Effects of Vertical Whole-Body Vibration Parameters on Rate of Muscle Fatigue in Submaximal Isometric Contraction: A Pilot Study

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ABSTRACT

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Vibration training is a modality used to improve human performance, measured by muscle strength and power via a reflexive muscle contraction called Tonic Vibration Reflex. Reported improvements of this novel training practice are inconsistent which leads to poor understanding of Whole-Body Vibration (WBV) and suggest lack of research supporting the beneficial physiological effects of the modality on the human body. This study examined the effects of vertical vibration parameters (frequency and amplitude) on the rate of muscle fatigue while subjects performed an isometric single leg squat exercise under WBV until exhaustion. Thirty healthy college level athletes volunteered in this study. Three levels of each independent parameter were examined for nine combinations of vibration. Surface electromyographic (SEMG) activity of eight muscles was measured: tibialis anterior, fibularis longus, vastus medialis oblique (VMO), gastrocnemius (medial head), biceps femoris, gluteus medius, rectus abdominis, and erector spinae (L4). Spectral analysis of the integrated EMG (iEMG) was performed to determine the rate of muscle fatigue under each vibration condition. Analysis of variance evaluating the effect of the vibration parameters was performed on the spectral analysis responses with a significance of $p \leq 0.05$. Results found no main effect of any individual vibration parameter or any interaction effect on the rate of muscle fatigue. These findings aid our understanding of vibration parameter effects on the human body. Since vibration training's popularity is still growing, further studies on the matter should be pursued.

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ABBREVIATIONS

Cps:	Cycles per Second
EA:	Electrical Activity
Hz:	Hertz
iEMG:	Integrated Electromyography
MF:	Median Frequency
MVC:	Maximal Voluntary Contraction
PSD:	Power Spectral Density
RPE:	Rating of Perceived Exertion
SEMG:	Surface Electromyography
TVR:	Tonic Vibration Reflex
VMO:	Vastus Medialis Oblique
WBV:	Whole-Body Vibration

PREFACE

This thesis follows the *Thesis Preparation and Thesis Examination Regulations* of Concordia University's school of graduate studies for the manuscript-based thesis. Due to the large amount of data collected for this particular study, the manuscript included in this thesis only illustrates a portion of the entire thesis. Any results and discussion from the thesis that do not appear in the manuscript are reported in the front section of the thesis.

This manuscript is being prepared for submission to the *Journal of Strength and Conditioning Research*. For the purpose of this thesis, all figures and tables will appear in the manuscript, and the text will be formatted according to the thesis guidelines. Since the manuscript's objectives are part of a subset of objectives set out for this thesis, they both share the same background information. For this reason, an overlap of information and redundancy in the manuscript introduction may be present.

The *Journal of Strength and Conditioning Research* requires the authors to present the results following specific requirements. It is required to put the most important findings in figure or table format and less important findings in the text. For this reason, written presentation of the results on the effects of WBV parameters on muscle activity and time-to-fatigue will be reported in the front section of the thesis. Table and graphical representation of the same results will be presented in the manuscript section of the thesis.

THESIS COMPOSITION

The following is a brief overview and description of each chapter of this manuscript-based thesis.

INTRODUCTION: Introduction to Whole-Body Vibration and the growing popularity of this novel modality in the fields of athletics and fitness as well as a listing of general objectives.

CHAPTER I: Description of Whole-Body Vibration and vibration training. Overview of the different vibration platforms available on the market and their physiological impact on the human body. Review of the literature on Whole-Body Vibration training and its benefits for human performance.

CHAPTER II: Presentation of a detailed rationale followed by the study's objectives and hypothesis.

CHAPTER III: Presentation of the methodology including a detailed description of the participants, the equipment used, and the task performed by the participants.

CHAPTER IV: Presentation of the results for the rate of muscle fatigue, time-to-fatigue and muscle activity as well as the discussion on the rate of muscle fatigue.

CHAPTER V: Manuscript – Brief introduction of whole-body vibration and vibration training, rationale and objectives of the study with respect to the effects of vibration parameters on muscle activity and time-to-fatigue, methods, as well as results and discussion for the muscle activity and time-to-fatigue section of the experiment.

CONCLUSION: Summary of the experimental results and a brief discussion about the relevance of the work from the front section and manuscript section of the thesis.

AUTHOR CONTRIBUTIONS FOR THE MANUSCRIPT

Mylène Saucier is the primary author of the manuscript as she was responsible for the literature review and the composition of the entire manuscript. Ms. Saucier was responsible for the complete operation of the study including subject recruitment, data collection, data analysis and the interpretation of the results.

Dr. Richard DeMont is the main supervisor of Ms. Saucier and was responsible for overseeing the study. He was also actively involved in the editing of the thesis.

Dr. Subhash Rakheja provided the laboratory space for data collection and provided assistance regarding mechanical engineering knowledge pertinent to the thesis in addition to helping with the machinery used in the lab. In addition, he provided general comments on the thesis.

INTRODUCTION

The use of vibration for the improvement of human performance was first brought to our attention in the 1960's. Originally called *Rhythmic Neuromuscular Stimulation*, scientists were interested in the effect of a cyclic oscillation on the human body [1]. The novelty of the vibration modality motivated researchers to find practical uses. In the 1990's, whole body vibration (WBV) was introduced and a vibration platform was patented on which the user could stand. The effects of oscillation on the body were believed to help with different aspects of human health. To date, research has demonstrated that an acute exposure of low frequency WBV (10-45Hz) improves flexibility of the lower body as well as balance [2-6]. Using the same range of frequencies, WBV led to increased bone mineral density in post-menopausal women [6, 7].

In the fields of athletics and fitness, scientists, health professionals, and coaches questioned the effects of WBV on the active population. The use of vibration as a modality to improve muscle strength and power was the main interest. Researchers looked at the effects of both acute and chronic exposure to vibration on the human body. Studies have demonstrated both positive and negative outcomes on human performance, and this lack of consistency may be explained by a poor understanding of the physiological effects of WBV.

The objective of this study is to look at and understand the effects of WBV on the human body to facilitate the design of a safe and effective vibration protocol for the healthy population. Better knowledge of WBV may bring consistency in the outcomes of future studies, and may lead to a reliable and beneficial use of vibration.

CHAPTER I: LITERATURE SURVEY

Whole-Body Vibration: Description

In WBV, the entire body is exposed to vibration. In the past decade, different platforms have been designed and made commercially available as vibration training devices for enhancement of human performance. Such machines are designed to generate oscillations that are transmitted to the person standing on the machine. Some platforms [8-12] allow the person to perform static or dynamic movements on the machine such as sitting, kneeling, squatting, lying, or placing their hands on the platform.

Although most of the commercially available vibration platforms generate predominant vibration along the vertical axis, some designs tend to induce vibration in different directions such as vertical, horizontal and rotational vibration. Not all vibration platforms use the same mechanism to generate oscillatory motions. Some platforms are designed with mechanisms that produce linear motions [9, 11-13] resulting in the platform motion in the vertical plane, while other plates encompass a rotary mechanism causing the platform to tilt about a central axis[10, 14]. The later type of mechanism yield transmission of vertical as well as rotational vibration to the human subject. A vibration platform capable of generating simultaneous motions along all three translational axes, laterally (y-axis), anterior-posterior (x-axis) and vertically (z-axis), has also been available [8]. Furthermore, the available designs exhibit varying magnitudes of vibration and frequencies of predominant vibration. Different vibration platforms thus provide widely different features in view of the nature of vibration (magnitude, direction and frequency). The magnitude of vibration power absorbed/dissipated into the body would thus differ greatly. It is thus of great importance to understand the influences of different vibration parameters on the human performance such as the type of excitation waveform, vibration frequency, displacement amplitude and acceleration. Table 1 and 2 demonstrate some of the platforms available on the market along with their individual characteristics.

Brand	Type	Waveforme	Frequency	Amplitude	Acceleration	Time	Weight Capacity
Power Plate	MI3	3 planes: 70° Vertical, 20° Horizontal, 10° Sagital	30 Hz to 50 Hz (↑options by 1 Hz or 5 Hz)	Low: 2-4mm High: 4-6mm	Max 6.36 g	pre-set: 30 or 60 s	
	Pro5						400 lbs
	Pro 5 air adaptive						500 lbs
VibraFlex	Home	Rotary Mechanism	5Hz-30Hz (↑ by 1 Hz)	0 mm to 3.9 mm	Max 11 g	full control	220 lbs
	550			0 mm to 5.2 mm	Max 18 g		353 lbs
	600			0 mm to 6.4 mm	Max 23 g		441 lbs
Vibe Plate	12"x40"	Vertical	20 Hz to 60 Hz	↓as Frequency↑	Fixed		1200 lbs
	24"x24"						1200 lbs
	24"x40"						1500 lbs
	30"x48"						1800 lbs
NEMES	Health LX-B	Vertical	20 Hz to 55 Hz (↑by 5 Hz)	2 mm to 4 mm	Max 30 g		140 Kg
Vibra-Pro	ultra 6100	3 planes	30 Hz to 50 Hz (↑by 5 Hz)	2mm			330 lbs
	vibrapro 7000		30 Hz to 45 Hz (↑by 5 Hz)	Low: 2 mm High: 6 mm			330 lbs
	V-force		30 Hz to 50 Hz (↑by 5 Hz)	Low: 2mm High: 5 mm			330 lbs

Table 1
Different vibration platforms available on the market with their individual characteristics. Grey cells indicate that information is not provided.

Brand	Type	Waveforme	Frequency	Amplitude	Acceleration	Time	Weight Capacity
VibraTrim	VT100	Rotary Mechanism	0 Hz to 55 Hz	0 mm to 10 mm	Max 3.5g		330 lbs
	VT200		0 Hz to 55 Hz	0 mm to 10 mm	Max 3.5g		330 lbs
	VT300			0 mm to 10 mm			440 lbs
Proellixe	Base Fitness Trainer	Rotary Mechanism	3 HZ to 30Hz	0 mm to 10 mm			397 lbs
	Proellixe Original		3 Hz to 30 Hz				297 lbs
	Proellixe 2007 Demo						397 lbs
Vibrogym	Evolution	Vertical	25 Hz to 50 Hz				396 lbs
	Professional		30 Hz to 50 Hz				300 lbs
	Medical		30 HZ to 50 Hz				300 lbs
Hypergravity Fit-n-Flex	elite	Vertical	10 Hz to 60 Hz (↑by 1 Hz)	Low: 2 mm High: 5 mm	Max 6 g		400 lbs
	Olympic		25 Hz to 60 Hz (↑by 5 Hz)	Low: 2 mm High: 5 mm	Max 6 g		400 lbs
	360		25 Hz to 60 Hz	Low: 3 mm High: 5 mm	Max 6 g		400 lbs
	Gym-o-Vibe		25 Hz to 60 Hz	Low: 2-3 mm High: 3-6 mm	Max 6 g		500 lbs
	Personal		25 Hz to 60 Hz	Low: 3 mm High: 5 mm	Max 6 g		300 lbs

Table 1 Continued
Different vibration platforms available on the market with their individual characteristics. Grey cells indicate that information is not provided.

As explained previously, some platforms oscillate vertically, but more precisely the platform will follow a sinusoidal wave created by the drive motors integrated within the platform. The frequency of this cyclical process is defined as the number of cycles per unit of time and is measured in hertz (Hz) or cycles per second (cps). In relation to WBV, 1 Hz means that the platform moves up and down once per second. The other important parameter of WBV is the amplitude of vibration, which is represented by the maximum change in the motion of the platform with respect to its static position (Fig. 1). The peak-to-peak amplitude corresponds to the difference in the position of the platform between its minima and maxima, as illustrated in Figure 1, which represents the total vertical displacement of the vibration platform. The combination of vibration frequency and amplitude generates acceleration forces on the body standing on the platform. The acceleration is relative to free-fall and is called the *g*-force where its unit of measure is *g*. As the frequency is increased, the rate of platform motion increases linearly with the frequency, while the acceleration increases as a square function of the frequency.

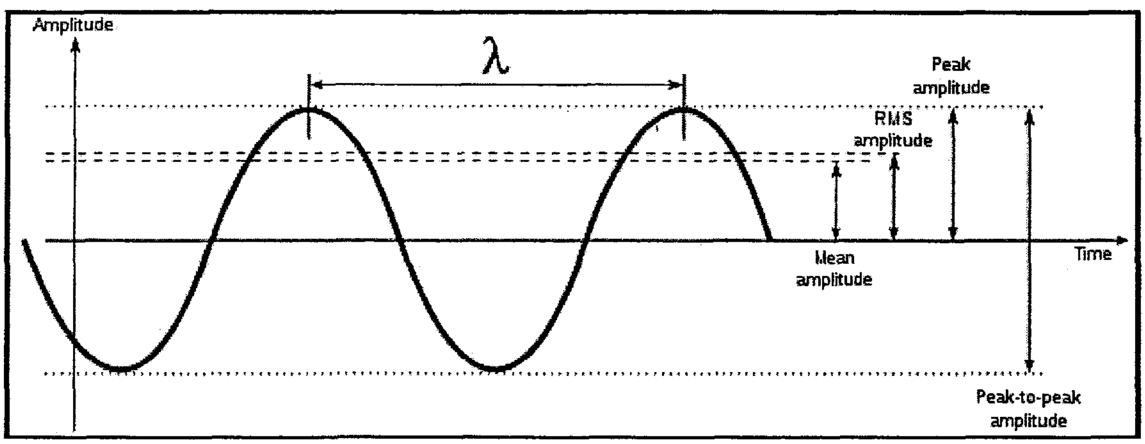

Figure 1
Sinusoidal waveform

Different vibration settings generate different acceleration responses on the human body; therefore, selection of the vibration parameters has to be done carefully to prevent injuries. Side effects of WBV exposure such as motion sickness, digestive system disorder, adverse effects on the female reproductive organs, peripheral veins disorders as well as aggravation of pre-existing back, neck or shoulder injury cannot be excluded [15]. Vibration disease caused by low-frequency WBV has been studied in some occupational health articles [16-18]. Even though disorders on the nervous, circulatory and digestive system are not defined to be predominantly WBV-specific, research has shown global environmental conditions, including vibration, to be partially responsible [16]. Furthermore, degenerative changes of the spine are prevalent in population exposed to WBV due to an increased spinal load from vibration [16].

Tonic Vibration Reflex (TVR)

TVR & Sensory Receptors

When eliciting a vibration response on the human body, the main contributing factors are the frequency and amplitude of vibration which will produce a rapid vertical and/or rotational displacement of the platform. The rapid change in the oscillatory motion causes the muscles to lengthen and activates the muscle spindles: small sensory receptors within the muscle belly which primarily detect changes in the length of the muscle [19]. The muscle spindles are aligned in parallel to the extrafusal fibres of the muscle. Consequently, when the muscle stretches, the spindle stretches as well, and, through a reflex response, initiates a muscle contraction to reduce the stretch. More specifically, the muscle spindle that responds to a muscle stretch activates afferent nerve fibres that carry the sensory impulse from the spindle through the dorsal root into the spinal cord. This impulse directly activates the anterior motor neuron which will travel back to the muscle to activate the muscle fibres [19]. The reflex muscle contraction caused by vibratory activation of muscle spindles is named a tonic vibration reflex (TVR) [20].

A deeper analysis of the physiology behind reflexive muscle contractions demonstrates an organized pattern of muscle spindle stimulation. The structural organization of the muscle spindle receptor involves two sensory afferent fibres and one motor efferent fibre. The primary afferent nerve fibre entwines the intrafusal fibres of the muscle spindle and responds directly to stretch; thus, as the muscle stretch increases, the primary afferent nerve firing frequency increases proportionally [19]. The secondary afferent nerve fibre also makes a connection to the intrafusal fibres of the receptor, but with lesser sensitivity to stretch than the primary afferent fibres[19]. Primary afferent nerves have the most sensitivity to vibration of low amplitude and frequencies up to 180 Hz with a maximum sensitivity to vibrations of 80 Hz [21, 22]. On the other hand, muscle spindle secondary afferent nerves show very little sensitivity to vibration [21, 22].

