this cause this muscle to be also a flexor of the hip. This action is also crucial to walking or running as it swings the leg forward into the ensuing step.

INNERVATION OF QUADRICEPS

As we already mentioned in WBV studies there is a large use of surface EMG signal analysis as a tool to monitor the electrical activity and metabolic conditions including local fatigue of muscles.

However, surface EMGs are affected by the electrode conditions, the characteristics of subcutaneous tissues and also affected by the position of recording electrodes with respect to the innervation zones and tendons.

Placed the electrodes on the innervation zones will result in different mutual interferences of motor unit action potentials (MUAPs), leading to an incorrect estimation of the power spectra and muscle fiber conduction velocity (MFCV).

These situations warrant advising the placing of electrodes between the innervation zones and tendons.
MUAPs arise from the innervation zones and propagate directionally along the muscle fibers to both fiber ends.

Since classical interference pattern is modified by the electrode positioning and by the innervation zones, the knowledge of the distribution of the innervation zones in the muscles concerned is important for correctly estimating the surface EMG. This would be desirable to understand were the muscles are innervated and how EMGs have been expected from that positioning.

Some authors reported the innervation zones of different body muscles. A study of Saitou et al, 2000 reports the innervation zones of lower limbs and in particular the innervation of Quadiceps muscle, such as rectus femoris, vastus medialis and vastus lateralis.

As reported from the study, the innervation zones of vastus lateralis and medialis were distributed in the middle of muscle fibers running upward from the common tendon of the quadriceps femoris. The muscles showed clear propagation of MUAPs.

Clear propagation of MUAPs as shown in Figure 12 has been rarely seen in the rectus femoris. The innervation zones of this muscle were distributed around the muscle belly irregularly.

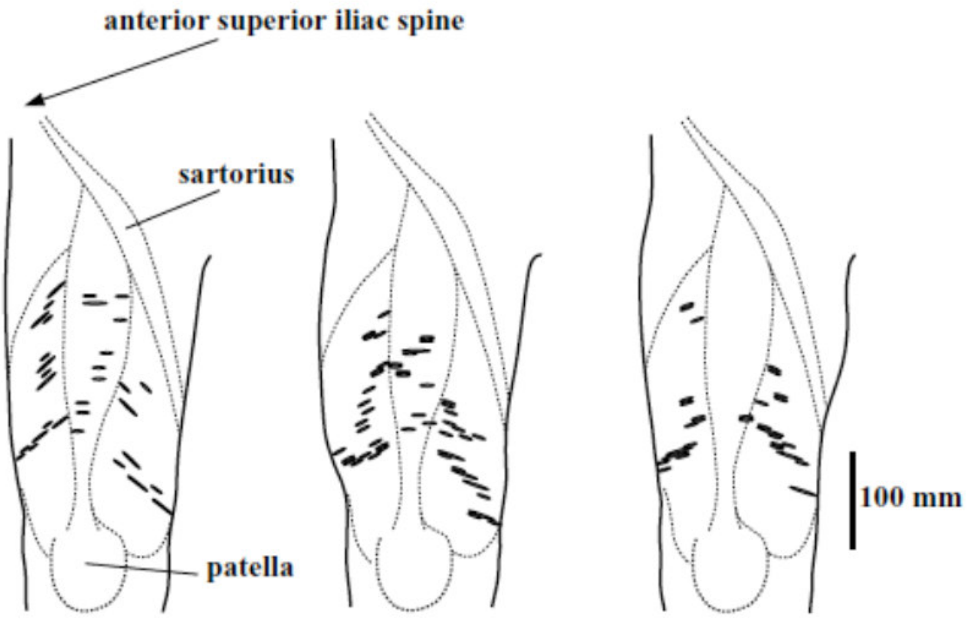


Figure 32: Innervation zones of Quadriceps (Adopted from Saitou et al, 2000)

CHAPTER 4 - EXPERIMENTAL SETUP

EXPERIMENTAL SETUP

The experimental setup used for the study is depicted in figure 13.

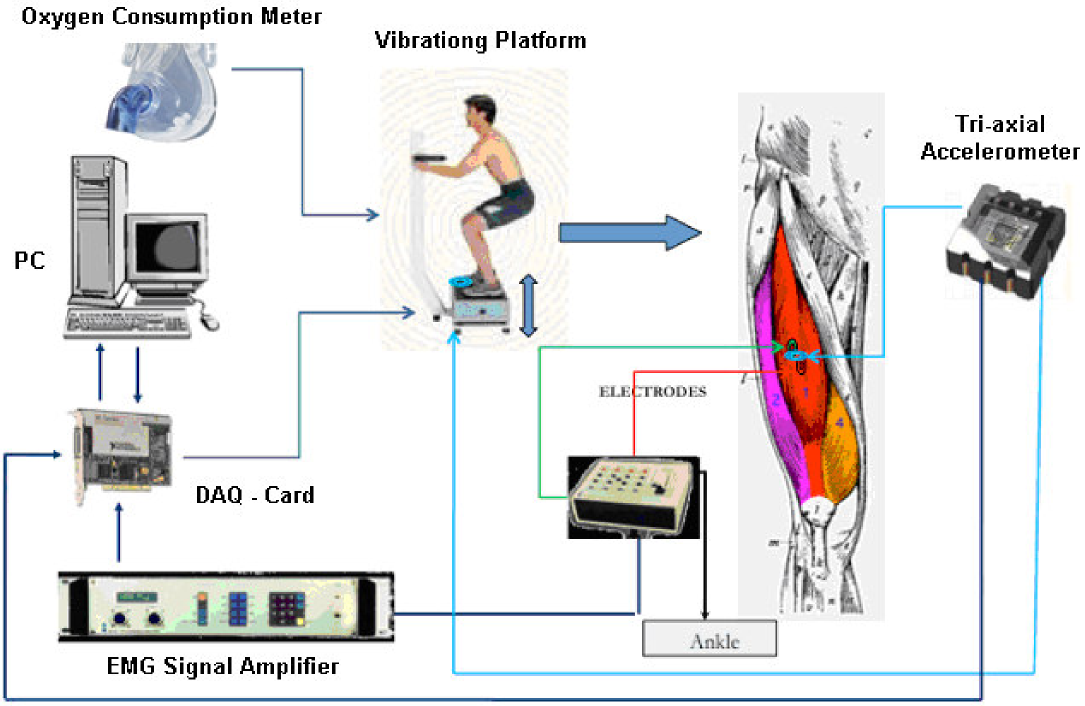


Figure 13: Measurement setup used for the study

The system is composed by:

- the vibrating platform (TSEM S.p.A., Padova, Italy);
- a PC (IBM-compatible);

- a data acquisition card (National Instruments NIDAQ-6251);
- four MEMS tri-axial accelerometers (Freescale);
- a Biosignal amplifier (Biomedica Mangoni BM-628)
- Fitmate Pro (Cosmed S.r.l.)

VIBRATING PLATFORM

The device used to deliver vibration was made available from the manufacturer TSEM S.p.A. (Padova, Italy). The vibrating platform uses two motors to produce vibration stimulus and an inverter to change the frequency of the generated vibration.

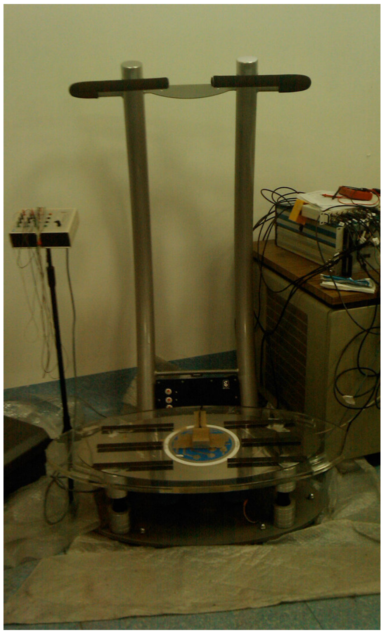


Figure 14: Vibration device

The device is also able to produce two types of vibration: vertical (named "high" amplitude from manufacturer) and elliptical (named “low” from manufacturer) depending on the choice of the operator. Platform was accurately modified by the producer to allow the remote control of the device from a PC via the acquisition card and via the function generator.

STIMULUS CONTROL AND DELIVERY

The vibrating platform were controlled by a digital output of the NIDAQ card with a voltage signals corresponding to a frequency of 26 Hz, since it is close to the activation frequency of the quadriceps muscle group (Abercromby et al, 2007, Cardinale and Lim, 2003, Rittweger et al, 2001).

The system platform/PC/NIDAQ card was calibrated in order to obtain a correct correspondence between voltage signal applied and frequency of vibratory stimulus. A linear function was found to be accurate for calibration:

$$V = a * f + b$$

where a was set equal to 0.0609 and b equal to -0.8296 (experimentally verified)

The amplitude used in this study was set at "high" and measured. The amplitude of the measured vibration was 3 mm (peak to peak displacement).

BIO-SIGNALS ACQUISITION

A PC was used to acquire surface electromyography (SEMG) and acceleration signals and to drive the vibrating plate. The PC was equipped with a multi-channel 16-bit data acquisition card (National Instruments DAQCard 6251 (main specs are detailed below)

National Instruments NIDAQ 6251

Output

- 2 channels: 2.00 MS/s
- DAC resolution: 16bits
- Output range: ±10V, ±5V
- Output current drive: ±5mA

Input

- Number of channels: 8 differential or 16 single ended
- ADC resolution: 16 bits
- Sampling rate: Maximum 1.25 MS/s single channel, 1.00 MS/s multi-channel
- Input range: ±10±, ±5V, ±2V, ±1, ±0.5V, ±0.2V, ±0.1V
- Input impedance: 10GΩ in parallel 100pF
- Small signal bandwidth (~3dB): 1.7 MHz
- Input FIFO size: 4.095 samples

All signals were sampled at a specific frequency (2048 Hz), analyzed and processed at the time of the test and stored in the PC hard-disk for future investigations.