Another specialized sensory receptor located near the tendon's junction to the muscle is the golgi tendon organ which detects differences in tension generated by active muscles [19]. Like the muscle spindle secondary afferent nerves, the golgi tendon organ does not respond primarily to vibration [21, 22].

Synchrony & Harmony

In WBV, a harmonic series consists of oscillations vibrating with a frequency that is an integral multiple of the same fundamental frequency (i.e. the lowest frequency of the harmonic series). Consequently, if the fundamental frequency is *f*, the harmonic series may consist of spectral components at *f*, 2*f*, 3*f* etc. Motion at subharmonic frequencies may also occur, which are fractions of the fundamental frequency (f/n; n=2, 3, ...). Thus if the fundamental frequency is 100Hz, subharmonic frequencies will be 50Hz, 25Hz etc. Examination of the relationship between the vibration frequency and the firing rate of the muscle spindle primary nerve fibres due to vibration suggests that they are both synchronized up to a frequency of 180 Hz [21, 22]. Up to a frequency of 80Hz, the discharge from the muscle spindle primary nerve fires harmonically with the vibration (e.g., 1 action potential of muscle spindle primary nerve per 1 cycle) and then discharged in a subharmonic manner (e.g., 1 action potential of muscle spindle primary nerve per 2 or more vibration cycles) with increasing vibration frequencies [22]. This one-to-one stimulus response with lower frequencies means that by altering the vibration frequency, the initiation of a proportional change in the muscle spindle primary nerve discharge frequency is possible[22].

TVR & Motor Units

A motor unit is a single alpha motor neuron with all of the corresponding muscle fibres it innervates[19]. When a motor unit is activated, all of its associated muscle fibres contract. A motor unit pool includes all of the motor units that service a single muscle. When a muscle is activated, not all of its motor units fire at the same time. The control of muscle force output depends on the number of motor units recruited and the frequency of discharge of the motor units [19]. Previous studies observed a modulation of the amplitude of TVR when humans were exposed to vibration. The variations in amplitude of vibration were proposed to be related to an increase in motorneuron depolarization from the firing frequency of muscle spindle primary nerve afferents [22, 23].

At frequencies below 100Hz, all of the muscle spindle primary nerve afferent are assumed to be recruited by the vibration stimulus[22]. Therefore, an increase in TVR in the lower frequency range results principally from an increase in motorneuron depolarization with increased firing frequency of muscle spindle primary nerve afferents. This increased motor neuron depolarization leads to a recruitment of motor units of increasing thresholds. At frequencies of above 100Hz, most muscle spindle primary afferents start to fire at random to vibration stimulus and lose the response in terms of 1:1 synchrony leading to subharmonic synchronization [22]. This change in behaviour leads to a derecruitment process affecting the motorneurons and their responsive fibres showing a reduction in the strength of TVR [23]. The motor unit recruitment in the development of muscle contraction from vibration and derecruitment does follow Henneman's size principle[24]. During TVR, motor units are generally recruited in order of smallest to largest (fewest fibers to most fibers) as contraction increases[24].

Vibration & Corticospinal Excitability

In the quest to find therapeutic use for vibration, scientists questioned the impact of vibration treatment at the supraspinal level. Excitory projections of Ia muscle afferents to the somatosensory cortex were found in studies reported in the late 1060's [25, 26]. Soon after, invasive electrophysiological research on cats led to the discovery of topographically and functionally specific corticocortical excitatory connections between somatosensory areas and frontal motor areas [27, 28]. The functional relevance of this knowledge from a human point of view is to use this conjoint activity of somatosensory afferent and motor intracortical circuits to induce motor cortical plasticity. In recent years, a growing amount of evidence has demonstrated the capacity of the primary cortex to reorganize due to various environmental changes in humans [29-31]. This remodelling response follows mainly long periods of repeated sensory input[32].

As explained in the previous section, body vibration is a proprioceptive stimulus producing Ia afferent input. This sensory input reaches both the primary somatosensory (S1) and motor (M1) cortices directly [33, 34]. Many previous transcranial magnetic stimulation studies have shown that local vibration on a muscle tendon or the belly (vibration provided by a mechanical stimulator mounted with a vibrator probe pressing perpendicularly on muscle tendon or belly) was able to induce different changes in corticomotor excitability of the vibrated versus non-vibrated muscle [35-39]. In two recent studies, local vibration on a wrist flexor muscle was applied using two different intervention protocols. In both cases, the cortical map volume for the wrist flexor muscle was either unchanged or significantly reduced post-vibration. The reduction lasted for two weeks [35, 36]. By contrast, results obtained from the extensor muscle revealed significant increases of motor map volumes when compared to pre-vibration. Again, this augmentation in volume size lasted for two weeks [35, 36].

In contrast to a local vibration protocol, WBV stimulates recruitment of agonist and antagonist muscles. Since all muscles are being exposed to vibration, the modulation of corticospinal and intracortical pathways is being questioned. A recent study looked at the effect of WBV (30 Hz/1.5 mm -frequency/amplitude) on the corticospinal and intracortical pathways in the tibialis anterior and soleus muscle during a static squat [40]. Compared to no-vibration, only the total cortical area of the tibialis anterior increased significantly. The results demonstrate that the effects of WBV are not restricted to the periphery but also involve corticospinal and intracortical processes and lead us to believe the possibility of cortical plasticity[40].

Other previous studies have shown long term changes in motor performance following muscle vibration intervention. Increased resistance to fatigue and improved postural stability were found to be statistically significant and can last for up to or than two weeks [41, 42]. The authors suggested long-lasting neuroplastic changes of motor control were responsible for the long lasting effects.

Vibration Training

A particular use of WBV is the superimposition of vibration to a person's initial strength training program or as a substitute for physical exercise. In the past decade, vibration training has become popular and increasingly available to athletes of all levels as well as the general population. Even though the novelty in strength training sounds attractive, there is still a lack of consistent scientific data supporting the beneficial effects of the modality on the human body. The studies on the effects of WBV on muscle strength and power show contradictory results. The discrepancies in the conclusions reduce the strength of any evidence supporting the use of vibration training.

For an optimal vibration training design, proper parameters need to be determined. The parameters include: frequency and amplitude of the vibration used, exposure time to vibration, posture held on the platform, and whether to include exercise while on the platform. Along with these parameters, a choice between a single bout versus a chronic exposure to vibration is required. A single session of WBV refers to an acute exposure to vibration and is usually employed as a warm-up with an objective to increase blood flow, muscle temperature, strength and/or power. A chronic exposure to vibration refers to the use of the modality over a longer period of time. In general, people using WBV as a replacement or to superimpose vibration to their strength training routinely use chronic exposure to vibration. Usually, this involves multiple sessions of vibration within the training session. The users may repeat the vibration training session three times a week for several months.

Over the past few years, the dangerous effects of vibration have been studied on the human body. It has been hypothesized that exposure to vibration of low amplitude and low frequency is a safe approach to exercise musculoskeletal structures. The available vibration platforms can deliver vibrations with frequencies ranging from 3 to 60 Hz and peak-to-peak amplitudes from less than 1 mm to 15 mm creating WBV exercise devices able to produce accelerations up to 20 *g*. Taking into account the wide array of combinations of amplitude and frequency, a broad variety of vibration training protocols can be used. Some of these combinations were tested to evaluate whether they had an effect on human performance [2, 5, 43-49].

Even though there is a lack of controlled studies on the effects of vibration training, current findings suggest that WBV may have beneficial acute and chronic training effects on neuromuscular performance (as measured by muscle strength and power). However, the results appear to depend on the vibration parameters as well as the exercise protocols used. Below, the effects of vibration training on neuromuscular performance with a focus on strength and power are examined. Exposure time is considered (acute vs. chronic) as well as the exercise protocol (maximal vs. submaximal and isometric vs. dynamic contraction). The interventions used to test strength and power are counter movement vertical jump, dynamic leg press, and isometric peak force evaluated by an isokynetic dynamometer.

Acute Effect of Vibration

Maximal Contraction

The effects of vibration on muscle strength and power can be analyzed during the vibration session or post exposure. Time is a very important variable that must be considered as it may have an impact on the neuromuscular system. If vibration stimulation is short, the testing of neuromuscular performance during or post vibration will be done in an unfatigued state. With longer exposure, fatigue will become more prominent and will have to be considered during analysis[50].

Examining maximal isometric contractions during vibration, some studies found no significant effect [46, 51, 52]. Studies by Humphries et al.(2004) and Samuelson et al.(1989) found an increase in muscle strength. On the other hand, a study by Bongiovanni et al.(1990) found a decrease in muscle strength. However, none of these studies showed significant differences compared to the control group [46, 51, 52]. In regards to isometric muscle strength post vibration, a study by Cormie et al.(2006) observed no change in isometric peak force. In contrast, Torvinen et al.(2002) observed an increase of 3.2% in isometric strength that lasted no longer than 1 hour [5, 45]. This contradiction in results is, in-part, likely due to the difference in vibration protocols.

Vibration training also has an impact on maximal isotonic contraction. Muscle power was increased by vibration while performing concentric elbow flexion; a difference being more pronounced in elite athletes (10.4% increase) compared to amateur athletes (7.9% increase) [47]. Post vibration, an increase in maximal dynamic leg press in national level female volleyball players was observed [43]. Another study found in females only an increase in leg power lasting no longer than 5 minutes [53, 54]. However, no significant differences in peak power during countermovement jump was observed following a single bout of vibration [45].

Submaximal Contraction

Evaluating the acute effects of vibration on submaximal contraction can be difficult since subjects would have to maintain a steady contraction during or post vibration treatments. However, the effects of vibration can be analysed by looking at the muscle activity by means of superficial electromyography (SEMG) during isometric and isotonic contractions. During an isometric contraction, more muscle activity is present while under vibration, regardless of the frequencies and amplitudes used as vibration parameters [48, 49, 55]. Similar findings have been demonstrated regarding isotonic contractions. A study by Torvinen et al.(2002) showed an increase in root mean square voltage of SEMG signal in the calf muscle [5]. Given the increase in the SEMG values by vibration during submaximal contractions, the application of vibration is likely to increase the submaximal contraction force.

Chronic Effect of Vibration

Early literature regarding chronic exposure to vibration reported contradictory results. In fact, a review article by Luo et al.(2005) found only two studies meeting their inclusion criteria regarding chronic exposure. Studies by Delacluse et al. (2003) and De Ruiter et al. (2003) found different changes in isometric strength gain [50, 56, 57]. The two studies used similar frequencies and durations (35-40Hz vs 30Hz, 12 weeks vs 11 weeks, respectively). Nevertheless, Delecluse et al.(2003) found an increase in isometric and dynamic knee-extensor strength of 16% whereas De Ruiter's group found no change. It appears that frequency and vibration exposure period are not the only parameters with an impact on the human body. The difference in amplitude (2.5 mm-5 mm vs. 8 mm, respectively) and a more demanding exercise protocol may explain the inconsistency. Moreover, the strength gain from Delecluse's group may not be due to vibration since the group exercising without vibration gained strength to a comparable level. A year later, a review investigated chronic exposure to vibration on muscle strength and/or jump performance[58]. The articles selected included a control group study in order to determine whether the change in neuromuscular performance was due to vibration and not to covariant variables such as exercise training. From the twelve articles considered, nine evaluated muscle strength performance. Muscle strength gains were reported in five articles with up to 24.4% improvements. Regarding muscle power, changes in jump performance were found in five articles ranging from 4.5% to 16% in the WBV-exposed-group [58]. Compared to the control groups, similar strength and power results can be noticed in the WBV groups. The authors suggested no effect on human performance could be ascribed to WBV per se, but rather to the exercise programs being performed on the vibration platform [58]. Once more, the wide array of combination of vibration parameters renders the evaluation of vibration training on the neuromuscular system difficult, since a lack of adequate knowledge regarding the effect of each parameter on the human body remains.

Vibration and Muscle Fatigue

In order to enhance muscle strength and power, one has to carefully follow the appropriate training program. It has been accepted that high resistance training improves muscular strength by promoting hypertrophy [59-61]. Along with hypertrophy, other important factors in the development of muscle strength have been reported: type of contractions, speed of training execution, frequency of contraction, and muscle fatigue amongst others [59-62]. However, the requirement of muscle fatigue is questionable. A previous study concluded that fatigue was not a critical stimulus to strength gain [63]. Rooney's group reported an increase in muscle strength of 56% in the fatigue group compared to 51% in the resting group [64]. Further research in this domain would thus be highly desirable.

For a better physiological understanding of muscle fatigue, the onset of muscle fatigue during submaximal isometric contraction was studied by relating motor unit activity and SEMG [65]. As soon as a certain level of muscular force was maintained, muscular activity began to change although tension and muscle lengths remained stable. This leads to believe that muscle fatigue begins as soon as the muscle contracts [65]. Furthermore, the motor unit recruitment and stays activated throughout the contraction [65]. In vibration training, the impact of vibration on muscle fatigue has been investigated. Luo et al.(2005) proposed that longer duration of vibration exposure induces more muscular fatigue, which may be due to a facilitation effect of vibration on muscle contraction force and activity during the early part of exposure [50]. This observation is also supported by studies reported by Cardinale et al. (2003) and Moras et al. (2006) who found an increase in normalized SEMGrms activity of the lower extremity muscles while standing on the vibration platform in a static squat position as compared to no vibration [44, 48]. From these two articles, one can further infer that muscle activity significantly increases under a vibration of 30Hz and as the physical demand on the muscles being tested increases. A study by Roelants et al. (2006) evaluated muscle activity of the lower extremity muscles under a vibration of 35Hz during different squat exercises [49]. The research group showed a higher muscle activity with WBV when more challenging (one leg squat vs. two legs squat) physical exercises were performed [49].

Time to muscle contraction failure was also assessed and showed to be shorter when exhaustive isometric and isotonic contractions are performed with vibration than without vibration [66, 67].

A second explanation to muscle fatigue from vibration may be due to a suppression effect of vibration on neuromuscular performance. Bongiovanni et al.(1990) suggested that vibration caused a gradual reduction of EMG activity, motor unit firing rates and increased contraction force during the course of about one minute of sustained contraction superimposed with vibration [51]. This type of reduction in neuromuscular function was observed during both sustained and intermittent maximal voluntary contraction and was accentuated by preceding muscle exercises [51]. It is suggested that contributing mechanisms for this suppression effect might be a vibration-induced presynaptic inhibition and/or transmitter depletion [51].

Muscle fatigue can also be related to a subjective factor referred to as psychological fatigue with effects including decline of alertness, mental concentration and motivation among others [68]. A subjective assessment of muscle fatigue can be performed using different scales such as the visual analogue scales, Borg scales, and Likert Scales [69]. Previous literature on lumbar muscle fatigue showed close relationship between EMG, endurance time to muscle fatigue, and the Borg Scale [68]. Further investigation on psychological fatigue could provide interesting insights to help understand muscle fatigue under vibration. In vibration training, subjective assessment of fatigue during and post intervention was rarely used to correlate objective findings with subjective assessments. A study by Rittwerger et al.(2003) used the Borg scale to compare repeated isotonic muscle contractions until exhaustion. The use of vibration led to a shorter exercise time and no significant differences in the Borg scale between the two treatments [66] . The subjective assessment allowed a more thorough evaluation of the effect of vibration training on muscle fatigue.

CHAPTER II: RATIONALE &OBJECTIVES

The use of a vibration platform as a training modality still presents a challenge to understand the effects of vibration on the neuromuscular performance. Vibration is complex and should not be looked at as a single element. Mechanical oscillations constitute different components (frequency, amplitude and duration) which can impact the exposed human body, either individually or in a coupled manner. Since different platforms provide different features, the understanding of the impact each vibration parameter has on the human body in designing beneficial training protocols, as well as maintaining consistency in the procedure used by the health and rehabilitation population, is of importance.

To summarize the general facts about vibration training, the transmission of vibration of acceleration greater than 1*g* to the standing body can lead to an improvement in neuromuscular performance [2, 43, 47]. Any combination of frequency and amplitude may have an effect on the human body such as an increase in muscle activity [44, 48, 49]. However, the previous literature exposes a lack of consistency in the resulting effects of vibration which may be due to a poor understanding of the present knowledge. The reported studies have employed widely different vibration parameters. The results thus do not provide definite trends for defining the optimal vibration settings. Further knowledge of the effects of each parameter on the human body is thus essential.

This study was proposed to investigate the effects of WBV mechanisms with the aim to determine the value of using vibration in human training. The goal was to provide the training and rehabilitation community with the suitable parameters for vibration training protocol. Specific to the current research, the objective was to find the effects of vertical vibration parameters (specific frequency/amplitude independently or in combination) on rate of muscle fatigue and time-to-fatigue. Since muscle activity is directly related to fatigue, a second objective was to investigate the effects of vibration parameters on muscle activity. Ten different combinations of frequency/amplitude were tested. The experiment looked at subjects standing on the platform maintaining a static squat position; thus, the attenuation of vibration by the body structures during transmission was taken into consideration. To achieve global understanding of the body response to vibration, a variety of muscles in close proximity and further away from the vibration source were examined since the attenuation factor could prove important to the issue of the overall rate of muscle fatigue.

Since studies on the effects of vibration parameters on the human body are almost nonexistent, structuring a hypothesis was a challenge. It was first hypothesized that the rate of muscle fatigue would decline faster with vibration of high acceleration levels compared to low acceleration levels. More specifically, the force created by the combination of the frequency and amplitude parameters would be responsible for the vibration effect. A similar assumption applied to time-to-fatigue as a higher acceleration level would lead to a shorter time-to-fatigue. After reviewing WBV literature, frequency was believed to be the main vibration parameter to affect the rate of fatigue and time-to-fatigue.

For the secondary objective, the initial hypothesis was that a high acceleration force, caused by a combination of a vibration frequency and amplitude, would lead to a higher muscle activity at any location on the lower extremity. Furthermore, a greater response in terms of muscle activity was expected to occur as we examined the muscles closer to the platform compared to those away from the vibration source. After studying existing WBV knowledge, the frequency parameter was hypothesized to mainly affect muscle activity with higher frequency leading to increased muscle activity. In combination with frequency, muscle demand from body posture or task performed on the platform was hypothesized to affect muscle activity with a higher activity in the primary muscles targeted from the exercise performed compare to those targeted secondarily.

CHAPTER III: METHODOLOGY

Variables

The effects of vertical WBV on the rate of muscle fatigue, time-to-fatigue and muscle activity was investigated with vibration frequency and amplitude as independent variables and rate to muscle fatigue, time-to-fatigue and muscle activity as the dependent variables. Three levels of each independent parameter were examined, using frequencies of 10, 20 and 30 Hz, and peak to peak amplitudes of 1, 2, 3 mm, leading to nine combinations: 10 Hz/1 mm, 10 Hz/2 mm, 10 Hz/3 mm, 20 Hz/1 mm, 20 Hz/2 mm, 20 Hz/3 mm, 30 Hz/1 mm, 30 Hz/2 mm, and 30 Hz/3 mm; and a control combination: 0 Hz/0 mm. The frequencies and amplitudes were selected so that the maximum acceleration exposed to the human body standing on the platform did not exceed 6g. Rate of muscle fatigue and muscle activity was evaluated from SEMG recorded during the exposure to vibration [68]. Time-to-fatigue was determined by the time counter located in the SEMG software.

Subjects

Prior to this experiment, a pilot study on the effects of vertical WBV on rate of muscle fatigue was conducted to determine the appropriate number of participants needed to achieve significance. In this regard, the power and effect size calculations suggested the need for an overwhelming number of participants. The rate of muscle fatigue section of the study could thus be considered a pilot project providing results with the potential to help present knowledge and future studies. Regarding the effects of WBV on muscle activity, a calculation of sample size was carried out with $\alpha=0.05$ and power of 80%, and using the results provided from previous studies that found differences between muscle activity under WBV [48, 49]. This provided a sample size of n=30 for the muscle activity segment of the study.

Thirty college level athletes, free of any conditions that could interfere with the task to perform during the experiment, participated in this study (age 19.47± 2.45 yr, Ht 172.23± 8.08 cm, Wt 73.3± 11.78 kg). Subject exclusion criteria included acute or chronic back injury, acute inflammation in the musculoskeletal system, acute migraine attack, acute or chronic musculoskeletal injury in the dominant leg, acute thrombosis, recent surgery, cancer, epilepsy, gallstones, kidney or bladder stones, open wounds in the dominant leg, pregnancy, rheumatoid arthritis and joint disorder, and diabetes. All subjects were screened for exclusion criteria prior to enrolment. Subjects were recruited on a volunteer basis via advertisement in the Athletic Department at Dawson College. All procedures were approved by the Concordia University Human Research Ethics Committee. All participants gave written informed consent to participate in the study on their first visit, following explanation of the risks associated with participating in the current research.

Material & Apparatus

Vibration Platform

The vibration platform *Vibraflex® 600* was purchased by the Concordia University Engineering Department (Fig. 2). This unit vibrates vertically about a central fulcrum and was selected for its specific features that offered: user variable controls over time, in-particular the frequency and amplitude of platform motion. The unit permits the operation at different frequencies ranging from 5 Hz to 30 Hz with the possibility of increments of 1 Hz. The peak to peak amplitude in the 0 to 12 mm range could be achieved by varying the medial to distal feet placement from the center of the platform. The unit could generate acceleration forces up to 21 g. Part of the vibration platform are handle bars

(Fig. 2) which allow for stability in addition to assisting the user, if needed, during safety use.

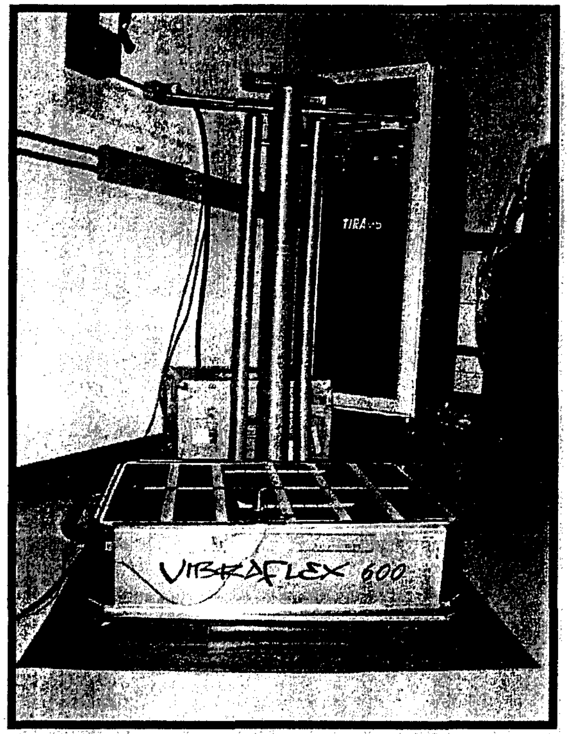

Figure 2
Vibration platform used during the experiment.
Vibraflex ® 600

Superficial Electromyography

SEMG from the dominant leg of the participants was collected. The leg dominance was determined by identifying the foot used most often to initiate a step in three separate trials [70]. Six muscles from the dominant leg and two from the trunk were analyzed: tibialis anterior, fibularis longus, medial gastrocnemius, biceps femoris, vastus medialis oblique (VMO), gluteus medius, rectus abdominis, and erector spinae L4; a reference electrode was placed over the tibial tuberosity. The placement of the electrodes was done according to Basmajian & Blumenstein and as described by DeMont, Lephart et al.(1999), and McGill, Karpowicz et al.(2009) [71-73]. Prior to placing the electrodes, hair on each location was shaved, the skin was slightly abraded with a nail file, and then cleaned with alcohol to remove any dead tissue improving electrode adhesion. Moreover, the cables were taped to the skin to minimize movement artefacts.

SEMG collection was carried out using Ag/AgCl adhesive electrodes. SEMG signal was sampled at 1000Hz and amplified (gain 500) by a 27-chanel amplifier (MYOPAC, RunTech Inc., Mission Viejo, CA) transmitted to a MYOPAC 16-channel receiver (RunTech Inc., Mission Viejo, CA) where it was further amplified (gain 500, total gain 1000), and A\D converted. The signal was then transmitted and stored in a Dell laptop computer where the signal was bandpass filtered (Butterworth) at 10 Hz and 500 Hz and rectified using DATAPAC2000 software (RunTech) [72]. The resulting signal became integrated electromyography (iEMG) and was used for subsequent analyses.

To perform the muscle activity analysis, mean iEMG amplitude was calculated for ten seconds. Since each subject was able to maintain the task position for different amounts of time, the section selected for analysis was the middle ten seconds of the task's iEMG recorded for each subject (Fig. 3). The iEMG amplitude was calculated for each muscle under each vibration condition.

The power spectral density (PSD) of SEMG signal describes how the variance of a time series is distributed with frequency. Using the spectral parameter *median frequency* (MF), which is the frequency that divides the PSD in two regions having the same amount of power, muscle fatigue can be measured. MF shifting towards low frequencies indicates metabolic fatigue of the muscle, which can be explained by a change in motor unit recruitment, change in motor unit synchronization, or change in muscle fibre conduction velocity [74]. In this experiment, PSD was used to examine rate of muscle fatigue. For each participant, the entire PSD was separated in 3.07 second sections. The MF of each section was used to plot a graph of MF over time creating a line of best fit from which a slope was obtained. The rate of muscle fatigue was measured using the slopes of MF [75].

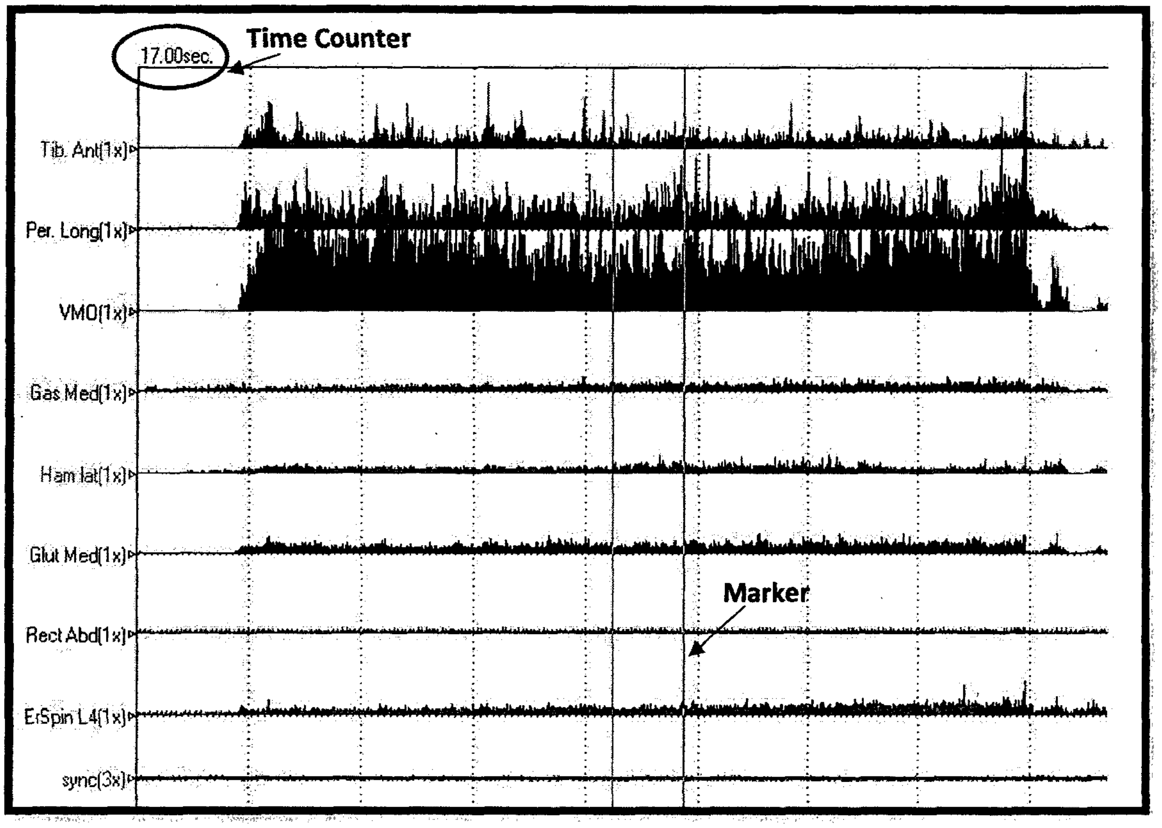

Figure 3
iEMG for the control (no vibration) condition. The long vertical lines represent the manually inserted markers identifying the ten seconds section for the iEMG amplitude to be analyzed. Each horizontal line represents the rectified EMG amplitude for each muscle (tibialis longus - Tib. Ant., fibularis longus - Per.Long.,vastus medialis oblique -VMO, gastrocnemius (medial head) - Gas. Med., biceps femoris - Ham. Lat., gluteus medius - Glut. Med., rectus abdominis - Rect.Abd., erector spinae - ErSpin L4). The *sync* line demonstrated the oscillation created by the platform. On the top left corner is the time counter used for the analysis of time-to-fatigue.

Time Recorder

Time-to-fatigue was measured by the time counter located inside the SEMG software (Fig. 3). The counter number at the beginning and end of the physical task was recorded. Subtraction of the starting counter number from the end number provided total time-to-fatigue.

Goniometer

Subjects' knee position was measured and controlled using a double-armed goniometer. Prior to the measurements, bony landmarks were marked on the subjects to standardize the goniometer placement and facilitate the readings. The bony landmarks included the greater trochanter, the lateral femoral condyle, and the lateral malleolus. The knee angle was measured with the center of the fulcrum positioned over the lateral condyle of the femur, the proximal fixed arm of the goniometer aligned with the femur using the greater trochanter as a reference point, and the distal arm aligned towards the lateral malleolus [76]. The goniometer was used to position the subjects into their experimental squat position as well as to ascertain that the subjects maintained that test position.

Borg Scale

The Borg category ratio scale was used to produce estimates of perceived exertion from the participants. Favoured over the Borg RPE (Rating of Perceived Exertion) Scale, this evaluation tool is an ordinal scale with values from 1 to 10 with verbal descriptions to standardize for comparison across individuals [69, 77]. The greater the exertion felt, the greater the number reported by the participants being tested. During or after a physical task, subjects can rate their physical effort or perceived exertion by saying the number between 1 and 10 that best represents their state (Appendix C).

Athletic Footwear

A factor to be considered during WBV is the wearing of athletic footwear. Partial absorption of vertical impact during physical activity does occur from the athletic shoe [78, 79]. Depending on the shoe support interface composition, the absorption or transmission of vertical force to the body may vary [79]. From this fact, the different footwear of people exposed to similar WBV acceleration force may actually transmit different vertical forces. In order to reduce any covariant variable able to decrease the strength of our results, each participant was fitted with the same brand and type of running shoes. Nike running shoes were available during the study for both men and women in different size accommodating every participant (Fig. 4). To prevent absorption of vertical vibration force by the shoes, the insoles inside the shoes were removed prior to the experiment.