SURFACE ELECTROMYOGRAPHY RECORDING

Surface EMG signals were recorded using small disc Ag/AgCl electrodes (mainly Arbo Kendall electrodes) with inter-electrode distance of 20 mm arranged in the direction of the muscle fibers. Electrode skin areas were shaved and cleaned before electrodes placement, conductive gel was used when necessary. Electrode placement was achieved in accordance with the guidelines of SENIAM Project. [Hermens et al, 1999]

Figure 15: Adhesive electrodes used for surface EMG recordings

For our purposes we focused on leg muscles.

Reference electrode was always located on the ankle of the leg of the examined muscle activity. EMG signals were amplified using a multi-channel, isolated biomedical signal amplifier (Biomedica Mangoni, Pisa, Italy - model. BM623) with an input impedance > 10 MOhm and CMRR > 100 dB (see figure). The gain was set to 1000 V/V;

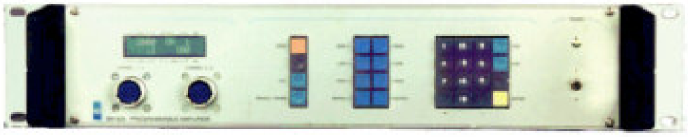


Figure 46: Biomedical signal multi-channel amplifier BM623

CARDIO-RESPIRATORY PARAMETER RECORDING

All subjects wore FitMate Pro silicone face mask that was fitted with a head cup to prevent air leakage, and a HR chest strap; both connected to the FitMate Pro (by Cosmed srl).

The subjects' oxygen uptake (VO_2) was continuously recorded by means of an oxygen consumption meter (Galvanic Fuel Cell sensors with an accuracy of ± 0.02%).[Nieman et al, 2007] Specific oxygen consumption (sVO_2) was obtained by dividing the instantaneous VO_2 by the body mass.

The sVO_2 values and the HR signals were monitored continuously during the whole EU in order to analyze their trends during the exercise.

To assess the intensity of each exercise, the subjects gave a rating of perceived exertion (RPE) at the end of each exercise [Borg, 1970 and 1990].

ACCELERATION SIGNAL RECORDINGS

To reveal the acceleration of the platform, acceleration signals were registered using tiny and lightweight (less than 10g with the board) accelerometer produced by Freescale. In particular we used a MMA7261QT (sensitivity of 0.12 V/g., i10g max). The accelerometers were placed at the center of the vibrating platform.

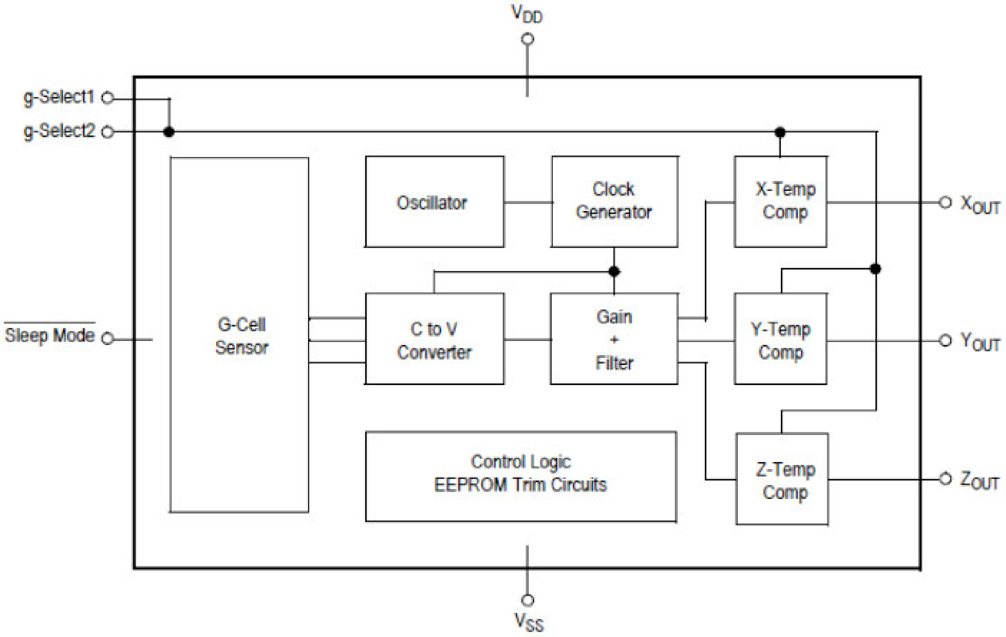


Figure 17: Simplified accelerometer block diagram

The accelerometers are capacitive MEMS sensors with a temperature compensation system and the possibility to operate in Sleep Mode (reduced power consumption), which makes them ideal for operation in battery—powered devices. Figure 18 shows the pinout description of the device:

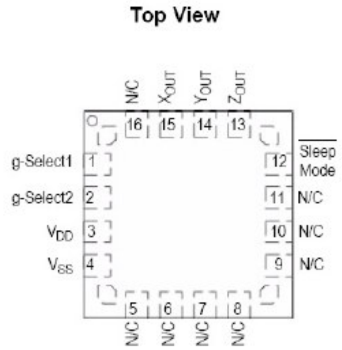


Figure 18: Pin connection for MMA7260QT MEMS accelerometer

ACQUISITION AND PROCESSING SOFTWARE SUITE

Specific software was developed to acquire, store, visualize and process both surface electromyography and specific oxygen uptake recordings. The software was written using MatLab IDE. In the following paragraphs a brief description of the suite is given.

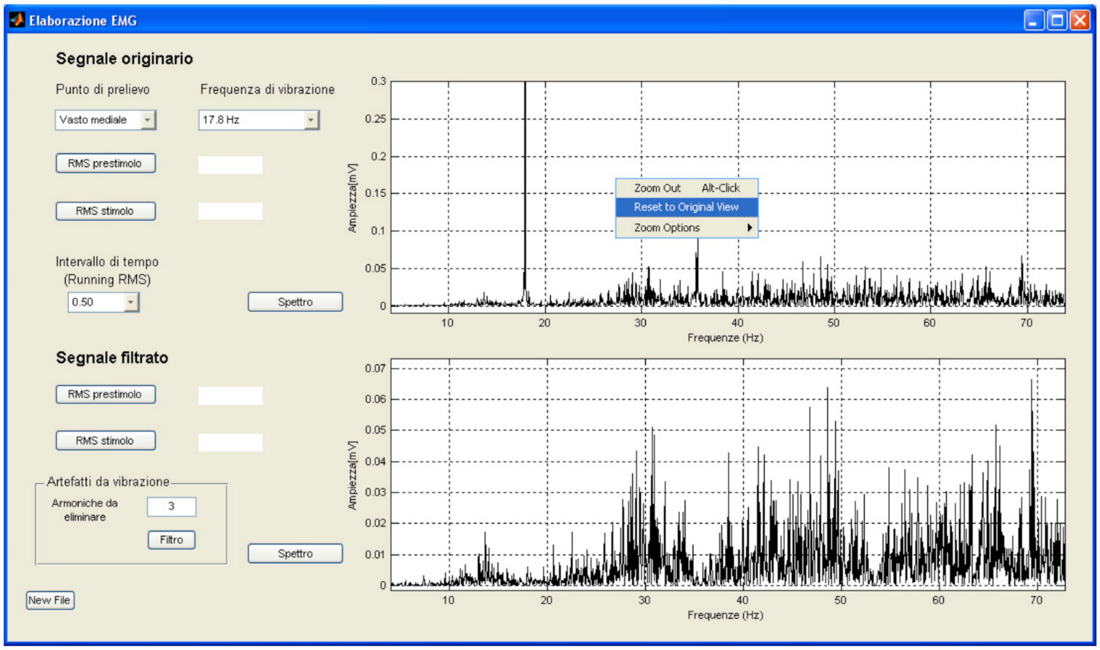
The software suite allows the operator to easily do some basic operations such as open and plot a file.

Spectral analysis and Signal Processing

A different section of the software is dedicated to the spectral analysis and signal processing. Spectral analysis allows the operator to compute and visualize either the amplitude and phase spectra or the power spectra of the signals.

Some basic filtering operations are possible in the processing section: High, low, band pass and notch filtering were implemented in this version; all the filter parameters (filter type, cut off frequency, filter band) are adjustable through simple command windows.

Each of the filtering operations can be seen at the time of the execution in the bottom window (see figure 19). Power and RMS values of the analyzed signal can also be easily computed, allowing the operator to compare, as an example, the total signal power with the power contained in specific target bands.



Elaborazione EMG

Segnale originario

Punto di prelievo: Vasto mediale

Frequenza di vibrazione: 17.8 Hz

Intervallo di tempo (Running RMS): 0.50

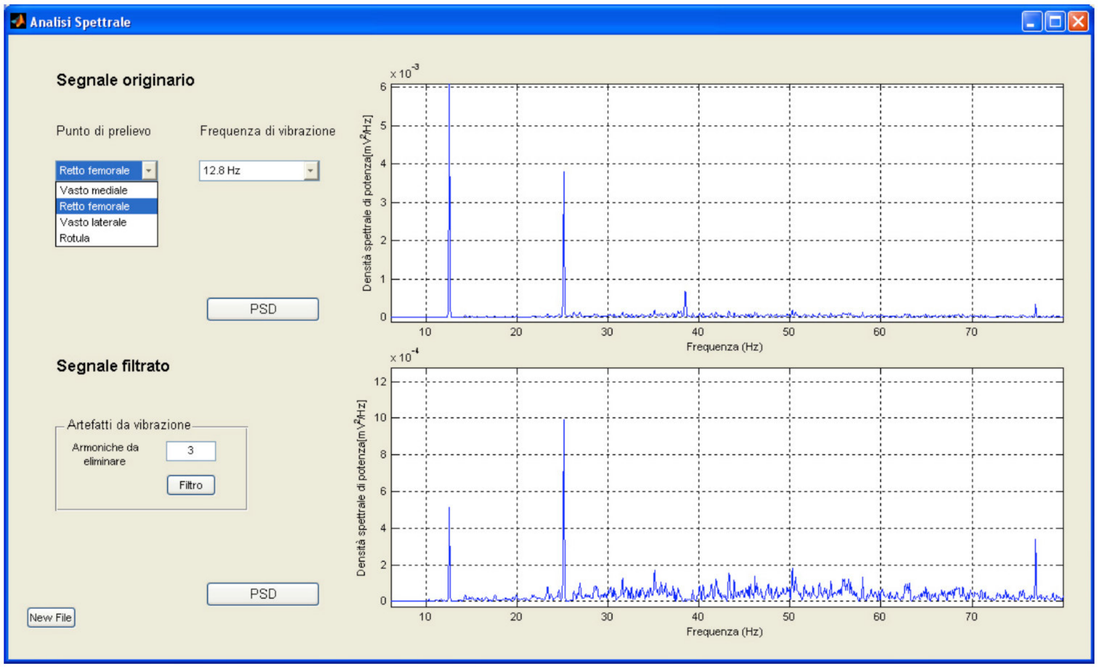
Segnale filtrato

Artefatti da vibrazione

Armoniche da eliminare: 3

Figure 19: Amplitude spectrum of a Vastus Medialis SMG. The windows shown the signal before (top window) and after (bottom window) a notch filter.