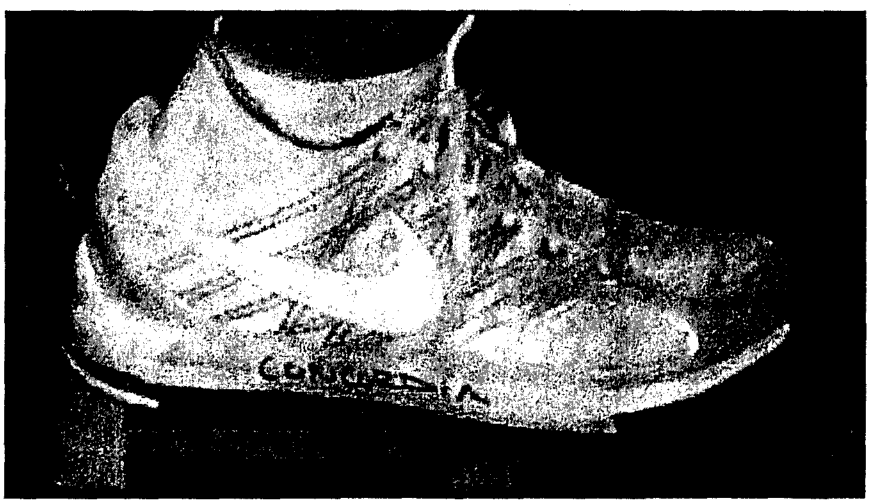

Figure 4
Athletic footwear used during the study for both men and women

Tasks

The physical task consisted of standing on the vibration platform holding a static one leg squat position until exhaustion. The participants were asked to squat down on their dominant leg to a knee angle of 125°[49]. The posture was controlled during the task by standardizing the knee angle with a goniometer as well as by requiring a straight back. The non-weight bearing leg was kept to the front or back of the participants depending on their comfort level. The participants familiarized themselves with the physical task with and without WBV stimulus before testing on their non-experimental leg. To prevent the risks of falling, the participants were asked to keep one to two fingers on the handle bars, while exerting only minimal weight on the bars. In any case, the handle bars were easy to reach if a participant felt unsteady.

During the experiment, subjects were verbally encouraged to sustain the task for as long as possible. To quantify exhaustion, the task terminated when the knee angle changed by 10° from its starting position for > 3sec, as detected by monitoring the goniometer [67], or when proper body position was not maintained by the participants despite verbal encouragement.

Procedure

Participants were asked to attend three days of data collection separated by one week in the CONCAVE Laboratory at Concordia University. Information about the study and the tasks to perform were given via telephone or electronic communication prior to the experiment and a consent form was signed upon arrival.

Once the set-up of the equipment was completed, SEMG signals were measured under WBV. Each subject was exposed to the ten vibration combinations (3 x 3 grid plus control) in counterbalanced order. They were asked to hold the static squat position until exhaustion. After each vibration exposure, each participant was asked to express their perceived rate of exertion using the Borg RC-10 scale. A rest period of 10 minutes was given in-between each exposure in order to rest the muscle adequately prior to the next vibration session [80]. The control combination required each subject to perform a static squat to exhaustion with a frequency of 0Hz and amplitude of 0mm (no-vibration). This control trial had the goal of ensuring that the squat position itself was not a cofounding variable. Similar to the other vibration combination, the control cell was provided to the participants in a counter-balanced manner.

Statistical Analysis

The statistical analysis was performed using SPSS Statistics GradPack 17.0 Release 17.0.0 (Chicago, IL, USA).

Muscle Activity, Rate of Muscle Fatigue and Time-to-fatigue

Muscle activity, rate of muscle fatigue and time-to-fatigue were analysed as a function of vibration frequency and amplitude using a 3 x 3 ANOVA with repeated measures to a significant level of $\alpha = 0.05$. A pairwise comparison was used when the main effect or interaction was found to determine differences between levels of the variables.

Vibration vs No-Vibration Comparison

The analysis of the control condition (no-vibration) was done by comparing the effects of vibration of 30 Hz / 3mm amplitude on muscle activity, rate of muscle fatigue and time-to-fatigue to the no-vibration condition. The vibration/no-vibration analysis was performed using a paired T-test to a significance level of $\alpha = 0.05$.

CHAPTER IV: RESULTS & DISCUSSION

Rate of Muscle Fatigue & Perceived Exertion

For each individual muscle in this experiment, the rate of muscle fatigue was not significantly affected by the vibration parameters individually or in combination (Figure 5 and 6). Tables 2 and 3 show raw data of mean slope from MF when exposed to each frequency and amplitude. Figure 5 compares the change in slope of MF of selected muscles when exposed to four different vibration frequencies, while Figure 6 illustrates the influence of four different amplitudes. Comparing the control no-vibration condition (0 Hz-0 mm) to the 30 Hz-3 mm vibration condition, the rate of muscle fatigue was not significantly affected by vibration (Figure 7 and 8). In regards to perceived exertion, participants evaluated their RPE at 8.83 ± 1.01/10 across all vibration conditions and the control no-vibration condition.

Time

Time-to-fatigue was significantly affected by the vibration amplitude ($F=4.596$, $p<0.05$) as subjects under higher amplitude held the squat position for a shorter amount of time. Table 4 and 5 demonstrate raw time-to-fatigue data when exposed to different frequencies (Tab. 4) and amplitudes (Tab. 5). From the vibration amplitude of 2mm (108.4 ± 8.0 sec) to 3mm (97.2± 6.5sec), the time-to-fatigue decreased by 11.2 ± 4.3 sec ($p= 0.013$). However, comparing time-to-fatigue from a 30 Hz/3 mm vibration condition to a no-vibration condition, the time was not significantly affected by vibration ($T= 1.047$ $p=0.304$).

Muscle	Frequency (HZ)	Mean Slope of Median Frequencies	*SD*
Erector Spinae L4	0	-0.093	0.201
	10	-0.109	0.023
	20	-0.163	0.025
	30	-0.117	0.027
Rectus Abdominis	0	-0.046	0.265
	10	0.011	0.024
	20	-0.014	0.043
	30	0.010	0.031
Gluteus Medius	0	-0.118	0.123
	10	-0.099	0.018
	20	-0.122	0.019
	30	-0.100	0.021
VMO	0	-0.206	0.194
	10	-0.235	0.036
	20	-0.224	0.038
	30	-0.193	0.030
Biceps Femoris	0	-0.197	0.193
	10	-0.167	0.027
	20	-0.212	0.040
	30	-0.233	0.036
Gastrocnemius	0	0.000	0.086
	10	-0.024	0.016
	20	0.045	0.027
	30	-0.018	0.024
Fibularis Longus	0	0.056	0.129
	10	0.079	0.024
	20	0.118	0.028
	30	0.054	0.025
Tibialis Anterior	0	0.021	0.164
	10	0.003	0.025
	20	0.005	0.032
	30	0.008	0.028

Table 2
Mean slope of MF when exposed to each frequency: 0Hz (no-vibration), 10Hz, 20Hz, 30Hz. n=30

Muscle	Peak to Peak Amplitude (mm)	Mean Slope of Median Frequencies	SD
Erector Spinae L4	0	-0.093	0.201
	1	-0.104	0.030
	2	-0.127	0.023
	3	-0.159	0.025
Rectus Abdominis	0	-0.046	0.265
	1	0.017	0.036
	2	0.019	0.036
	3	-0.028	0.026
Gluteus Medius	0	-0.118	0.123
	1	-0.105	0.015
	2	-0.109	0.023
	3	-0.108	0.021
VMO	0	-0.206	0.194
	1	-0.208	0.033
	2	-0.220	0.038
	3	-0.224	0.033
Biceps Femoris	0	-0.197	0.193
	1	-0.210	0.042
	2	-0.180	0.024
	3	-0.222	0.033
Gastrocnemius	0	0.000	0.086
	1	0.003	0.021
	2	-0.010	0.015
	3	0.009	0.018
Fibularis Longus	0	0.056	0.129
	1	0.07	0.023
	2	0.081	0.026
	3	0.100	0.030
Tibialis Anterior	0	0.021	0.164
	1	0.000	0.038
	2	0.030	0.025
	3	-0.018	0.029

Table 3
Mean slope of MF when exposed to each peak to peak amplitude: 0mm (no-vibration), 1mm, 2mm, 3mm. n=30

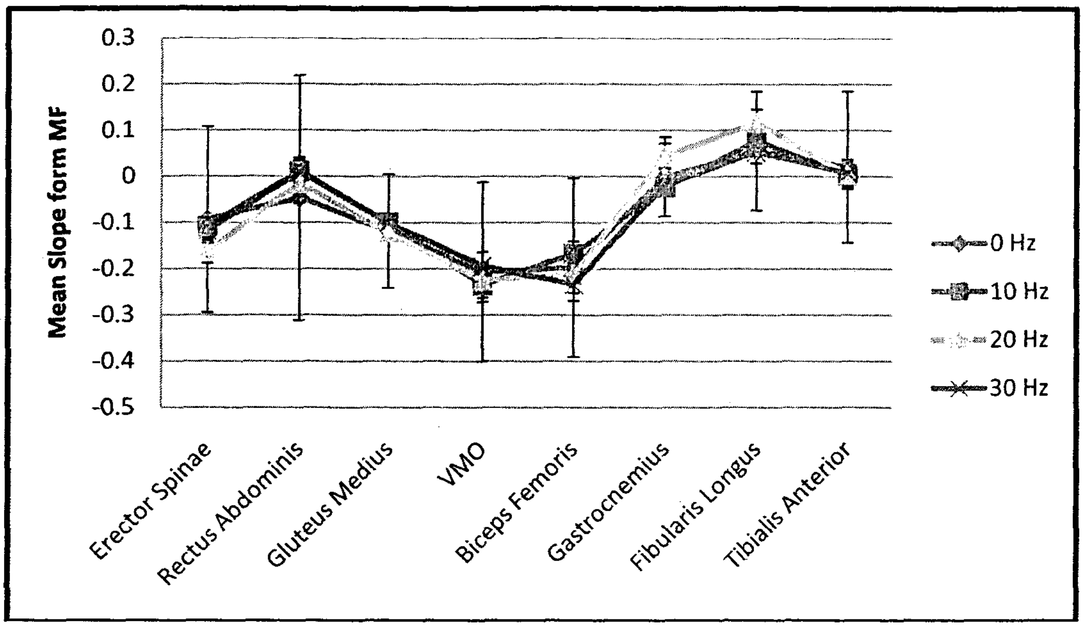

Figure 5
Group means of the slope from MF when exposed to 0 Hz, 10 Hz, 20 Hz and 30 Hz frequencies. No significant difference between frequencies. *n*= 30.

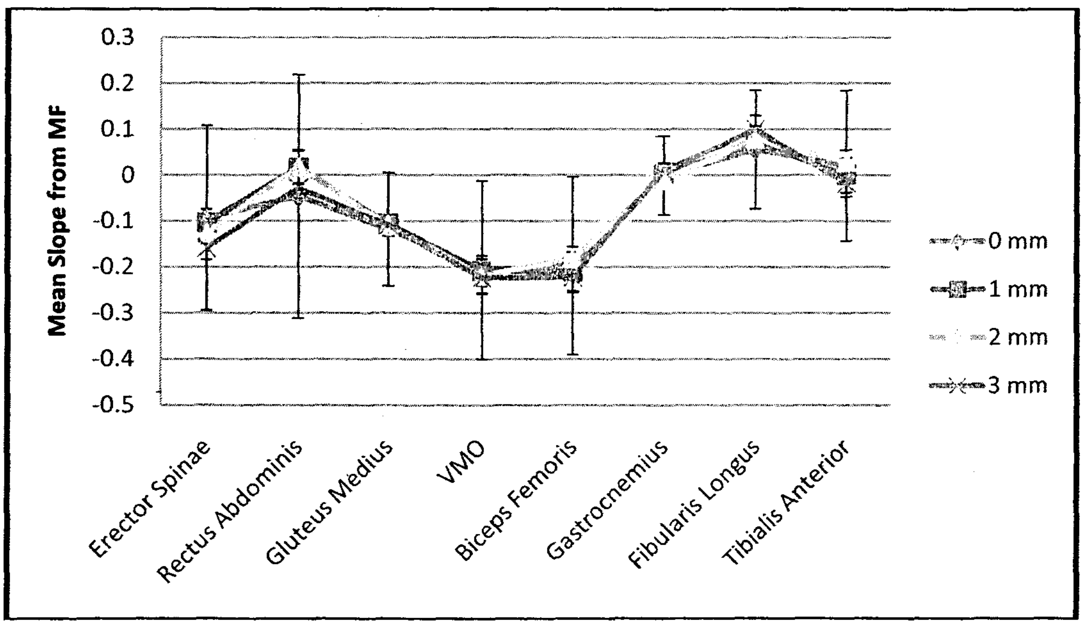

Figure 6
Group mean slope from MF when exposed to 0 mm, 1 mm, 2 mm and 3 mm peak-to-peak amplitudes. No significant difference between amplitudes. *n*= 30.

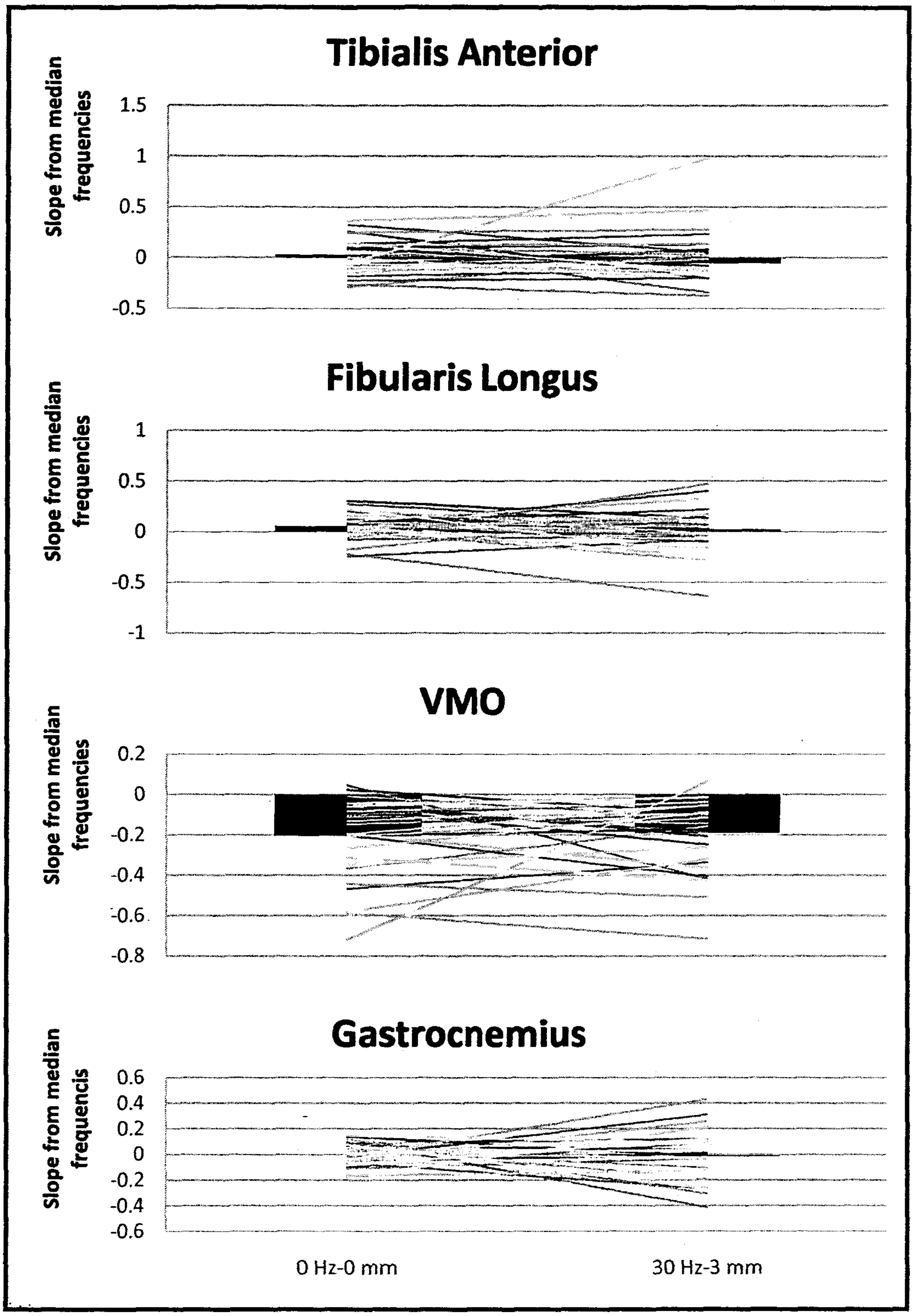

Figure 7
Rate of muscle fatigue differences between the control no-vibration (0 Hz-0 mm) condition and vibration of 30 Hz-3 mm condition in the tibialis anterior, fibularis longus, VMO and gastrocnemius muscles. Each line represents rate of muscle fatigue differences for a single subject; bars represent mean rate of muscle fatigue. No significant difference between the 0 Hz-0 mm and 30 Hz-3 mm conditions. *n*=30.

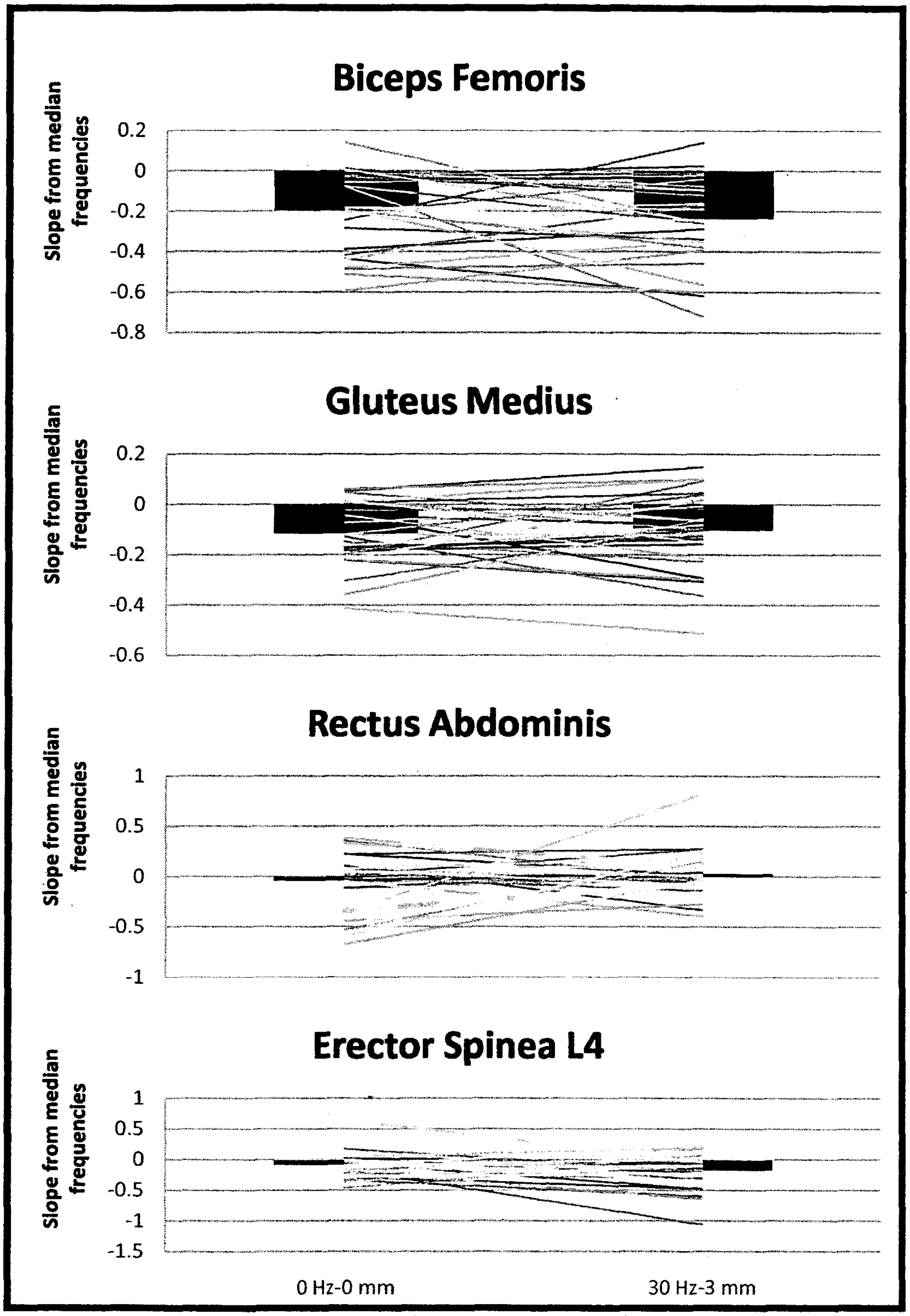

Figure 8
Rate of muscle fatigue difference between the control no-vibration (0 Hz/0 mm) condition and vibration of 30 Hz/3 mm condition in the biceps femoris, gluteus medius, rectus abdominis and erector spinae muscles. Each line represents rate of muscle fatigue difference of a single subject; bars represent mean rate of muscle fatigue. No significant difference between the 0 Hz/0 mm and 30 Hz/3 mm conditions. *n*=30.

Frequency (Hz)	**Mean Time (sec)**	***SD***
0	103.0	37.5
10	106.9	8.0
20	99.4	6.2
30	101.3	7.6

Table 4
Mean time-to-fatigue (sec) for each frequency level (10Hz, 20Hz, 30Hz) and without vibration (0Hz), *n*=30.

Peak to Peak Amplitude (mm)	**Mean Time (sec)**	***SD***
0	103.0	37.5
1	102.1	7.4
2	108.4	8.0
3	97.2	6.5

Table 5
Mean time-to-fatigue (sec) for each amplitude level (1mm, 2mm, 3mm) and without vibration (0mm), *n*=30.

Muscle Activity

During vibration, the muscle activity of gluteus medius (F=24.17, $p<0.05$), VMO (F= 18.951, $p<0.05$), biceps femoris (F= 3.925, $p<0.05$), gastrocnemius (F=3.923, $p<0.05$), fibularis longus (F= 6.226, $p<0.05$), and tibialis anterior (F=10.458 $p<0.05$) were all significantly affected by frequency as iEMG increased with increasing frequency. Tables 6 and 7 show raw data of muscle activity when exposed to each frequency and amplitude. Figure 9 demonstrates rectified SEMG amplitude for the VMO muscle under each vibration parameter combination. Gluteus medius muscle activity increased by 7.7± 2.3% ($p<0.05$) from 10Hz (35.1± 2.9%mvc) to 20Hz (42.8± 3.7%mvc), 19.3± 3.3% ($p<0.05$) from 10Hz to 30Hz (54.3±4.9%mvc), and 11.6± 2.8% ($p<0.05$) from 20Hz to 30Hz. VMO muscle activity increased by 30.1± 5.8% ($p<0.05$) from 10Hz (82.1±8.7%mvc) to 30Hz (112.2 ± 11.8%mvc), and 23.7± 5.8% ($p<0.05$) from 20Hz (88.5 ±7.8%mvc) to 30Hz. Biceps femoris muscle activity increased by 11.7± 5.6% ($p<0.05$) from 10Hz (16.9±2.1%mvc) to 30Hz (18.1 ± 2.1%mvc). Gastrocnemius muscle activity increased by 5.4± 1.2% ($p<0.05$) from 10Hz (11.7 ± 1.4%mvc) to 20Hz (17.1 ± 1.8%mvc), and 13.7± 6.1% ($p<0.05$) from 10Hz to 30Hz (25.4 ± 6.5%mvc). Fibularis longus muscle activity increased by 4.6± 1.3% ($p<0.05$) from 10Hz (23.8 ± 2.4%mvc) to 20Hz (28.4 ± 2.4%mvc), and 6.8± 2.4% ($p<0.05$) from 10Hz to 30Hz (30.7 ±2.9%mvc). Tibialis anterior muscle activity increased by 4.2± 1.5% ($p<0.05$) from 10Hz (15.6± 2.3%mvc) to 20Hz (19.8 ± 2.7%mvc), and 5.9± 1.3% ($p<0.05$) from 10Hz to 30Hz (21.5 ± 2.7%mvc).

The muscle activity of VMO (F=4.587, $p<0.05$) and gastrocnemius (F=3.225, $p<0.05$) were also significantly affected by amplitude as iEMG increased with increasing displacement. VMO muscle activity increased by 21.1± 6.5% ($p<0.05$) from 10Hz (85.5 ± 9.2%mvc) to 30Hz (106.6 ± 12.4%mvc). Gastrocnemius muscle activity increased by

3.1± 1.1% ($p<0.05$) form 10Hz (13.5 ±1.4%mvc) to 20Hz (16.6 ± 1.8%mvc). There were no interaction effects (frequency x displacement) on muscle activity for each muscle.

Comparing the iEMG of each muscle from a 30Hz/3mm amplitude vibration condition to a no-vibration condition, results demonstrated a vibration effect on the rectus abdominis (T= -2.88, $p<0.05$), gluteus medius (T=-3.862, $p<0.05$), VMO (T= -3.891, $p<0.05$), and fibularis longus (T=-3.5.87, $p<0.05$) as their muscle activity increased while holding the squat position under vibration. Rectus abdominis muscle activity increased by 5.24± 10.68% from no-vibration (5.39 ± 1.06 %mvc) to vibration (10.63 ± 2.44 %mvc). Gluteus medius muscle activity increased by 25.72± 36.48% from no-vibration (32.97± 12.71 %mvc) to vibration (58.69± 36.89 %mvc). VMO muscle activity increased by 49.56 ± 69.76% from no-vibration (76.12± 49.43%mvc) to vibration (125.68± 93.17%mvc). Fibularis longus muscle activity increased by 9.00 ± 13.61% from no-vibration (23.09± 12.75%mvc) to vibration (32.1± 20.2 %mvc).

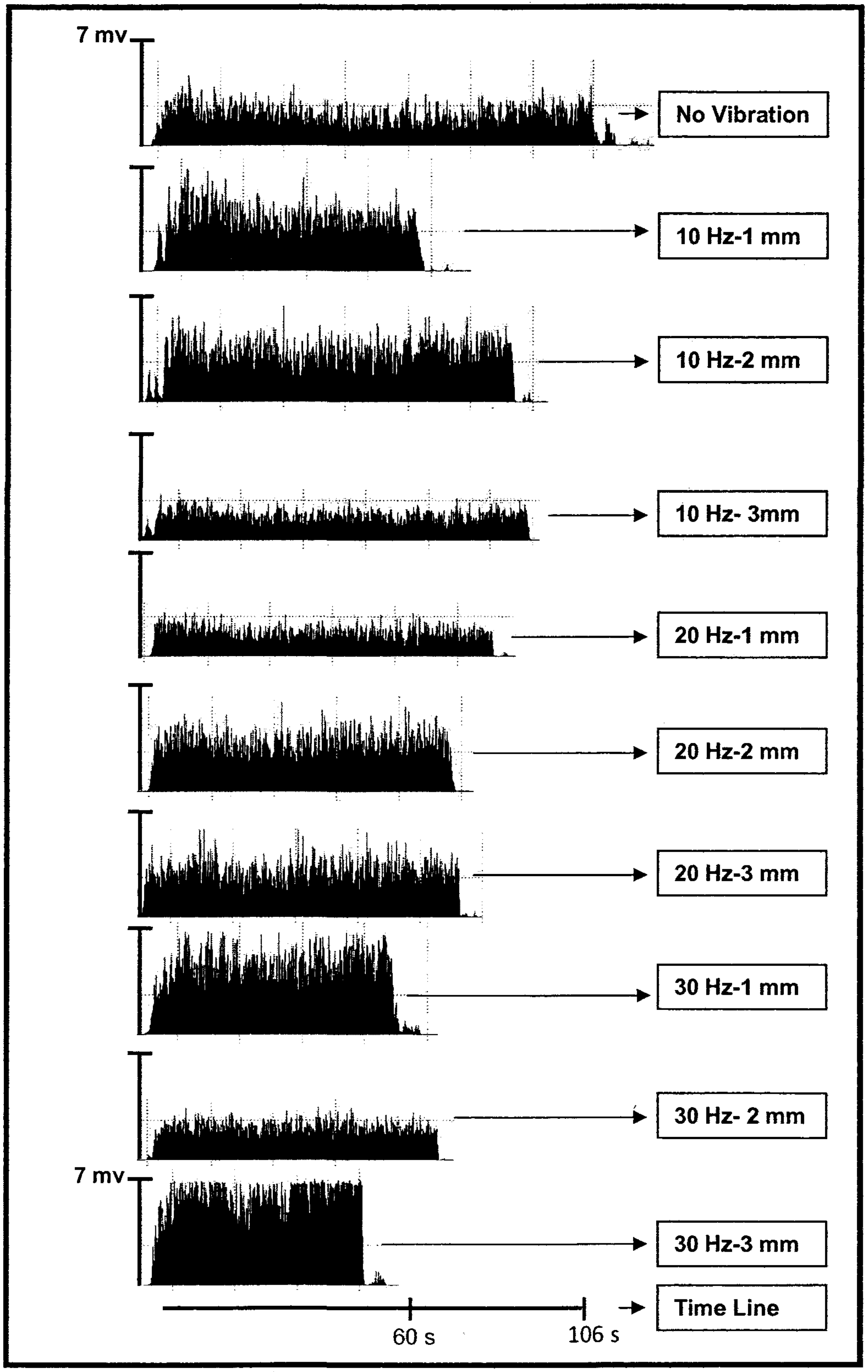

Figure 9
Rectified SEMG amplitude for the VMO muscle under each vibration parameter combination: control no vibration, 10 Hz-1 mm, 10 Hz-2 mm, 10 Hz-3 mm, 20 Hz-1 mm, 20 Hz-2 mm, 20 Hz-3 mm, 30 Hz-1 mm, 30 Hz-2 mm, 30 Hz-3 mm. The time line represents the total time-to-fatigue for the VMO no vibration condition. The vertical line represents the maximal peak muscle activity amplitude for the VMO. Maximal activity was found under the 30 Hz-3 mm condition.

Muscle	Frequency (HZ)	Mean Muscular Activity (%MVC)	*SD*
Erector Spinae L4	0	18.9	10.9
	10	18.7	2.2
	20	27.4	4.9
	30	33.6	9.2
Rectus Abdominis	0	5.4	5.8
	10	13.0	7.3
	20	44.5	36.5
	30	14.0	3.6
Gluteus Medius	0	33.0	12.7
	10	35.1	2.9
	20	42.8	3.7
	30	54.3	4.9
VMO	0	76.1	49.4
	10	82.1	8.7
	20	88.2	7.8
	30	112.2	11.8
Biceps Femoris	0	15.0	11.2
	10	16.9	2.1
	20	18.1	2.1
	30	28.7	5.6
Gastrocnemius	0	11.0	6.6
	10	11.7	1.2
	20	17.1	1.8
	30	25.4	6.5
Fibularis Longus	0	23.1	12.8
	10	23.8	2.4
	20	28.4	2.4
	30	30.7	2.9
Tibialis Anterior	0	16.2	15.7
	10	15.6	2.2
	20	19.8	2.5
	30	21.5	2.7

Table 6
Mean muscular activity (%MVC) for each frequency level and without vibration in the erector spinae, rectus abdominis, gluteus medius, VMO, biceps femoris, gastrocnemius, fibularsi longus and tibialis anterior muscles.

Muscle	Peak to Peak Amplitude (mm)	Mean Muscular Activity (%MVC)	SD
Erector Spinae L4	0	18.9	10.9
	1	27.7	4.8
	2	29.2	7.9
	3	22.7	3.2
Rectus Abdominis	0	5.4	5.8
	1	44.7	37.1
	2	11.2	2.8
	3	15.5	7.7
Gluteus Medius	0	33.0	12.7
	1	42.7	3.9
	2	42.7	3.3
	3	46.9	4.1
VMO	0	76.1	49.4
	1	85.5	9.2
	2	90.6	8.0
	3	106.6	12.4
Biceps Femoris	0	15.0	11.2
	1	17.7	2.0
	2	20.4	2.3
	3	25.6	5.7
Gastrocnemius	0	11.0	6.6
	1	13.5	1.4
	2	16.6	1.8
	3	24.0	6.0
Fibularis Longus	0	23.1	12.8
	1	25.6	2.3
	2	28.3	2.7
	3	28.9	2.7
Tibialis Anterior	0	16.2	15.7
	1	17.9	2.4
	2	18.7	2.5
	3	20.4	2.5

Table 7
Mean muscular activity (%MVC) for each amplitude level and without vibration in the erector spinae, rectus abdominis, gluteus medius, VMO, Biceps femoris, gastrocnemius, fibularis longus and tibialis anterior muscles.