EMG power spectrum is computed using Welch‘s averaged, modified periodogram method. RMS values are estimated using 500 ms time window without overlapping



Punto di prelievo: Retto femorale

Frequenza di vibrazione: 12.8 Hz

Armoniche da eliminare: 3

Figure 20: Power spectrum of a Rectus Femoris SEMG. The windows show the signal before (top window) and after (bottom window) a notch filtering operation.

STUDY PROTOCOLS

Different individuals were involved in the study; they were almost all students, not affected by any known neurological or musculoskeletal disorders, and voluntarily joined the study giving their informed, written consent to participate. All the subjects familiarized with the device and the postures to be assumed on the platform before the test.

Two different postures were utilized in this study:

- unloaded static squat: subject is standing with feet apart, knees bent at the angle 90°

- unloaded dynamic squat: the subjects performed cyclic motions squatting between an angle of 110° and an angle of 90° of knee flexion with a rate of repetition equal to about 20 squats per minute

Before each exercise, stance of participants was monitored by checking that the distance between their heels was shoulder-width and the knee angle was evaluated by means of a goniometer.

The exercise sequence for each subject was randomized and between each exercise all the participants rested for about 20 min, until they felt recovered and their HR and sVO2 signals were returned to initial values.

CHAPTER 5 - ANALYSIS OF THE EFFECTS OF VIBRATION ON OXYGEN UPTAKE AND ELECTROMYOGRAPHIC SIGNAL

ANALYSIS OF THE EFFECTS OF VIBRATION ON MUSCLE

The most cited mechanism to explain the effects of vibration treatment extended to the whole body is the elicited neuromuscular activation via the tonic vibration reflex (TVR). [Nordlund and Thorstensson, 2008]

The theory was initially proposed by Eklund and Hagbarth [Eklund and Hagbarth , 1966] as the result of a vibration exposure applied directly to the tendon.

However, WBV stimulation is clearly different from a localized tendon vibration, and the connection between WBV and the TVR has not been fully discussed or demonstrated in the literature. [Nordlund and Thorstensson, 2008].

From the review analysis presented in chapter 2, other aspects were pointed out. Results in literature were found not yet coherent and as already mentioned, this may be attributable to different reasons.

The methods to assess acute effects of vibration, such as EMG activity analysis under vibration, has to be refined, artifacts may arise from electrodes altering the treatment efficacy assessment.

The real local (muscle) vibratory stimulation has to be characterized in individuals undergoing vibration treatments to obtain a clear knowledge of the effective muscle stimulation.

Subject postures during treatment and the real kinematic chains involved in vibration transmissibility have to be pointed out.

Nevertheless, studies on WBVT should have a detailed description of the stimulation and measurement protocols; individual postures, amplitude and frequency of vibration may be chosen depending on the target of the treatment.

This work's aim was to focus on the above detailed key points of vibratory stimulation to contribute to a better understanding of the phenomena that are responsible for the positive (and negative) effects ascribed to WBVT.

This section offers in detail the entire work carried out during these years. The chapter is partitioned to discuss each step of the study in a chronological order.

All the findings of the entire research activity are here presented.

THE EFFECT OF WHOLE BODY VIBRATION ON OXYGEN UPTAKE AND ELECTROMYOGRAPHIC SIGNAL OF THE RECTUS FEMORIS DURING STATIC AND DYNAMIC SQUAT

As already cited, many studies report a significant increase of oxygen uptake during vibration training. These studies are based on the assumption that the sVO_2 response is due to the increased number of muscle fibers (and thus the increased muscle activity) activated by the vibrations (Martin and Park, 1997; Person and Kozhina, 1992; Roll et al, 1989; Romaiguére et al, 1991).

In fact, Rittweger et al. [Rittweger et al, 2001] reported that simple standing and dynamic squats performed on a WBV platform increased sVO_2 compared to the same exercise without vibration. Later, Rittweger et al. [Rittweger et al, 2001] showed that the sVO_2 was increased when vibration frequency and amplitude were increased.

Similarly, after monitoring sVO_2 and heart rate (HR) during and 24 hrs after a WBV exercise session and a second session without vibration (NoV), Hazell and Lemon [Hazell and Lemon, 2011] reported that sVO_2 was 23% higher during WBV training session.

Other research activities showed a significant increase of EMG RMS values in the lower body muscles during vibration training; these changes suggest an increase in neuromuscular activity [Cardinale et al, 2003; Verschueren et al, 2004]. Specific WBV frequencies also seem to produce a higher EMG RMS signal than others [Cardinale and Lim, 2003]. Frequency that maximizes the RMS corresponds to the highest muscular response [Cardinale et al, 2003].

Nevertheless, it is well known that during surface bio-potential recording, motion artifacts arise from relative motion between electrodes and skin and also between skin layers. Also the only skin stretch, modifying the internal charge distribution, results in a variation of electrode potential [Turker et al, 1993; De Talhouet et al, 1996; Odman et al, 1982; Tam et al, 1977].

In literature mainly deals with motion artifact affecting clinical recording, as ECG, EEG, EMG, electrical impedance pneumography, etc. In electrocardiography, motion artifact voltage amplitude can result even ten times larger than signal and can be particularly troublesome either in ambulatory ECG recordings and much more during exercise ECG (Holter monitoring or stress tests) [Clancy et al, 2001]. Since typical power density of these types of artifacts is below 20 Hz, 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.), frequency content of motion artifact is also considered below 10-20 Hz, then the general approach to motion artifact reduction is to apply a high-pass filter (e.g. with a cut-off frequency of 20 Hz): little of the EMG signal power is lost, whilst most motion artifact is rejected [Hermens et al, 1999]. However, in particular situation as vibration treatment, power of motion artifacts is not confined below 10-20 Hz and standard high-pass filters are not suitable for filtering out this artifact.

However, it is important to point out that the studies presented in literature investigated WBV effects only on muscular activity by recording electromyographic signal [Abercromby et al, 2007; Roelants et al, 2006] or on metabolic power by monitoring the sVO_2 [Hazel and Lemon, 2011; Rittweger et al, 2001 and 2002] without standard protocol and using different exercise parameters. The purpose of this study was to monitor simultaneously both signals in a novel approach. We investigated the differences due to WBV effects on VO_2 and EMG between static and dynamic squat exercises. This was done to identify the better exercise characteristics for improving neuromuscular activation and progress in training efficacy. Monitoring VO_2 throughout the exercise and not just during the last seconds (sVO_2) of the exercise [Rittweger et al, 2001 and 2002] allows for analyzing the curves from the beginning of the exercise in order to find out possible differences in the sVO_2 trend and differences in how it is reached at steady-state.

METHODS

Subjects

Fourteen subjects in good health and not affected by any neurological or musculoskeletal disorder participated in this study. All subjects (11 males and 3 females) had been practicing regularly physical activity or non-competitive sports. The subjects were 22 to 31 yrs of age with mean and standard deviation, respectively, of 26.4 and 3.2 yrs. Their height was between 165 and 182 cm (171±6 cm), and their body weight was between

55 and 81 kg (68±9 kg). The experiments were conducted in accordance with the Declaration of Helsinki and all the subjects signed a written informed consent.

Exercises

Before the testing session, the subjects were familiarized with the vibration platform and squat exercises. The warm-up consisted of exercising on a bicycle ergometer at a load of 70 W for 10 min followed by stretching exercises for 5 min. All subjects wore socks without shoes. They performed a protocol of four kinds of exercise units (EU) that lasted 3 min and 30 sec. In the first two EU (Figure 21a), the subjects ran through an unloaded static (isometric) squat (knee angle at ~90°), without and with vibration (SS and SSV, respectively). In the other EU (Figure 21b), the squat exercises were dynamic (i.e., the subjects performed cyclic motions squatting between an angle of 110° and an angle of 90° of knee flexion with a rate of repetition equal to about 20 squats per minute) without and with vibration (DS and DSV, respectively). The exercises with no vibration (SS and DS) were used as control.

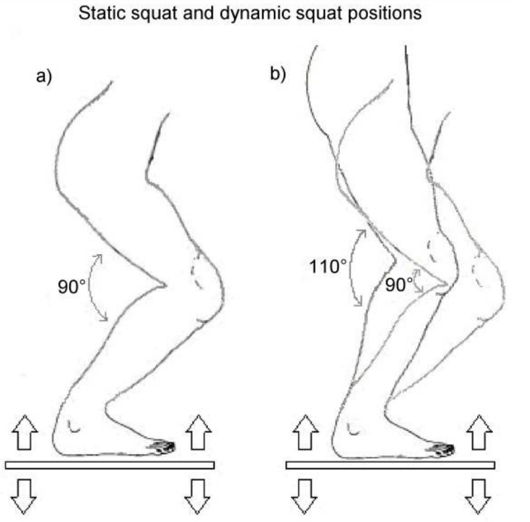


Figure 21: Static squat (a) and dynamic squat (b) positions.

Before each EU, stance of participants was monitored by checking that the distance between their heels was shoulder-width and the knee angle was evaluated by means of a goniometer. The EU sequence for each subject was randomized and between each exercise all the participants rested for about 20 min, until they felt recovered and their HR and sVO_2 signals were returned to initial values. We used CE-marked Medical Devices within the limits and according to the standard training protocols specified by the manufacturers.

Whole-body vibration treatment (WBV)

The WBV treatment was performed by using a vertical oscillating WBV platform (Vibroplate provided by TSEM SpA). The platform provided a sinusoidal vibration at a frequency of 26 Hz and a peak-to-peak displacement of 3 mm. The value of 26 Hz was chosen since it is close to the activation frequency of the quadriceps muscle group [Abercromby et al, 2007; Cardinale and Lim 2003; Rittweger et al, 2001]. The platform oscillation frequency was checked through a triaxial accelerometer based on MEMS technology placed in the platform center.

Surface EMG

Surface EMG (sEMG) signals were recorded by using small disc Ag/AgCl electrodes (diameter 5 mm) with inter-electrodes distance of 20 mm arranged in the direction of the muscle fibers, placed on the rectus femoris (RF) in accordance with the literature [Hermes et al, 1999 and 2000]. In order to reduce skin impedance (<3 kΩ), electrode skin areas were shaved, cleaned with alcohol and a conductive gel was used. For the purpose of this study, we focused on the RF of the dominant leg [Petit et al, 2010] and reference electrode was located on the ankle of the same leg.

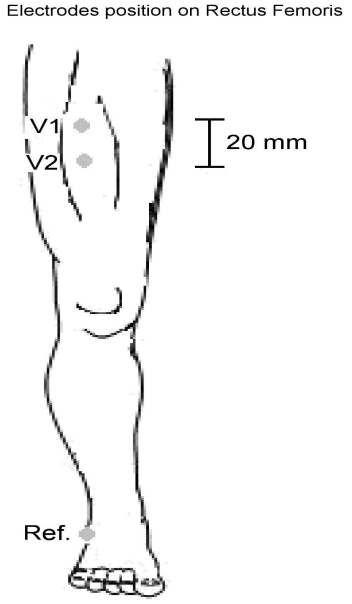


Figure 22: Electrodes position on Rectus Femoris according to SENIAM project [Hermens et al, 1999 and 2000] .

The sEMG signals were amplified by using a multi-channel, isolated biomedical signal amplifier BM623 (Biomedica Magoni) with an input impedance >10 MOhm and CMRR >100 dB. The amplifier was set with a gain of 1000 V/V and a band pass filtering with cut-off frequencies of 5–500 Hz. The signals were acquired by using a PC multi-channel 16-bit data acquisition card with a sample frequency of 2048 Hz (DAQCard 6251 by National Instruments).

It is well-known that during a surface bio-potential recording, the motion artifacts that arise from relative motion between electrodes and skin result in a variation of electrodes potential. Hence, vibrations generate motion artifacts on electrodes that could be non-negligible and could affect the sEMG signals analysis [Fratini et al, 2009a; Ritzmann et al, 2010]. Since vibration frequency and its harmonics lie in the sEMG frequency band of 20 – 450 Hz, in order to reduce artifacts contribution, the acquired signals were processed by using sharp notch filters (band width of ±0.8 Hz) centered at the vibration frequency and its harmonics [Abercromby et al, 2007; Fratini et al, 2009a; Pollock et al, 2010; Roy et al, 2007]. Filters were applied to all recordings including those without vibration to ensure that loss of signal power due to the filtering procedure was the same in all recordings. Running root mean square values of the sEMG (EMGrms) were estimated by using 500 ms time window to assess muscular activity during the EU [Abercromby et al, 2007; Fratini et al, 2009a]. The mean value of the EMGrms curve (mEMGrms) of each recording was computed. The mEMGrms values for the SSV and DSV were compared respectively with the controls (SS and DS), thus normalization relative to maximal voluntary contractions was unnecessary [Marin et al, 2009]. Signal processing was done by using MATLAB® R2010b (The Mathworks Inc., Natick, MA).

Specific Oxygen Uptake

The subjects' oxygen uptake (VO_2) was continuously recorded by means of an oxygen consumption meter (Galvanic Fuel Cell sensors with an accuracy of ± 0.02%).[Nieman et al, 2007] Specific oxygen consumption (sVO_2) was obtained by dividing the instantaneous VO_2 by the body mass.

All subjects wore FitMate Pro silicone face mask that was fitted with a head cup to prevent air leakage, and a HR chest strap; both connected to the FitMate Pro. The sVO_2 values and the HR signals were monitored continuously during the whole EU in order to analyze their trends during the exercise. To make a comparison between the static and the dynamic squat exercises, the data acquired during the last 30 sec was used [Rittweger et al, 2001].

Rate of Perceived Exertion and Heart Rate

To assess the intensity of each EU, the subjects gave a rating of perceived exertion (RPE) at the end of each exercise [Borg, 1970 and 1990]. Resting HR was monitored before each exercise to check that the subjects recovered completely. The mean value of HR was estimated in the last 30 sec (HR_{30}) of each EU to investigate the effect of WBV on the cardio-circulatory system [Bogaerts et al, 2009; Hazell and Lemon, 2011]. In particular, estimated HR30 values were used to compute for each subject the increase in beats·min^{-1} (dHR_{30}) between the exercise NoV and the correspondent WBV one, according to the formula: $dHR_{30} = HR_{30WBV} - HR_{30NoV}$

Statistical Analysis

Variables, sVO_2, mEMGrms, and dHR_{30}, were tested for normal distribution with the Kolmogorov-Smirnov test (level of significance equal to 0.05) [Marsaglia et al, 2003; Smirnov, 1948]. Paired t-test was used to test differences in the sVO_2 and mEMGrms values obtained in WBV versus NoV exercises, while a one-sample t-test was performed on dHR_{30} to check the possibility of rejecting the null hypothesis (no difference in HR between exercises with WBV and NoV). Statistical significance level was set at $P \leq 0.05$. Statistical analysis was done by using the software IBM SPSS statistics 19.

RESULTS

Surface EMG

The analysis of the sEMG activity of all subjects showed that the computed EMGrms signals kept on average constant along the exercise, but their values were higher in the WBV exercises respect to the correspondent NoV (Figure 23). The mEMGrms values were normally distributed (Kolmogorov-Smirnov's test and their means and standard deviations (Figure 24), in static and dynamic squat, indicated respectively a rise of about 63% (0.205±0.078 vs. 0.325±0.091 mV) and 108% (0.152± 0.055 vs. 0.317±0.109 mV). Paired t-test of the mEMGrms proved that the differences between WBV and NoV for both static and dynamic exercises are significant ($P \leq 0.05$) showing that whole body vibration increased muscle activity.

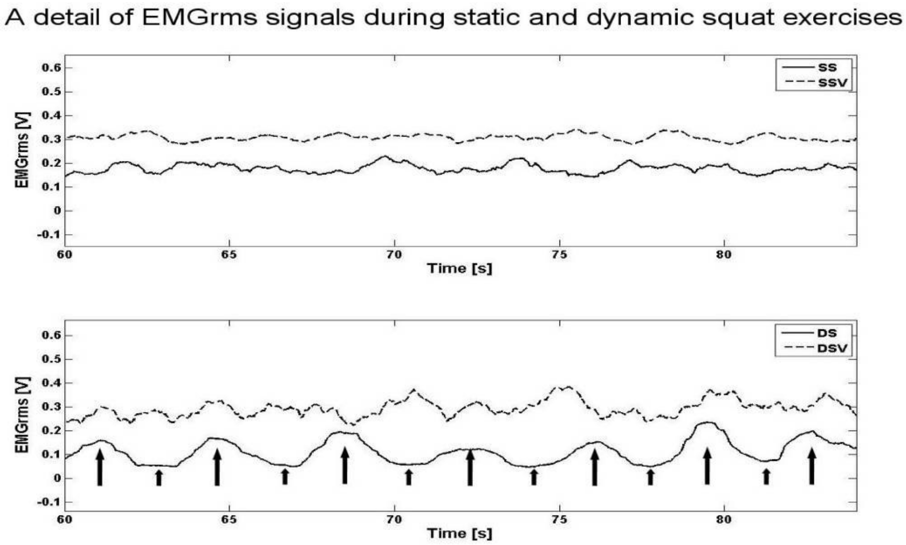

A detail of EMGrms signals during static and dynamic squat exercises

Figure 23. A detail of EMGrms signals during static (top) and dynamic (bottom) squat exercises of subject # 9. During DS exercise, EMGrms varied periodically according to the knee angle (long and short arrows in correspondence of respectively 90° and 110° angles), however its mean value holds constant.

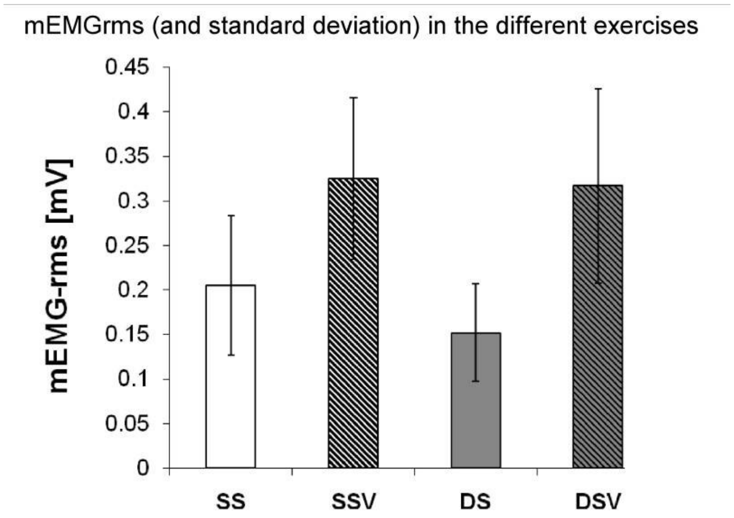


Figure 24. mEMGrms (and standard deviation) in static and dynamic exercises, with and without WBV.