Discussion

Rate of muscle fatigue – The results of the study showed no effect on the rate of muscle fatigue from vibration parameters. This result was expected as the number of participants was lower than what was calculated prior to the beginning of this experiment. Post data collection, a second sample size calculation was performed using the values obtained during the experiment to determine how many subjects would have been needed to obtain significance with our results. Due to the large experimental matrix, calculation was performed for the VMO, gluteus medius, and fibularis longus muscles only as these muscles had the main effect on muscle activity in WBV condition compared to no vibration. The mean slope of median frequencies for the no-vibration condition and 30Hz/3 mm vibration condition was used for the calculation with power set at 0.80 and $\alpha=0.05$. From the calculation, significance would have been obtained with 1166 subjects for the VMO, 252 subjects for the gluteus medius and 23,269 subjects for fibularis longus. From the extensive range of sample numbers, the number and recruitment of the appropriate number of subjects would be difficult.

In pilot studies, even though significance in the results could be absent, analysis of collected data may suggest some evidence, observations which may be useful in future WBV studies. In this study, no trends in the results were observed, questioning the fatigue evaluation technique. Since subject's perceived exhaustion at the end of each squat was similar amongst all subjects ($8.83 \pm 1.01/10$), the participants' capability of maintaining the squat position until perceived physical exertion was not of concern. Therefore, a different approach for fatigue data collection would be needed. A technique suggested by Luttmann et al.(2000) may be more appropriate as fatigue was determined by a joint analysis of SEMG spectrum and amplitude [81]. This method is based on the relationships between muscular force production and fatigue state and the SEMG amplitude and spectrum, as illustrated in Figure 10. In regards to SEMG amplitude, increases will take place with an increased in force as well as with the occurrence of fatigue [81]. On the other hand, fatigue will produce a left shift in the spectral distribution and an increased force production to right shift in the distribution [81]. From this knowledge and this evaluation technique, the occurrence of fatigue may be more easily and accurately detected leading to a better analysis of fatigue which may lead to significant results.

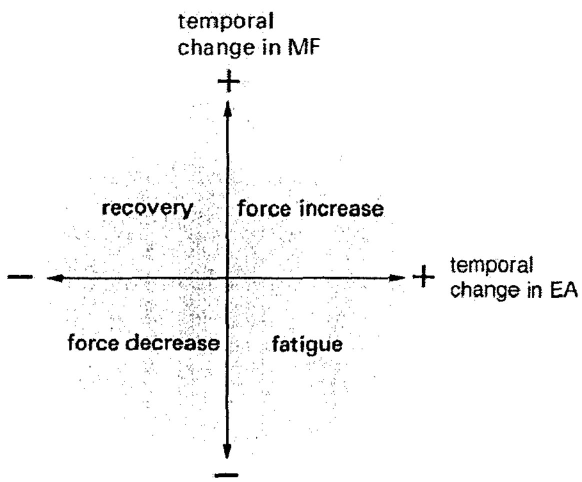

Figure 10
Schematic representation of the method for the Joint Analysis of EMG Spectrum and Amplitude: Time-related changes in the Electrical Activity (EA) and the Median Frequency (MF) are considered jointly in order to differentiate between various EMG-change causations. Representation taken from Luttman et al. (2000)

CHAPTER V: MANUSCRIPT
JOURNAL OF STRENGTH AND CONDITIONING RESEARCH™

Effects of Vertical Whole-Body Vibration Parameters on Muscle Activity and Time-to-Fatigue in Submaximal Isometric Contraction

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ABSTRACT

Effects of Vertical Whole-Body Vibration Parameters on Muscle Activity and Time-to-Fatigue in Submaximal Isometric Contraction

The purpose of this study was to examine the effects of vertical Whole-Body Vibration parameters (specific frequency / amplitude independently or in combination) on muscle activity and time-to-fatigue during submaximal isometric contraction. Thirty healthy college level athletes participated in the study. Three levels of each independent vibration parameter were examined using frequencies of 10, 20 and 30 Hz, and amplitudes of 1, 2, 3 mm, for a total of nine combinations of vibration dosage parameters. Surface electromyographic activity was measured from eight muscles: tibialis anterior, fibularis longus, vastus medialis oblique (VMO), gastrocnemius (medial head), biceps femoris, gluteus medius, rectus abdominis and erector spinae (L4). Analysis of variance with repeated measures evaluating the effects of the vibration parameters was performed on the measured integrated electromyography (iEMG) responses as well as time-to-fatigue. Main frequency effect was observed on the muscle activity of tibialis anterior, fibularis longus, VMO, gastrocnemius, biceps femoris and gluteus medius as their iEMG significantly increased with rising frequencies. The largest change was observed in the VMO with a 30.1± 5.8% ($p<0.005$) SEMG gain from 10 Hz (82.1 ± 8.7% mvc) to 30 Hz (112.2 ± 11.8% mvc). Time-to-fatigue was significantly affected by amplitude as time decreased by 11.22 ± 4.25 s ($p<0.005$) from an amplitude of 2 mm (108.42 ± 7.97 s) to 3 mm (97.22 ± 6.49 s). The results suggest frequency to be the principal parameter responsible for an increase in muscle activity under WBV and amplitude for a decrease in time-to-fatigue. The design of WBV training with the aim of

increasing muscle activity should be centered on frequency, with a frequency of 30 Hz for greater muscle activity.

Key Words : Frequency, Amplitude, Acceleration Force, Electromyography

INTRODUCTION

Vibration training involves the superimposition of vibration to one's initial strength training or the use of whole-body vibration (WBV) as a substitution for physical exercise. Since the introduction of the novel modality in fitness and rehabilitation centers, health professionals have used WBV in the belief that the effects of the oscillation on the body standing on the platform will help with different aspects of human health, such as increasing bone density, improving balance and flexibility amongst others [2, 3, 5, 6]. In the fields of athletics and fitness, health professionals, personal trainers and coaches use acute and chronic exposure to WBV with the aim of increasing power and strength in human neuromuscular performance [43, 54, 56]. The main objective in such training is to increase strength and power via a reflexive muscle contraction response from vibration known as a Tonic Vibration Reflex (TVR) [20].

In the design of an optimal training protocol to achieve muscle strength or power improvement, there have been inconsistencies in the program parameters. In such studies, several parameters need to be determined, such as body position held on the platform, sets and reps of exercise performed, vibration parameters - i.e. frequency and amplitude - and vibration exposure time. In the past, several studies differed in their training protocol [54, 56, 82-86]. These studies use a variety of settings: a frequency setting ranging from 15 to 50 Hz, an amplitude ranging from 2 to 10 mm, both of these creating an array of acceleration forces exposed to the human body that reaches up to 15 *g*. Vibration should not be looked at as a single element. Mechanical oscillations have a direct influence on the human body through different individual components. Since different platforms provide different features, it is of great importance to understand the impact each vibration component has on the human body when designing training protocols which are believed to be beneficial. Side effects such as motion sickness, digestive system disorder, adverse effects on the female reproductive organs, peripheral veins disorders as well as aggravation of pre-existing back, neck or shoulder injury cannot be excluded [16-18]. The lack of consistency across studies is of concern; however, the absence of a solid rationale behind the use of the parameters is additionally problematic, as the understanding of the response of the human body under WBV remains uncertain.

A solid rationale would begin with an understanding of the impact which frequency and amplitude of vibration have on the human body. From current knowledge, frequency and amplitude have an effect on muscle activity independently or in combination [48, 54, 87, 88]. The concern with those statements is that each study looked at only one independent variable (frequency or amplitude), or studied the combination of frequency and amplitude (acceleration force) only. These studies make understanding the effect of each component on the body difficult as the comparison of effects does not occur within a single study. To determine the effects of the vibration component individually or combined, an experimental design requires inclusion of a series of frequency and amplitude and needs to evaluate their effects within the same experiment.

Results from previous studies on human performance may be beneficial in the design of WBV training, as positive outcomes provide successful WBV training protocol. However, studies have demonstrated both positive and negative outcomes regarding increases in strength and power [2, 43, 47]. Although several studies evaluated chronic and acute WBV effect on human performance, few incorporated a control group [2, 43, 45, 82, 85, 86, 89]. Of these studies, a smaller amount succeeded in demonstrating significant improvements on strength and/or power from vibration compared to the control group [2, 43, 45]. Such a lack in significance and consistency in the results may be explained by a poor understanding of the human physiology behind WBV, or more precisely how vibration parameters affect the human body.

The purpose of this study is to look at and understand the effects of vibration parameters on the human body in order to facilitate the design of a safe and effective vibration protocol for the healthy population. The objective was to find the effects of vertical vibration parameters (specific frequency and amplitude independently or in combination) on muscle activity and time-to-fatigue during submaximal isometric muscular contraction. To our knowledge, this study would be the first to look at vibration parameters separately and in combination within the same experiment. From present WBV knowledge, frequency was hypothesized to be the main vibration parameter affecting muscle activity and time-to-fatigue during isometric muscular contraction under WBV.

METHODS

Experimental Approach to the Problem

A 3 x 3 repeated measures study design was used to investigate the effects of vertical WBV on muscle activity and time-to-fatigue during an isometric single leg squat exercise until exhaustion. The independent variables included vibration frequency and amplitude and the dependent variables were muscle activity and time-to-fatigue. Three levels of each independent parameter were examined using frequencies of 10, 20 and 30 Hz, and vertical peak-to-peak amplitudes of 1, 2, 3 mm, leading to nine combinations: 10 Hz/1 mm, 10 Hz/2 mm, 10 Hz/3 mm, 20 Hz/1 mm, 20 Hz/2 mm, 20 Hz/3 mm, 30 Hz/1 mm, 30 Hz/2 mm, and 30 Hz/3 mm; and a control combination: 0 Hz/0 mm (Tab. 9). The frequencies and amplitudes were selected based on previously used vibration parameters in preceding WBV studies. The frequency of 10 Hz was included to assess the effect of even lower frequencies than previously used on the human body.

Frequency / Peak Amplitude	0 Hz	10 Hz	20 Hz	30 Hz
0 mm	0.0 *g*			
0.5 mm		0.201 *g*	0.805 *g*	1.811 *g*
1 mm		0.402 *g*	1.61 *g*	3.622 *g*
1.5 mm		0.604 *g*	2.415 *g*	5.433 *g*

Table 8
Peak acceleration forces (*g*) created by the combination of frequencies (Hz) and amplitudes (mm) selected for the experiment.

Subjects

Thirty college-level athletes (age 19.47± 2.45 yr, Ht 172.23± 8.08 cm, Wt 73.3± 11.78 kg), free of any conditions that could interfere with the task to perform during the experiment, volunteered to participate in this study. Subject exclusion criteria included acute or chronic back injury, acute inflammation in the musculoskeletal system, acute migraine attack, acute or chronic musculoskeletal injury in the dominant leg, acute thrombosis, recent surgery, cancer, epilepsy, gallstones, kidney or bladder stones, open wounds in the dominant leg, pregnancy, rheumatoid arthritis and arthropathy, and diabetes. All subjects were screened for exclusion criteria prior to enrolment. All procedures were approved by the Concordia University Human Research Ethics Committee. All participants gave written informed consent to participate in the study on their first visit, following explanation of the risks associated with participating in the current research.

Testing Procedures

Participants were asked to attend three days of data collection separated by one week. On the subject's first visit, leg dominance was determined and maximal voluntary contractions (MVC) were recorded for each tested muscle to normalize recorded muscle activity. Leg dominance was determined by identifying the foot used most often to initiate a step in three separate trials [90]. Each subject was then exposed to the ten vibration combinations (3 x 3 grid, plus control) in a counterbalanced order. Three combinations were completed during the first visit, four combinations during the second visit and three combinations during the last visit. A rest period of 10 minutes was given in between each exposure in order to rest the muscle adequately prior to the next vibration session [80]. The vibration platform used during the experiment was the *Vibraflex® 600*, a unit that vibrates vertically about a central fulcrum. Each participant was fitted with the same brand and type of running shoes in order to protect the subjects' feet and maintain consistency in the delivery of the vibration. To prevent excessive absorption of the vertical vibration force from the footwear, the insoles inside the shoes were removed prior to the beginning of the experiment.

The physical task consisted of standing on the vibration platform holding a static one leg squat position until exhaustion. The participants were asked to squat down on their dominant leg to a knee angle of 125° [49] while keeping a straight back (Fig. 11) Subjects' knee position was measured and controlled using a double-armed goniometer. Prior to the measurements, bony landmarks were marked on the subjects to standardize the goniometer placement and facilitate the readings. The bony landmarks included the greater trochanter, the lateral femoral condyle, and the lateral malleolus. The knee angle was measured with the center of the fulcrum positioned over the lateral condyle of the femur, the proximal fixed arm of the goniometer aligned with the femur using the greater trochanter as a reference point, and the distal arm aligned towards the lateral malleolus

[76]. The goniometer was used to position the subjects into their experimental squat position as well as to ascertain that the subjects maintained that test position. The non-weight bearing leg was kept to the front or back of the participants depending on their comfort level. The participants familiarized themselves with the physical task both with and without WBV stimulus before testing on their non-experimental leg. To prevent the risk of falling, the participants were asked to keep one to two fingers on the handle bars while exerting only minimal weight on the bars.

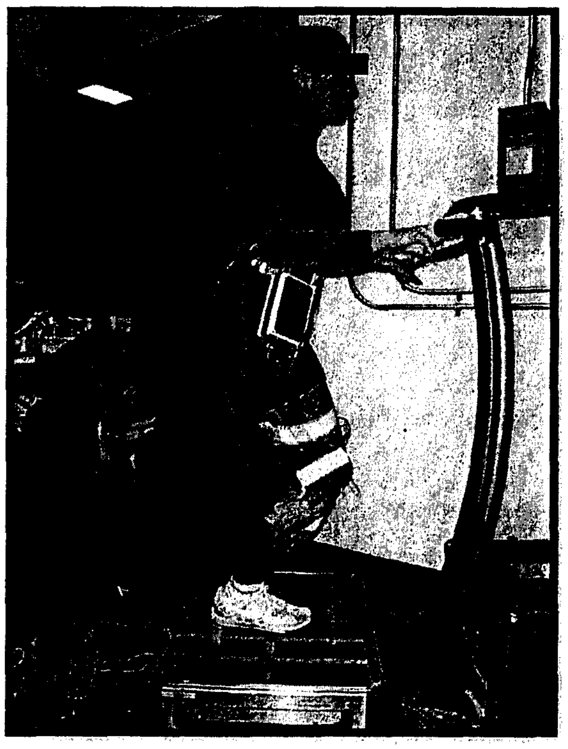

Figure 11
Position held by subjects during data collection. 125° knee flexion with a straight back.

While exposed to a vibration condition, the task time started as soon as the subject adopted the testing position. During the experiment, subjects were verbally encouraged to sustain the task for as long as possible. To quantify exhaustion, the task terminated when the knee angle changed by 10° from its starting position for over 3 s as detected by monitoring the goniometer, or when proper body position was not maintained by the participants despite verbal encouragement [67]. At that moment, trial time ended.