Specific Oxygen Uptake

Figures 25, 26, and 27 illustrate examples of VO_2 monitored during static and dynamic exercises, with and without vibration. The WBV treatments increased the sVO_2 during the whole EU session versus the same exercise NoV, and this effect was present in all the subjects. In most of the recordings, the sVO_2 increased during the exercise up to a plateau reached approximately after the 3rd min. Thus, the mean and standard deviation of the sVO_2 values of the last 30 sec ($sVO_{2\text{-}30s}$) were chosen to compare the different EU conditions [Rittweger et al, 2001].

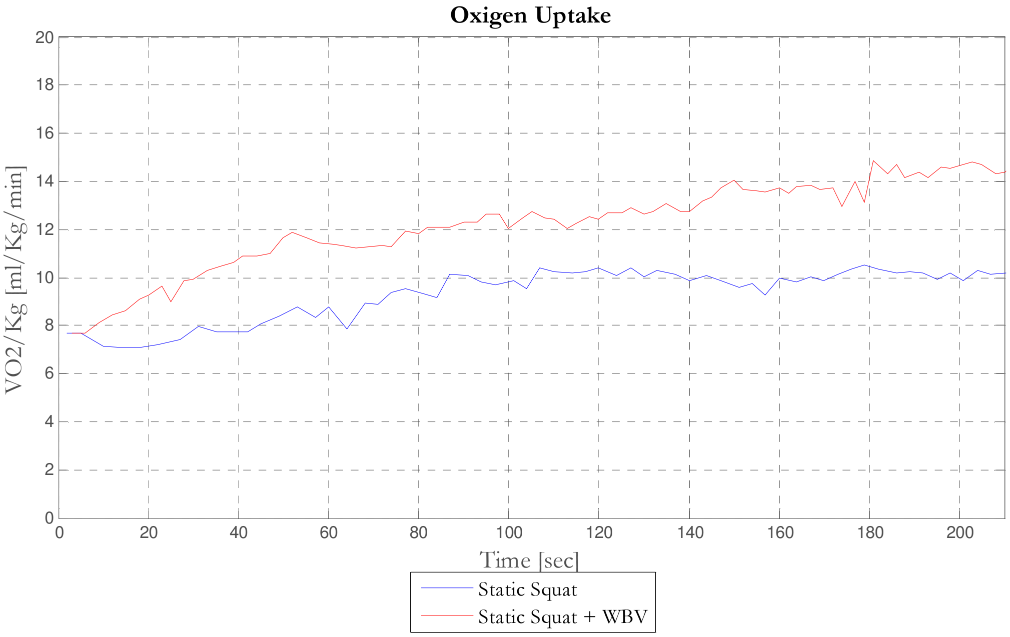


Figure 25. Oxygen uptake of subject #5 during SS and SSV. sVO_2 during SS grew for 90 sec, then it achieved a steady-state at the maximum value of 10.4 [ml·kg^{-1}·min^{-1}]. During SSV, sVO_2 increased to a maximum value of 14.9 [ml·kg^{-1}·min^{-1}].

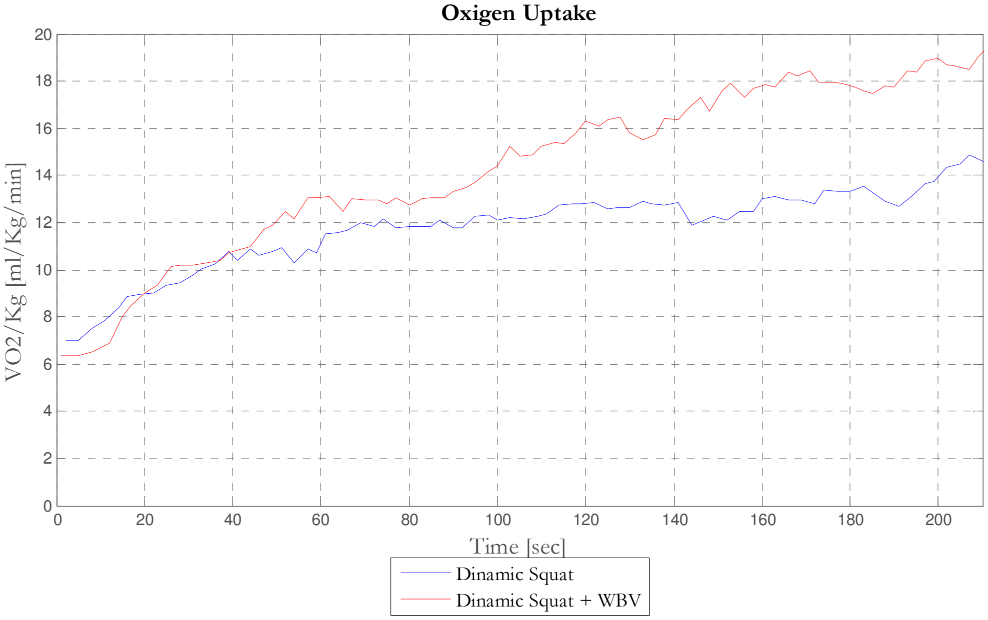


Figure 26. Oxygen uptake of subject #5; sVO_2 curves for DS and DSV show a similar pattern for the first 90 seconds and then diverge until the end. As for the static squat, sVO_2 during DS reached a plateau value around 13 [ml·kg^{-1}·min^{-1}] while sVO_2 in DSV showed an increase along the whole exercise up to a maximum value of 19.1 [ml·kg^{-1}·min^{-1}].

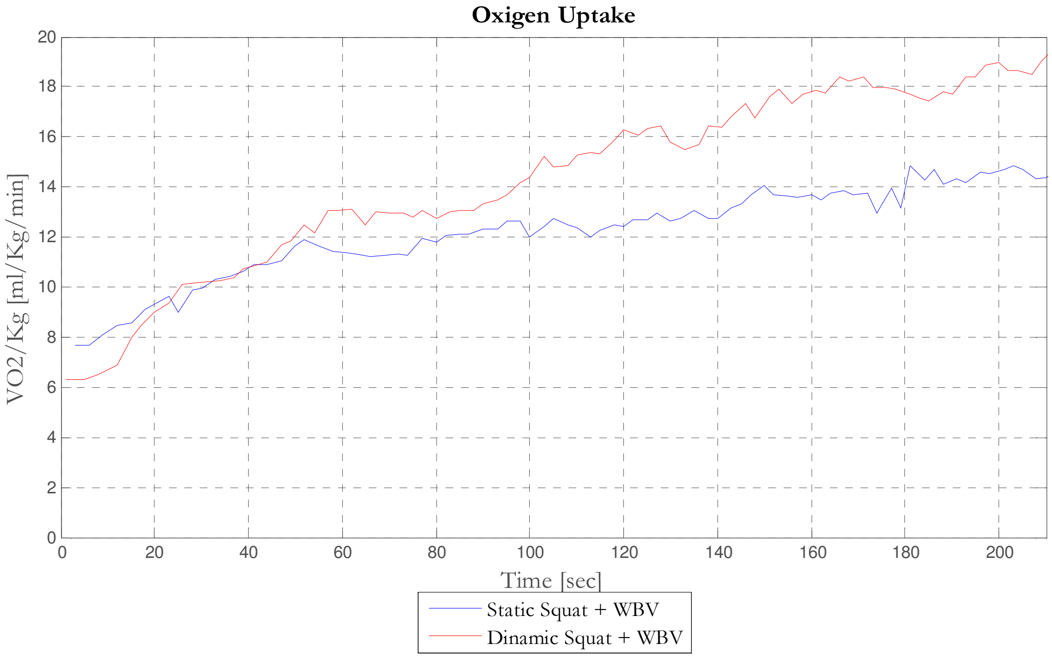


Figure 27. Oxygen uptake of subject #5; sVO_2 curves for SSV and DSV show a similar pattern for the first 50 sec and then diverge until the end, with higher values of sVO_2 in DSV.

In the majority of static squat recordings (Figure 25), for the same subject, the sVO_2 curves during SSV and SS exercises started from the same point and then diverged with different slope, higher in SSV curves. On the other hand, comparing data from DS and DSV (Figure 26) or SSV and DSV (Figure 27) exercises, sVO_2 trends were similar at the beginning and diverged significantly after about the 1st min. The $sVO_{2\text{-}30s}$ values were normally distributed and paired t-test confirmed the separation of the data over the NoV and WBV treatments in both static and dynamic EU. The WBV treatment showed a significant increase $sVO_{2\text{-}30s}$ that grew respectively of 44.0% (10.0±2.8 vs. 14.4±3.5 $[ml{\cdot}kg^{-1}{\cdot}min^{-1}]$) and 29.4% (14.3±2.7 vs. 18.5±3.9 $[ml{\cdot}kg^{-1}{\cdot}min^{-1}]$) (Figure 28).

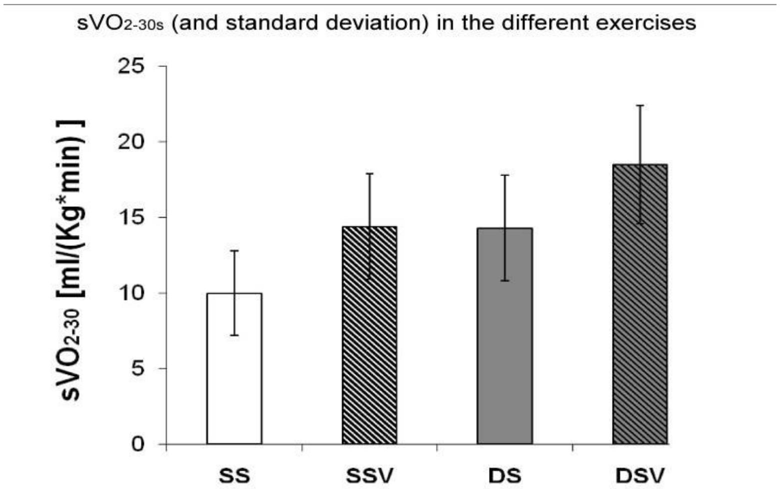


Figure 28. Mean values with standard deviations of the $sVO_{2\text{-}30s}$ estimated for all subjects. sVO_2 increased by 44.0% in presence of vibrations during static exercise, while in dynamic exercise the increment is of 29.4%.

Rate of Perceived Exertion and Heart Rate

Means and standard deviations for RPE during the static squat were 15.1±2.9 for NoV and 12.3±3.5 for WBV, while during the dynamic squat were 13.6±4.2 for NoV and 14.4±3.8 for WBV. No significant changes were observed between NoV and WBV exercises. However, the subjects seemed to perceive a greater effort after the static squat than the dynamic ones. The t-test results from the analysis of HR indicated that WBV treatment increased significantly the dHR_{30} for both static and dynamic squat exercises ($P \leq 0.05$), showing increments respectively equal to 11.1±9.1 beats·min^{-1} for static squat and 7.9±8.3 beats·min^{-1} for dynamic squat. Summarizing, the results are shown in the following Table 2.

Table 2. T-Test Results

	NoV	**WBV**	**p**
RPE SS	15.1 ± 2.9	12.3 ± 3.5	> 0.05
RPE DS	13.6 ± 4.2	14.4 ± 3.8	> 0.05
sVO_2 SS ($ml \cdot kg^{-1} \cdot min^{-1}$)	10.0 ± 2.8	14.4 ± 3.5	< 0.05
sVO_2 DS ($ml \cdot kg^{-1} \cdot min^{-1}$)	14.3 ± 2.7	18.5 ± 3.9	< 0.05
EMGrms SS (mV)	0.205 ± 0.078	0.325 ± 0.091	< 0.05
EMGrms DS (mV)	0.152 ± 0.055	0.317 ± 0.109	< 0.05
dHR_{30} SS	11.1 ± 9.1		< 0.05
dHR_{30} DS	7.9 ± 8.3		< 0.05

The t-tests summary on 14 subjects of the studied parameters in case of NoV and WBV treatment. Means, standard deviations and p-values were reported. Only for dHR_{30} a one-sample t-test was used to test the null hypothesis that the population mean is equal to zero (no differences due to WBV).

DISCUSSION

Whole-body vibration (WBV) training was initially used in the fitness industry, but has expanded to rehabilitation, therapy, and sports. The most common effect of WBV on the muscles is the increase in strength. But, given the lack of details in the methodologies applied in various research studies, it is difficult to investigate and verify the treatment outcomes. The purpose of this study was to analyze the effects of WBV treatment on 14 healthy subjects who performed squat exercises. We evaluated the muscular activity of the rectus femoris using EMGrms parameter estimated by electromyographic signals [Abercromby et al, 2007; Cardinale and Lim, 2003;

Fratini et al, 2009b; Marín et al, 2009]. All signals were filtered [Fratini et al, 2009a; Ritzmann et al, 2010] to reduce negligible motion artifacts due to vibrations while other signals and parameters were simultaneously taken into account. Oxygen consumption (VO_2) was used to estimate the exercise related metabolic power. Also, relative VO_2 was used to compare the VO_2 among different subjects. Heart rate and RPE provided information about the subjects' cardiac activity and the intensity of the exercise as perceived by each individual.

The main finding of this study was that WBV has the potential to increase both muscular and metabolic power, thus supporting the hypothesis that WBV has a stimulating effect on both twitch and tissue oxygenation of the muscles. In fact, our results demonstrate that estimated mEMGrms values are higher in the WBV exercises respect to the correspondent NoV of about 63% and 108% in the static and dynamic exercises, respectively. This finding agrees with the findings of Abercromby et al. [Abercromby et al, 2007]. They reported a significant improvement in neuromuscular activation during WBV exercises. In addition, our results indicated a higher increment of EMGrms correlated to WBV in the DSV than in the SSV.

The analysis of the NoV exercises showed that sEMG in the dynamic squat had a mean value less than the static one. This is in agreement with the observation that during the dynamic squat the twitch varies according to the knee angle. That is, since it is lower for angles >90°, the twitch in the static squat is always higher since the knee angle during the exercise is about 90°. Therefore, we hypothesized that the WBV effect would be more pronounced during the dynamic exercise, when the average of voluntary muscular contraction (not due to vibration) is lower.

Rittweger et al. [Rittweger et al, 2001] investigated the effect of vibration on VO_2 in different kinds of exercises. They reported incremental responses in sVO_2 with WBV treatments. Other studies are in agreement with the finding [Hazell and Lemon, 2011; Rittweger et al, 2002]. However, it appears that no one has either monitored the sVO_2 trend during the whole exercise or compared a single bout of static and dynamic squat with WBV. In our study, monitoring the VO_2 trend since the beginning of exercises provided the opportunity to compare the slope of the curves for the different squat modalities. As a result, in general, the sVO_2 curves for the same subject during SSV and DSV were similar at the beginning and diverged significantly after about the 1st min. Consequently, WBV treatment for duration ⍰60 sec, followed by a resting period, could not cause remarkable differences on oxygen uptake between static and dynamic squat. Our findings show also that the sVO_2 trend and $sVO_{2\text{-}30s}$ values were similar in SSV and DS exercises and, as a consequence, it is clear that vibration resulted in an increase in VO_2 during the static squat exercise comparable to the VO_2 obtained in the dynamic squat exercise without vibration.

The $\%HR_{30}$ results showed also an increase in the subjects' HR due to WBV of about 7.3% and 5.5% for the static and the dynamic squat exercises, respectively. Furthermore, there was no significant effect of WBV upon RPE, although values depicted a greater effort after the static exercise than the dynamic exercise. The reason of these results could lie in the nature of the exercise. During the static squat, the subjects held the same knee angle and the muscles were continuously twitched. On the other hand, during the dynamic squat exercise, the contraction is reduced in the higher angle phases.

THE EFFECT OF WHOLE BODY VIBRATION ON OXYGEN UPTAKE DURING STATIC AND DYNAMIC SQUAT

Over the past decade, whole-body vibration (WBV) exercise has become an increasingly popular training modality. Although occupational vibration exposure (i.e. sitting driving large equipment) is unhealthy, WBV exercise which involves shorter intermittent exposures at much greater vibration frequencies has been proposed to be beneficial in several ways.

In theory, the vertical oscillations generated via a platform induce short and rapid changes in muscle fibre length which stimulate reflexive muscle contractions in a response akin to monosynaptic reflexes [Cardinale and Bosco 2003; Hagbarth and Eklund 1966; Ritzmann et al, 2010]. These vertical oscillations may also increase instability [Abercromby et al, 2007] or cause a muscle tuning response via one's attempt to dampen the transmission of the vibration signal [Wakeling and Nigg 2001].

Regardless of the mechanism responsible, acute WBV exercise (both synchronous and side-alternating) has been shown to increase muscle activity, blood flow, and muscle/ skin temperature [Abercromby et al, 2007; Cardinale and Lim 2003; Cochrane et al, 2008; Hazell et al, 2007 and 2010;

Marin et al, 2009; Ritzmann et al, 2010; Roelants et al, 2006] and has even been reported to increase strength, power, and performance [Bosco et al, 1999; Da Silva-Grigoletto et al, 2009; McBride et al, 2010; Ronnestad, 2009; Torvinen et al, 2002]. However, there are also data showing little effect [de Ruiter et al, 2003; Erskine et al, 2007; Guggenheimer et al, 2009; Torvinen et al, 2002b] perhaps indicating that a wide range of exercise intensities are possible with WBV exercise.

Completing dynamic squats on a WBV platform (side-alternating) increased measured VO_2 * 3–5 ml kg-1 min-1 compared to the same exercise without vibration [Rittweger et al, 2001]. Moreover, Hazell et al. [Hazell et al, 2008] have demonstrated minimal cardiovascular stress (heart rate, blood flow, or mean arterial pressure with the addition of WBV to a static semi-squat position) suggesting that static WBV exercise is not a very strenuous form of exercise.

However, dynamic WBV squats at least with an external load (35–40% body mass) can increase VO_2 significantly (up to *50% of VO2max; [Rittweger et al, 2001 and 2002] indicating that the stimulus can be substantial. The greatest increase in VO_2 (0.7 ml kg-1 min-1) versus NoV during dynamic squatting was seen while performing a 2 s squat cycle (1 s down 1 s up; [Garatachea et al, 2007] compared to slower squatting cadences (4 or 6 s cycles).

The purpose of this study was to quantify VO_2 during static and dynamic squat exercises with and without vibration monitoring VO_2 throughout the exercise, and not just during the last seconds (sVO_2). [Rittweger et al, 2001 and 2002]. Hence we could analyze curves from the beginning of the exercise in order to find out possible differences in the sVO_2 trend and differences in how it is reached at steady-state.

METHODS

Subjects

Eleven healthy subjects, 3 male and 8 female, (age 22.5 + 3.1 years, height 175.2 + 5.2 cm, weight 69.2 + 10.2 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 athletically trained.

Exercises

Before the testing session, the subjects performed a warm-up on a bicycle ergometer (load of 70 W for 10 min) followed by stretching exercises for 5 min.

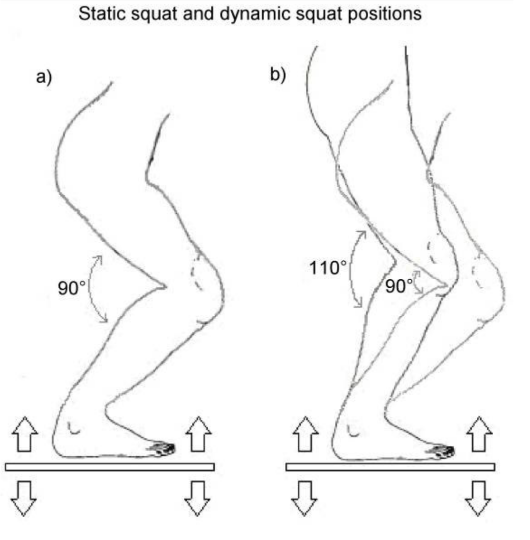


Figure 29: Static squat (a) and dynamic squat (b) positions.