Electromyographic & Time Recording

SEMG from the dominant leg of the participants was collected. Six muscles from the dominant leg and two from the trunk were analyzed: tibialis anterior, fibularis longus, medial gastrocnemius, biceps femoris, vastus medialis oblique (VMO), gluteus medius, rectus abdominis, and erector spinae (L4); a reference electrode was placed over the tibial tuberosity. The placement of the electrodes was done according to Basmajian & Blumenstein and as described by DeMont, Lephart et al. (1999), and McGill, Karpowicz et al. (2009) [71-73]. Prior to placing the electrodes, hair on each location was shaved, the skin was slightly abraded with a nail file, and then cleaned with alcohol to remove any dead tissue improving electrode adhesion. Moreover, the cables were taped to the skin to minimize movement artefacts.

SEMG collection was carried out using Ag/AgCl adhesive electrodes. EMG signal was sampled at 1000 Hz and amplified (gain 500) by a 27-channel amplifier (MYOPAC, RunTech Inc., Mission Viejo, CA), than transmitted to a MYOPAC 16-channel receiver where it was further amplified (gain 500, total gain 1000), and A\D converted. The signal was then transmitted and stored in a Dell laptop computer where the signal was bandpass filtered (Butterworth) between 10 Hz and 500 Hz and rectified using Runtech

DATAPAC2000 software [72]. The resulting signal became integrated electromyography (iEMG) and was used for analysis.

To perform our muscle activity analysis, mean iEMG amplitude was calculated for ten seconds. Since each subject was able to maintain the task position for different amounts of time, the section selected for analysis was the middle ten seconds of the task's iEMG recorded for each subject. The iEMG amplitude was calculated for each muscle under each vibration condition. Time-to-fatigue was measured by the time counter located inside the SEMG software. The time counter numbers at the beginning and the end of the task were recorded. The subtraction of the starting time counter number from the ending time counter number provided total time-to-fatigue.

STATISTICAL ANALYSIS

Prior to this experiment, a pilot study on the effects of vertical WBV on muscle activity was done in order to find the appropriate number of participants needed to achieve significance. The calculation of the sample size was carried out with $\alpha=0.05$ and power of 80%, providing a sample size of $n=30$ for this study.

The statistical analysis was performed using SPSS Statistics GradPack 17.0 Release 17.0.0 (Chicago, IL, USA). Muscle activity and time-to-fatigue were analyzed as a function of vibration frequency and amplitude using a 3 x 3 ANOVA with repeated measures to a significance level of $\alpha= 0.05$. A pairwise comparison was used when the main effect or interaction was found to determine differences between levels of the variables.

The analysis of the control condition (no-vibration) was done by comparing the effects of vibration of 30 Hz / 3 mm amplitude on muscle activity and time-to-fatigue to the no-vibration condition. The vibration/no-vibration analysis was performed using a paired T-test to a significance level of $\alpha=0.05$.

RESULTS

Muscle Activity

During vibration, the muscle activity of gluteus medius (F=24.17, $p<0.05$), VMO (F= 18.951, $p<0.05$), biceps femoris (F= 3.925, $p<0.05$), gastrocnemius (F=3.923, $p<0.05$), fibularis longus (F= 6.226, $p<0.05$), and tibialis anterior (F= 10.458, $p<0.05$) were all significantly affected by frequency as iEMG increased with increasing frequency (Fig. 12). The muscle activity of VMO (F=4.587, $p<0.05$) and gastrocnemius (F=3.225, $p<0.05$) were also significantly affected by amplitude as iEMG increased with increasing amplitude (Fig. 13). There were no interaction effects (frequency x amplitude) on muscle activity for each muscle.

Comparing the iEMG of each muscle from the 30 Hz/3 mm vibration condition to the control no-vibration condition, results show a vibration effect on the rectus abdominus (t= -2.88, $p<0.05$), gluteus medius (t=-3.862, $p<0.05$), VMO (t= -3.891, $p<0.05$), and fibularis longus (t=-3.5.87, $p<0.05$) as their muscle activity increased while holding the squat position under vibration (Figs. 14 and 15).

Time

Time-to-fatigue was significantly affected by vibration's amplitude (F= 4.596, $p<0.05$) as subjects under bigger amplitude held the squat position for a shorter amount of time. However, comparing time-to-fatigue from a 30 Hz/3 mm vibration condition to a no-vibration condition, time was not significantly affected by vibration (t= 1.047, $p<0.05$) (Figs. 16, 17 and 18).

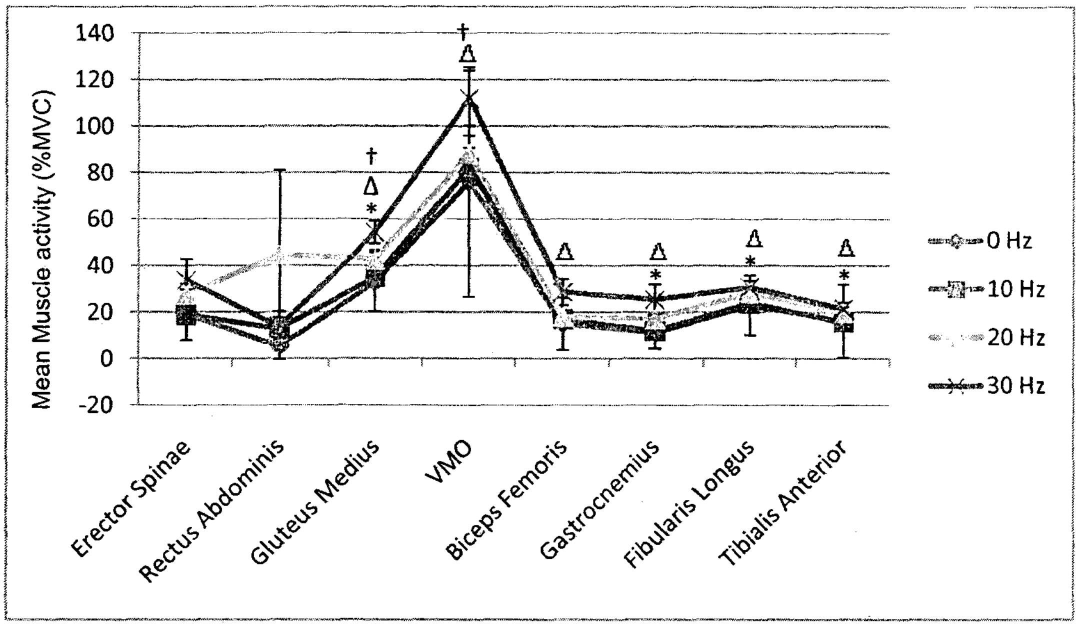

Figure 12
Mean muscle activity (%MVC) when exposed to frequency of 0 Hz, 10 Hz, 20 Hz and 30 Hz. *Significant difference between frequencies of 20 Hz &10 Hz, Δ significant difference between frequencies of 30 Hz &10 Hz, † significant difference between frequencies of 30 Hz & 20 Hz. *n*= 30.

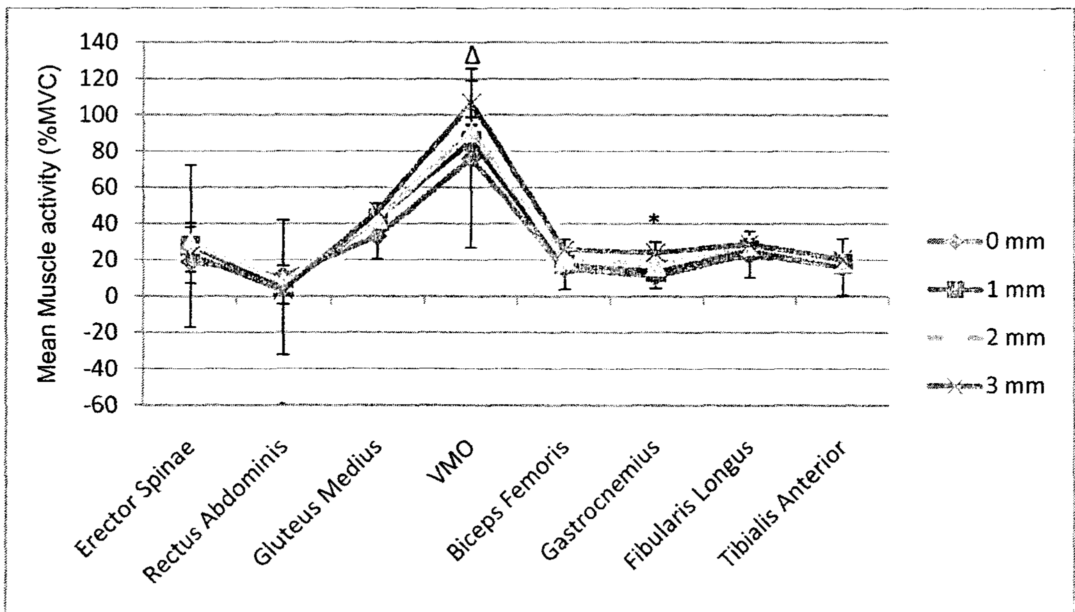

Figure 13
Mean muscle activity (%MVC) when exposed to peak-to-peak amplitude of 0 mm, 1 mm, 2 mm and 3 mm. *Significant difference between frequencies of 2 mm &1mm, Δ significant difference between frequencies of 3 mm & 1mm. *n*= 30.

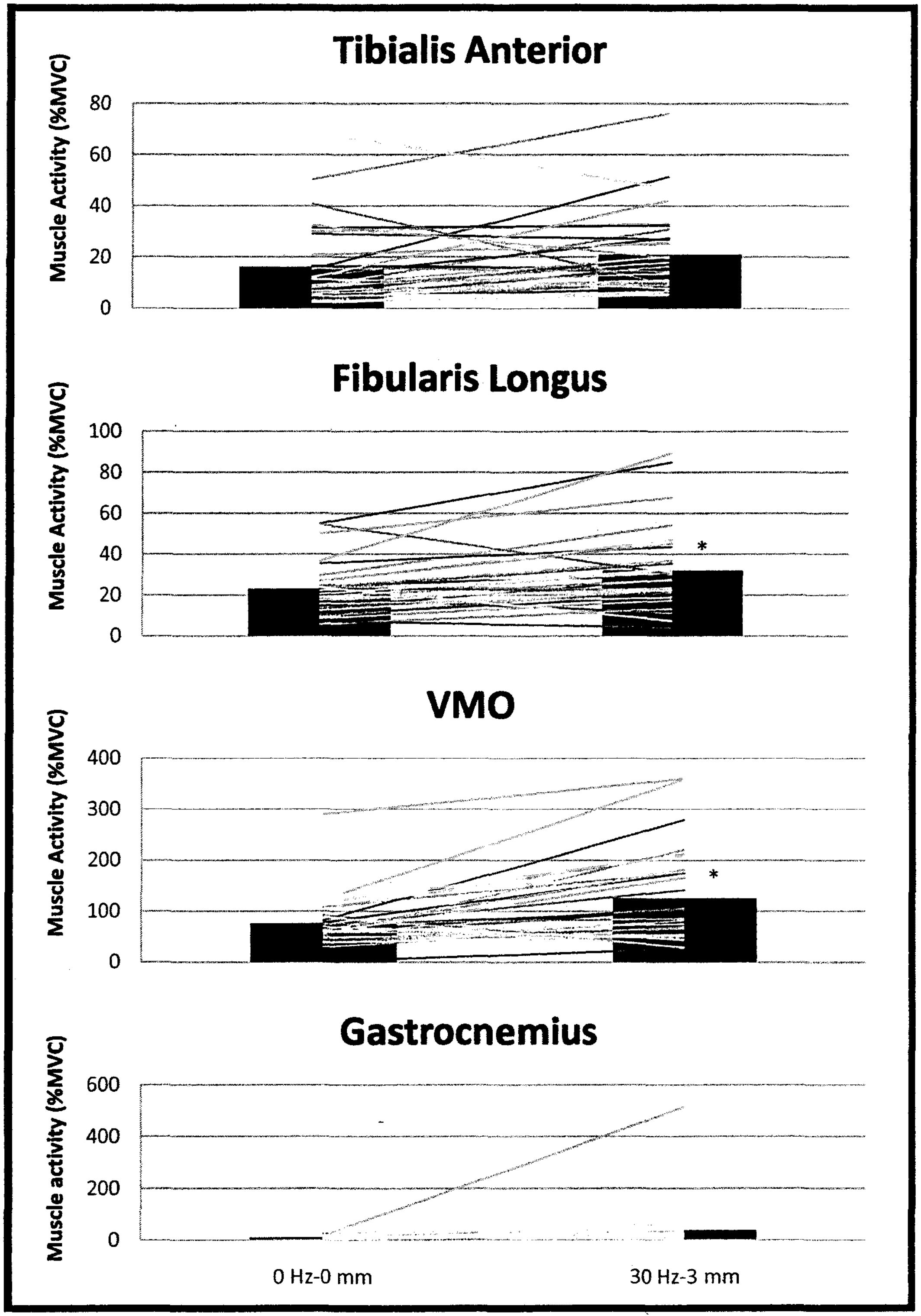

Figure 14
Muscle activity (%MVC) *difference between the control no-vibration* (0 Hz-0 *mm) condition and* vibration of 30 Hz- 3mm condition in the tibialis anterior, fibularis longus,VMO and gastrocnemius muscles. Each line represents a single subject; bars represent mean muscle activity for all 30 subjects. *Significant difference between the 0 Hz/0 mm and 30 Hz/3 mm conditions. n=30.

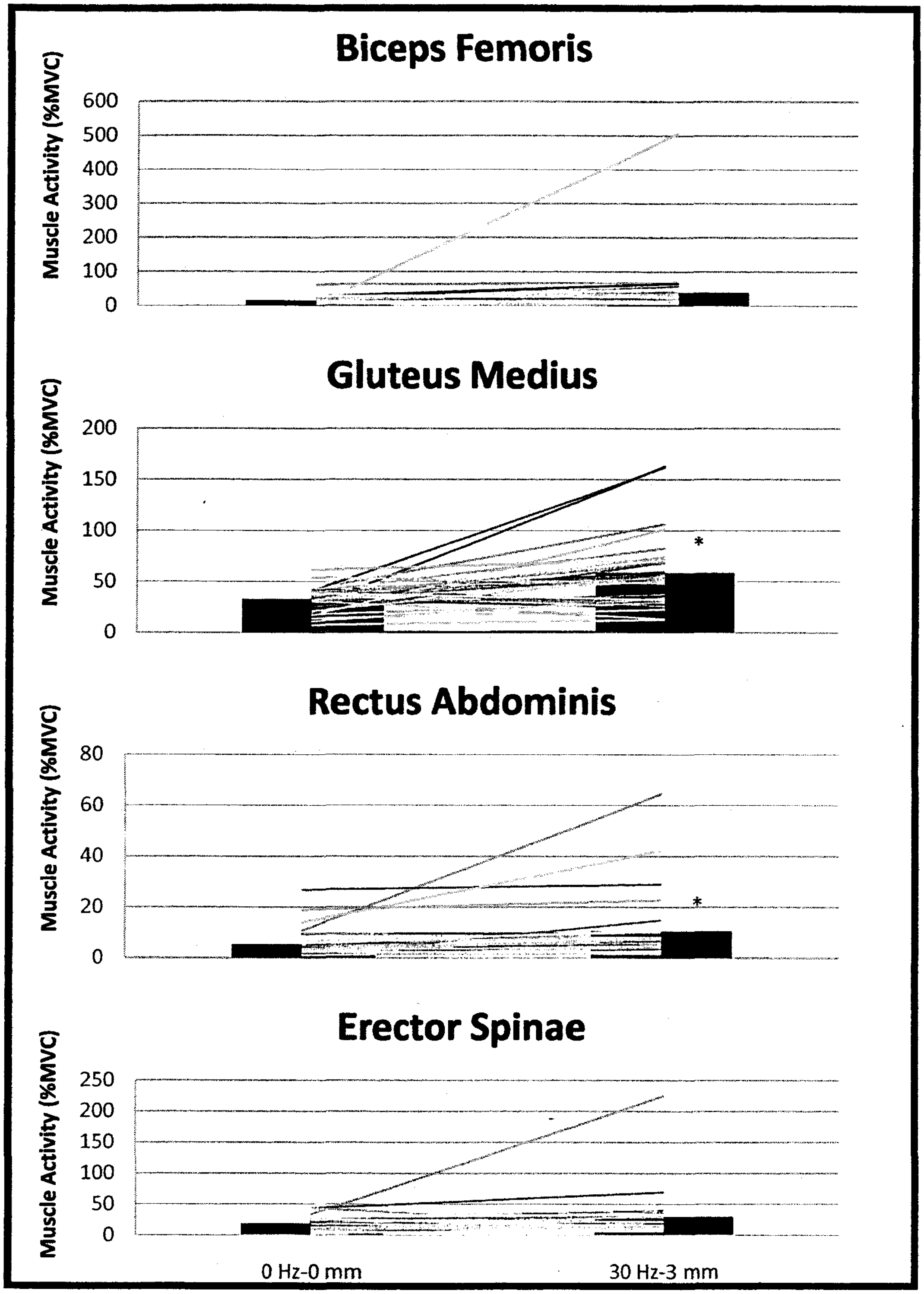

Figure 15
Muscle activity (%MVC) difference between the control no-vibration (0 Hz-0 mm) condition and vibration of 30 Hz-3 mm condition in the biceps femoris, gluteus medius, rectus abdominis and erector spinae muscles. Each line represents a single subject; bars represent mean muscle activity for all 30 subjects. *Significant difference between the 0 Hz/0 mm and 30 Hz/3 mm conditions. *n*=30.