They performed a protocol of four exercises that lasted 3 min and 30 sec, with a rest period of 15 seconds every minute. In the first two EU (Figure 29a), the subjects ran through an unloaded static (isometric) squat (knee angle at

~90°), without and with vibration (SS and SSV, respectively). In the other EU (Figure 29b), the squat exercises were dynamic (i.e., the subjects performed cyclic motions squatting between an angle of 110° and an angle of 90° of knee flexion with a rate of repetition equal to about 20 squats per minute) without and with vibration (DS and DSV, respectively). The exercises with no vibration (SS and DS) were used as control.

Before recording, the subjects were instructed about proper positioning on the platform and they were familiarized with the device. The exercises sequence for each subject was randomized and between each exercise all the participants rested for about 20 min, until they felt recovered and their HR and sVO_2 signals were returned to initial values.
We used CE-marked Medical Devices within the limits and according to the standard training protocols specified by the manufacturers.

Whole-body vibration treatment (WBV)

The WBV treatment was performed by using a vertical oscillating WBV platform (Vibroplate provided by TSEM SpA). The platform provided a sinusoidal vibration at a frequency of 26 Hz and a peak-to-peak displacement of 3 mm. The value of 26 Hz was chosen since it is close to the activation frequency of the quadriceps muscle group [Abercromby et al, 2007; Cardinale and Lim 2003; Rittweger et al, 2001].
The platform oscillation frequency was checked through a triaxial accelerometer based on MEMS technology placed in the platform center.

Specific Oxygen Uptake

The subjects' oxygen uptake (VO_2) was continuously recorded by means of an oxygen consumption meter (Galvanic Fuel Cell sensors with an accuracy of ± 0.02%). [Nieman et al, 2007] Specific oxygen consumption (sVO_2) was obtained by dividing the instantaneous VO_2 by the body mass. All subjects wore FitMate Pro silicone face mask that was fitted with a head cup to prevent air leakage, and a HR chest strap; both connected to the FitMate Pro. The sVO_2 values and the HR signals were monitored continuously during the whole EU in order to analyze their trends during the exercise. To make a comparison between the static and the dynamic squat exercises, the data acquired during the last 30 sec was used [Rittweger et al, 2001].

Rate of Perceived Exertion and Heart Rate

To assess the intensity of each EU, the subjects gave a rating of perceived exertion (RPE) at the end of each exercise [Borg, 1970 and 1990]. Resting HR was monitored before each exercise to check that the subjects recovered completely. The mean value of HR was estimated in the last 30 sec (HR_{30}) of each EU to investigate the effect of WBV on the cardio-circulatory system [Bogaerts et al, 2009; Hazell and Lemon, 2011]. In particular, estimated HR_{30} values were used to compute for each subject the increase in beats·min^{-1} (dHR_{30}) between the exercise NoV and the correspondent WBV one, according to the formula: $dHR_{30} = HR_{30WBV} - HR_{30NoV}$

Statistical Analysis

sVO_2 and dHR_{30} were tested for normal distribution with the Kolmogorov-Smirnov test (level of significance equal to 0.05) [Marseglia et al, 2003;

Smirnov, 1948]. Paired t-test was used to test differences in the sVO_2 values obtained in WBV versus NoV exercises, while a one-sample t-test was performed on dHR_{30} to check the possibility of rejecting the null hypothesis (no difference in HR between exercises with WBV and NoV). Statistical significance level was set at $P \leq 0.05$.

Statistical analysis was done by using the software IBM SPSS statistics 19.

RESULTS

Specific Oxygen Uptake

Figures 30, 31, and 32 illustrate examples of VO_2 monitored during static and dynamic exercises, with and without vibration. The sVO_2 during the exercise WBV versus the same NoV are similar, and this effect was present in all the subjects. In most of the recordings, the sVO_2 increased during the exercise up to a plateau reached approximately after the 3rd min. Thus, the mean and standard deviation of the sVO_2 values of the last 30 sec ($sVO_{2\text{-}30s}$) were chosen to compare the different EU conditions [Rittweger et al, 2001].

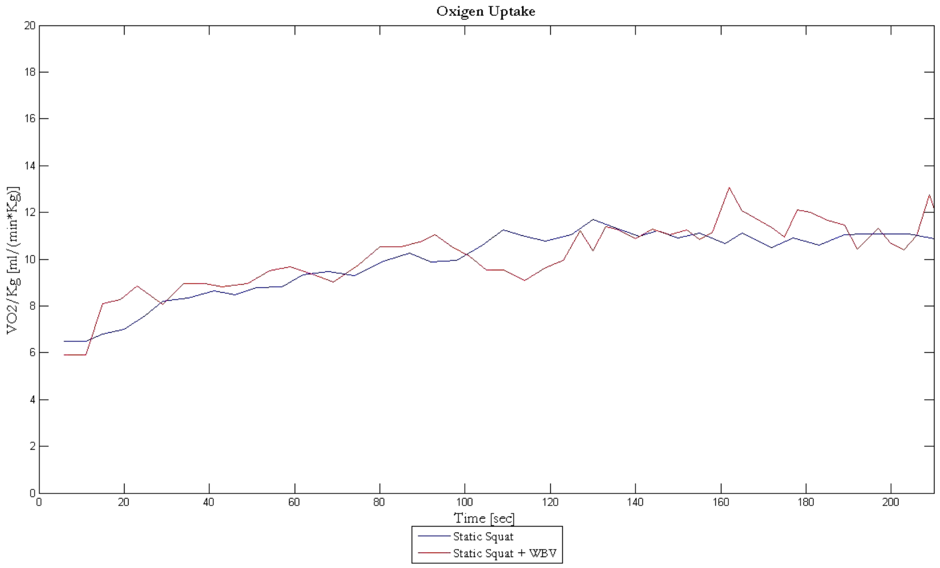


Figure 30. Oxygen uptake of subject #3 during SS and SSV, sVO_2 show a similar pattern for the entire exercise.

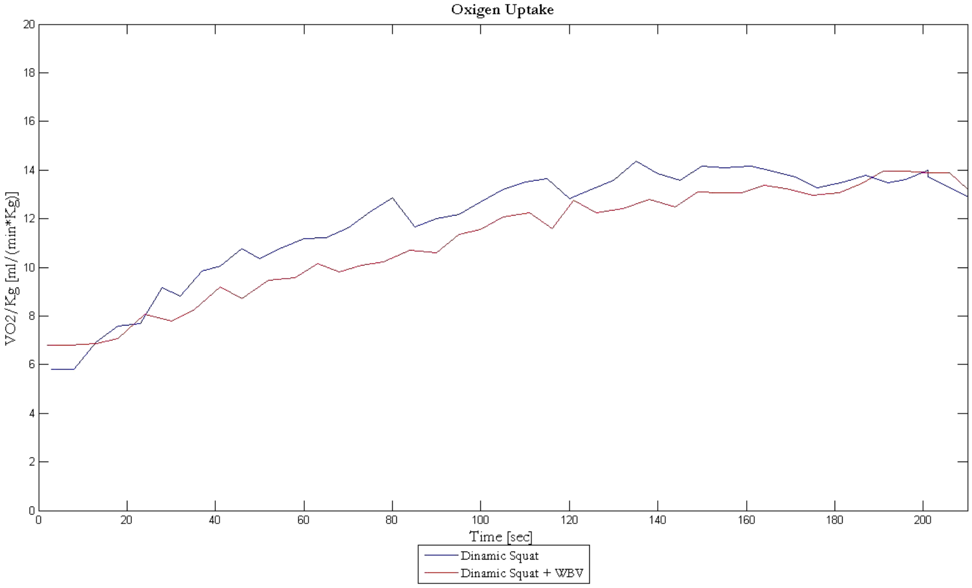


Figure 31. Oxygen uptake of subject #3, during DS and DSV, sVO_2 show a similar pattern for the entire exercise.

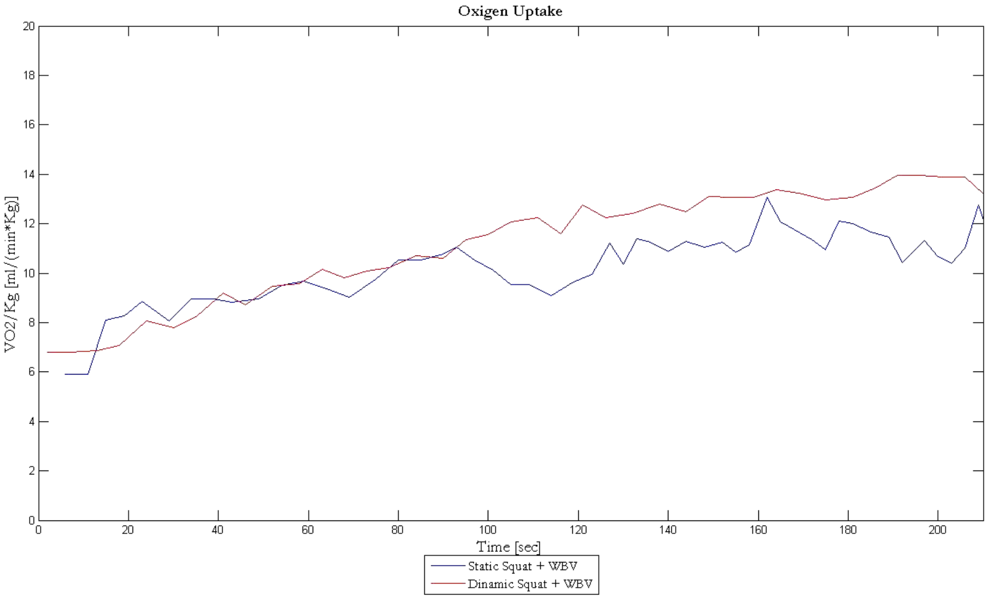


Figure 32. Oxygen uptake of subject #3, during SSV and DSV, sVO_2 show a similar pattern for the entire exercise.

Rate of Perceived Exertion and Heart Rate

Means and standard deviations for RPE during the static squat were 13.1±2.1 for NoV and 10.3±2.6 for WBV, while during the dynamic squat were 12.6±3.9 for NoV and 13.1±4.1 for WBV. No significant changes were observed between NoV and WBV exercises. However, the subjects seemed to perceive a greater effort after the static squat than the dynamic ones. The same result was obtained for the analysis of HR, t-test indicated that WBV treatment not increased significantly the dHR_{30} for both static and dynamic squat exercises.

DISCUSSION

Rittweger found increased oxygen uptake and heart rate when squatting on a vibration platform, as compared to squatting without vibration [Rittweger et al, 2000 and 2002]. The increases in heart rate and oxygen uptake were only mild, arguing against stimulating effects on cardiorespiratory fitness in young subjects.

Da Silva, however, found that vibration training provides cardiovascular stimuli similar to those experienced during moderate walking at 4 km/h [Da Silva et al, 2007]. In seated WBV, older and young adults showed an increase in heart rate and in oxygen uptake by 0.35 metabolic equivalent [Cochrane et al, 2008a]. Squat exercises on a vibration plate (3s up-3s down) lead to a similar metabolic rate as cycling at 70 W [Cochrane et al, 2008b].

Differently from literature research, we don’t find a significant improvement of metabolic power, heart rate and rate of perceived exertion in presence of vibration. The reason of this result could be find in several causes: different exercises parameter, subjects training level and anthropometrics characteristic, vibrating platform settings. Indeed, it is important to point out that in the studies presented in literature the subjects run through exercises that lasted 3 minutes and 30 seconds without rest period.

This is an important difference because the inclusion of two rest period could significantly modify the oxygen consumption during the exercises.

Furthermore all subjects were athletically trained and capable to control breathing during exercises.

THE EFFECT OF WHOLE BODY VIBRATION ON RESONANT FREQUENCIES OF LEG MUSCLES

It is well known that localized, direct applications of vibratory stimuli to a single muscle or a tendon produce reactions of muscle spindles.[Marsden et al, 1969; Desmedt and Godaux, 1975 and 1978; De Gail et al, 1996] Local tendon vibrations induce activity of the muscle spindle la fibers, mediated by monosynaptic and polysynaptic pathways.

A reflex muscle contraction known as the Tonic Vibration Reflex (TVR) arises in response to such vibratory stimulus.[Roll et al, 1996; Bongiovanni et al, 1990; Romaiguere et al,1991; Person and Kozhina, 1992; Martin et al, 1997] Vibratory stimulations transferred to the whole body, i.e. whole body vibrations (WBV), were also largely studied for their impact on muscular activity, neuromuscular and postural control.[Verschueren et al, 2004; Bosco et al, 1999a and 1999b; Mester et al, 1999; Homma et al, 1981] A great deal of interest was in fact made around WBV treatment as a possible application of the TVR occurrence to the entire body.[Torvinen et al, 2002]

Many studies have accounted for WBV effects in the fields of exercise physiology, sport and rehabilitation medicine.[Bautmans et al, 2005; Kerschan-Schindl et al, 2001; Mester, 2006; Rittweger et al, 2001; Bosco et al, 1998; lssurin and Tenenbaum, 1999; Lebedev and Polyakov, 1992] In these treatments, vibrations are delivered to the whole body by the use of vibrating platform. Many of these devices produce vertical sinusoidal oscillations (while some other an alternating rotation) of a platform across a frequency range from 10 to 80 Hz and peak to peak displacements from 1 to 10 mm.[Cardinale and Wakeling, 2005]

Vibrations are then transferred from the platform to a specific muscle group through the subject body; different positions of the subject on the platform correspond to different muscle mechanical stimulations. Soft tissues act as wobbling masses vibrating in a damped manner in response to mechanical excitation; neuromuscular system works to damp the soft tissue resonance that occurs in response to pulsed and continuous vibrations.[Wakeling et al, 2002]

Since vibration loads are applied, mechanical and metabolic responses arise from the neuromuscular system.[Homma et al, 1981;Bautmans et al, 2005; Kerschan-Schindl et al, 2001;Bosco et al, 2000; Issurin et al, 1994; Rubin et al, 2004]

A significantly higher level of electromyographic activity appears in muscles during WBV treatment with respect to a rest condition; specific WBV frequencies also seem to produce a higher EMG-RMS signal than others.[Cardinale and Lim, 2003]

Nevertheless, the findings in literature are not yet coherent, part of the previous studies suggest some muscular improvement, whereas other results indicate no significant variation.[Bosco et al, 1999 (a,b); Cardinale and Wakeling, 2005; Issurin et al, 1994; Delecluse et al, 2003]

Muscle response to vibration is a complex phenomenon as it depends on different parameters, like muscle-tension, muscle or segment-stiffness, amplitude and frequency of the mechanical vibration.[Wakeling et al, 2002]

Since few studies in literature demonstrated that muscles resonant frequencies vary between subjects and muscle groups, in this part of the work we aims to identify a relationship between the resonant frequencies of legs muscles and the anthropometrics characteristic of the subjects.

Simultaneous recordings of EMG of Rectus Femoris, Bicep Femoris and Gastrocnemius from twenty-three subjects undergoing vibration treatments were collected.

METHODS

Subjects

Twenty-three healthy subjects not affected by any neurological or musculoskeletal disorder participated in this study.

All subjects, 7 males and 16 females (age 25.1 + 6.5 years, height 172.2 + 7.5 cm, weight 65.2 + 11.7 kg), had been practicing regularly physical activity or non-competitive sports.

The experiments were conducted in accordance with the Declaration of Helsinki and all the subjects signed a written informed consent.

Exercises

Before the testing session, the subjects performed a warm-up on a bicycle ergometer (load of 70 W for 10 min) followed by stretching exercises for 5 min.

They performed a protocol of two exercise of 1 min.

In the first exercise (Figure 32a), the subjects ran through an unloaded static (isometric) squat (knee angle at ~90°), and in the other exercise (Figure 32b) a calf (knee angle ~150°).

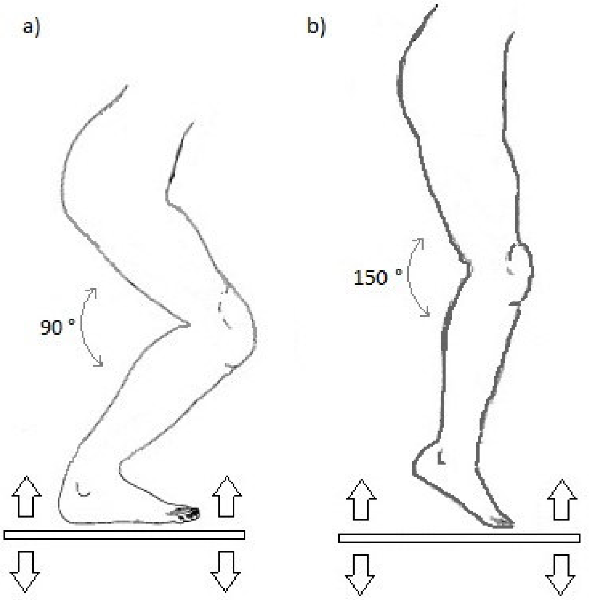


Figure 32: Static squat (a) and calf (b) positions.

Before recording, the subjects were instructed about proper positioning on the platform and they were familiarized with the device. The exercises sequence for each subject was randomized and between each exercise all the participants rested for about 20 min, until they felt recovered and their HR and sVO_2 signals were returned to initial values.

We used CE-marked Medical Devices within the limits and according to the standard training protocols specified by the manufacturers.

Whole-body vibration treatment (WBV)

A vibrating platform (TSEM S.p.A., Padova - Italy) was used to deliver vibration to the patients. The platform was modified (for our purpose) 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 horizontal shift, nor pitch, roll or yaw); platform displacement was sinusoidal with an intensity (peak-to-peak displacement) set to 1.2 mm and with a frequency ranging from 10 to 80 Hz. Obviously, being the peak-to-peak displacement constant, the maximum acceleration impressed to the patients depends on the square of the pulsation.

Surface EMG

Signals from the Rectus Femoris (RF), Bicep Femoris (BF) and Gastrocnemius (GC) of the dominant leg were collected. Signals were recorded using small disc Ag/AgCl electrodes (5mm in diameter, inter—electrode distance of 20 mm arranged in the direction of the muscle fibers). Electrode skin areas were shaved and cleaned before the placement of electrodes and conductive paste was used. All the electrodes ware placed in accordance with the guidelines of SENIAM Project [Hermens et al, 1999] and were secured (specific adhesive tape was used) to prevent the cables from swinging and from causing induced artifact. Reference electrode was located on the ankle of the same leg.

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

A PC multi-channel 16-bit data acquisition card (National Instruments DAQCard 6251) was used to acquire SEMG signals and to drive the vibrating plate. Specific software was designed on purpose using the Lab-Windows/CVI (National Instruments) environment. All signals were sampled at 1536 Hz.

To quantify SEMG signal, RMS values were computed using 500 ms time window without overlapping. Motion artifact components on recorded EMG signals were filtered out using a set of standard notch filters (with a -3dB band of 1.5 Hz) centered on the applied vibration stimulus frequency and its harmonics.

RESULTS and DISCUSSION

In order to obtain a mathematical model that relates the resonance frequency of the muscle groups with the anthropometric characteristics of the subjects numerous data are required. For this reason, has not yet been possible to identify a model that establishes a relationship between the parameters under evaluation, and the experiments are still in progress.

CHAPTER 6 - REFERENCES

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