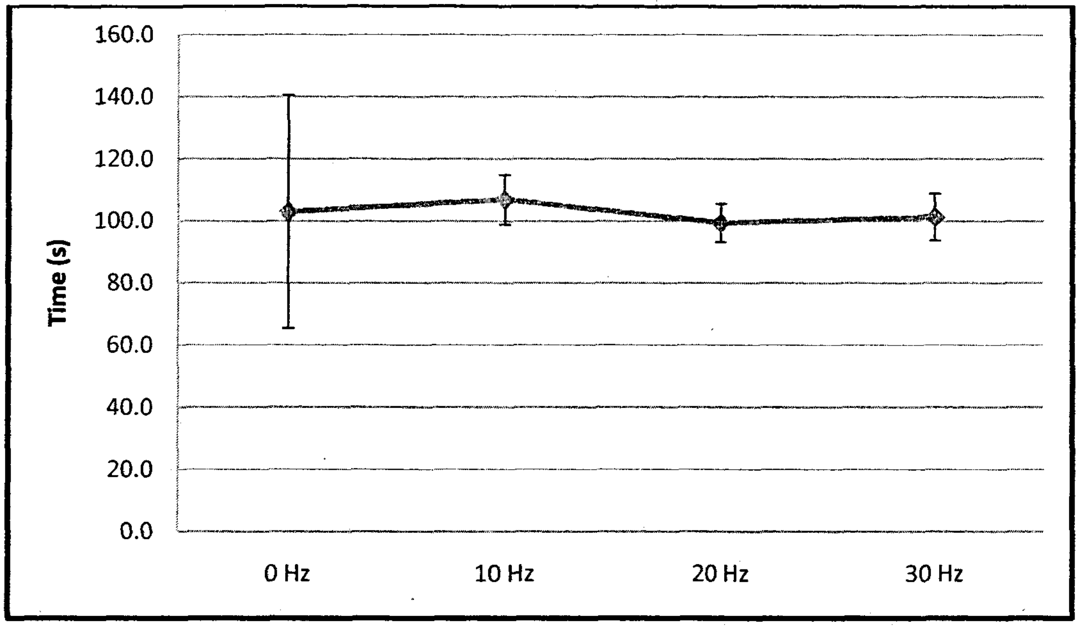

Figure 16
Mean time-to-fatigue (s) when exposed to frequencies of 0 Hz, 10 Hz, 20 Hz and 30 Hz. No significant difference between frequencies. *n*= 30.

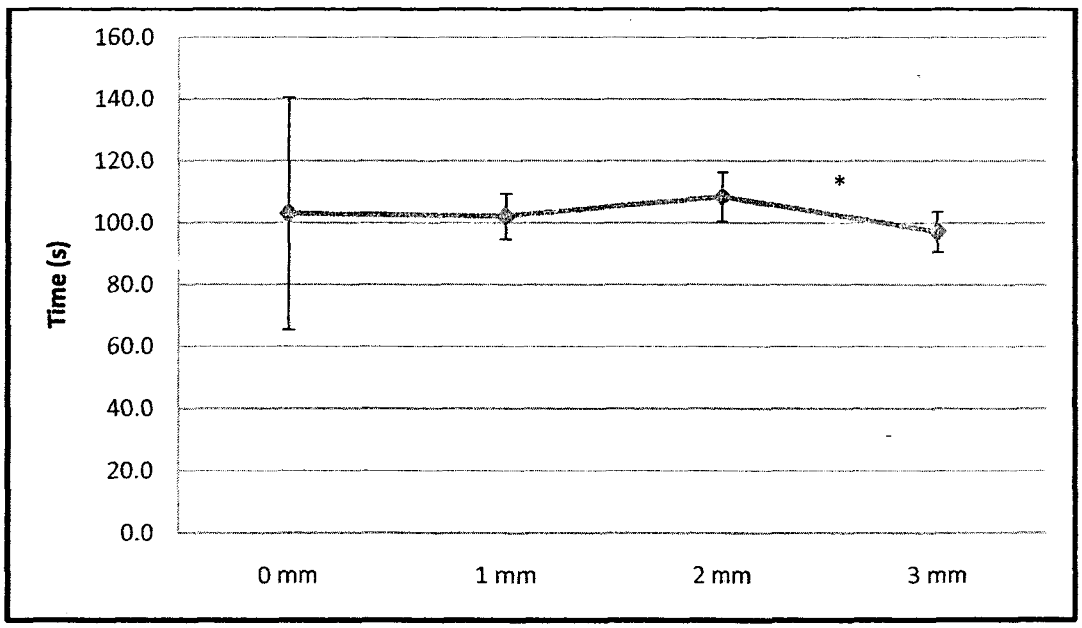

Figure 17
Mean time-to-fatigue (s) when exposed to peak-to-peak amplitudes of 0 mm, 1 mm, 2 mm and 3 mm.*Significant difference between amplitudes of 2 and 3 mm. *n*=30.

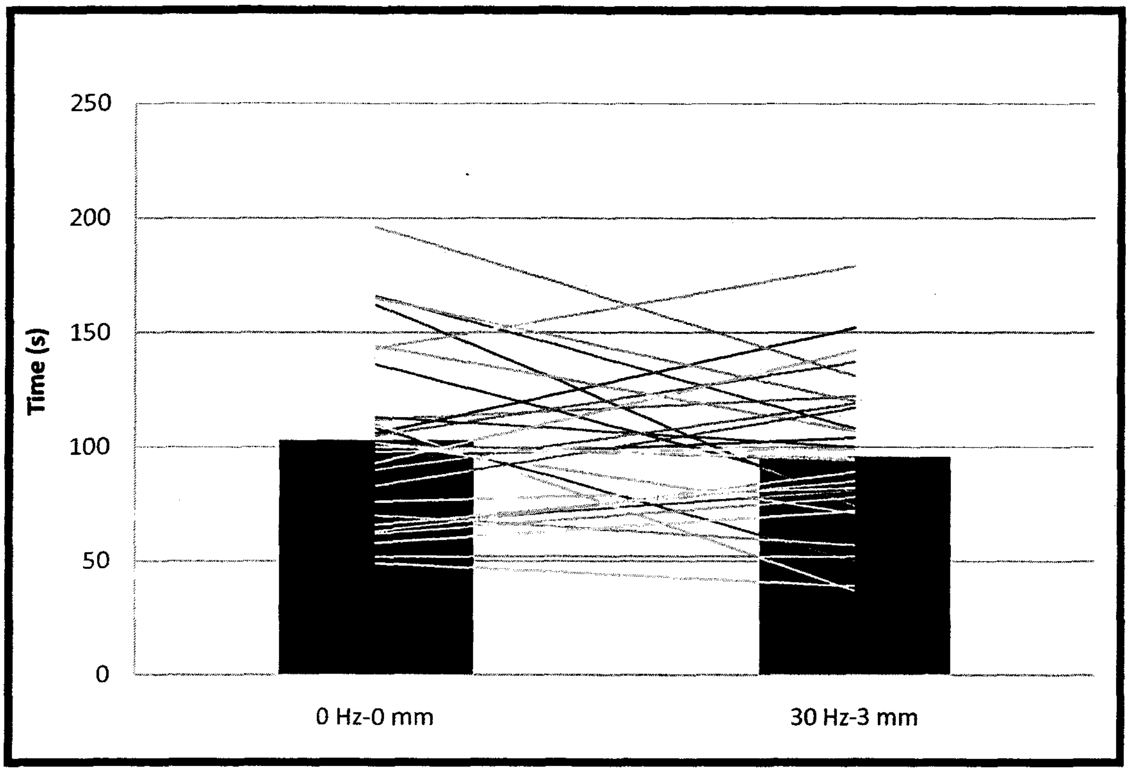

Figure 18
Mean time-to-fatigue differences (s) between the control no-vibration (0 Hz-0 mm) condition and vibration of 30 Hz-3 mm condition. Each line represents a single subject's time; bars represent mean time-to-fatigue for all 30 subjects. No significant difference between the 0 Hz – 0 mm and 30 Hz – 3 mm conditions. n=30

DISCUSSION

Muscle Activity & Frequency - The results of the study show frequency to be the major vibration parameter to impact overall muscle activity during WBV. Increasing the frequency seems to affect muscle activity as activity increased with increasing frequencies. A physiological explanation of this finding may be related to the reflexive tonic vibration response from vibration. This reflexive muscle contraction would be the result of primary afferent nerve sensitivity to vibration - sensitivity being predominant in frequencies up to 180 Hz with maximum sensitivity to vibration of 80 Hz [21, 22]. The vibration frequency and the firing rate of the muscle spindle primary nerve fibres due to vibration were shown to be connected as they are both synchronized to a frequency up to 180 Hz [21, 22]. Moreover, the discharge from muscle spindle primary nerve fibres was revealed to fire harmonically with vibrations up to 80Hz (e.g., 1 action potential of muscle spindle primary nerve : 1 Hz (or cycle per second)) and then discharge in a subharmonic manner (e.g., 1 action potential of muscle spindle primary nerve : 2 vibration cycle) with increasing vibration frequencies [22]. The one-to-one stimulus response under lower frequencies means that by altering the vibration frequency the initiation a proportional change in the Ia afferent discharge frequency is possible. More specifically, as frequency increases to a maximum of 80Hz, discharge of Ia afferent increases.

The control of muscle force output depends on the amount of motor units recruited and the frequency of discharge of the motor units [19]. Looking at the relation between tonic vibration reflex (TVR) and motor units, a previous study demonstrated a modulation of the amplitude of TVR when humans were exposed to vibration, a variation explained by an increase in motorneuron depolarization from the firing frequency of Ia afferents. [23]. At frequencies below 100 Hz, all of the Ia afferents are assumed to be recruited by the vibration stimulus [23]. An increase in TVR in the lower frequency range results principally from an increase in motorneuron depolarization with increased firing frequency of Ia afferent. This increased motor neuron depolarization leads to a recruitment of motor units of increasing threshold. At frequencies above 100 Hz, most Ia afferents start to fire at random to vibration stimuli and lose the response in terms of 1:1 synchrony leading to subharmonic synchronization [23]. This change in behaviour leads to a derecruitment process affecting the motorneurons and their responsive fibres showing a reduction in the strength of TVR [23].

Reviewing WBV studies, predominant frequencies used in the vibration protocol ranged from 15 to 50 Hz [54, 56, 82-86]. Considering current knowledge on afferent nerve / motor units and vibration, a frequency of 80 Hz may be preferable in order to obtain maximal muscle activation from TVR. A study by Steyvers et al. (2003) investigated the effects of muscle tendon vibration at different frequencies on corticospinal excitability. The results demonstrated an increase sensitivity of the Ia afferent at 75 Hz compared to a smaller increase in excitability at 120 Hz and an absence of change at 25 Hz [38]. A similar outcome from WBV exposure with a frequency of 80Hz is suggested.

A different suggestion for the increased muscle activity is the presence of muscular fatigue. When analyzing iEMG, a shift in the frequency spectrum towards lower frequencies or an increase in the amplitude are interpreted as signs of muscular fatigue [81]. Since the iEMG amplitude and its spectral content may also represent force production, a recovery period, or force reduction, change in the iEMG amplitude cannot be only attributed to muscle fatigue [81]. However, in the presence both increased amplitude and spectral shift to lower frequency at the same time, one can infer the presence of muscle fatigue. In this study, joint analysis of EMG spectrum and amplitude was not performed making the presence of muscular fatigue a second interpretation of our results.

Muscle Activity & Squat Task - Even though WBV exposes the entire body to vibration, each muscle does not respond to the same extent. The amount of muscle activity for each individual muscle may be from the combination of a specific frequency setting in addition to the physical demand from the task performed on the platform. From existing knowledge, the higher the physically demand on a specific muscle from the task performed on the platform, the greater the increase in muscle activity of that specific muscle from vibration [48, 49].

In this experiment, the iEMG analysis of muscle activation during the isometric single leg squat task without vibration showed VMO to be the most requested muscle, followed by gluteus medius, fibularis longus, erector spinae tibialis anterior, biceps femoris, gastrocnemius medialis, and rectus abdominis. This order of muscle demand is similar to the one observed in a previous study on squat exercise that did not include vibration as a parameter [91]. Looking at the mean muscle activity difference from the control no-vibration condition to the 30 Hz-3 mm condition of this study, the results show similar muscle activation pattern as the iEMG amplitude of the VMO, gluteus medius and fibularis longus were all significantly affected by vibration compared to the other muscles.

Time-to-fatigue & Amplitude - The results of the study showed vibration amplitude to have a significant effect on time-to-fatigue as increased amplitude decreased task time. The explanation for this outcome may have different origins, muscle fatigue being one of them. The impact of vibration on muscle fatigue has been investigated with results suggesting long exposure to vibration induces more muscular fatigue due to a facilitation effect of vibration on muscle contraction force and activity during the early part of the exposure [44, 48, 50]. In this study, since amplitude had little effect on muscle activity, muscle fatigue simply from increased muscle activity is not believed to be responsible for decreased task time. A second explanation for muscle fatigue from vibration may be from a suppression effect of vibration on neuromuscular performance [51]. A previous study demonstrated vibration to cause a reduction of EMG activity, motor unit firing rates and contraction force that increased gradually during the course of about one minute of sustained superimposed vibration [51]. A suggested contributing mechanism for this suppression is vibration-inducing presynaptic inhibition and/or transmitter depletion [51]. We cannot infer this explanation since our study did not directly analyse the effect of vibration parameters on motor unit firing rates or contraction force, but this could be a plausible explanation of the situation and this suggestion should be further studied.

The decreased time-to-fatigue may also be related to more subjective factors such as comfort level from vibration exposition and psychological fatigue with effects including decline of alertness, mental concentration and motivation among others [68]. Increased vibration amplitude may create an uncomfortable sensation leading subjects to discontinue the physical task. The subjective assessment of comfort of fatigue was not performed in this study allowing us to only suggest increased discomfort as a reason for decrease fatigue time from increased vibration amplitude.

Comparing time-to-fatigue from the vibration condition to the control no vibration condition, results show no significant change. From this observation, setting a long versus short task time while using WBV as a training modality must not become a factor of concern in terms of WBV affecting task time-to-fatigue. However, the user's safety is of great importance and harmful effects from vibration should not be underestimated. Vibration exercise time can become a dangerous parameter to the user if exposed to vibration for too long.

In conclusion, WBV training increases muscle activity, activation mainly due to the vibration frequency parameter. From this fact and existing knowledge, maximal muscle activation is suggested to occur with vibration frequencies around 80 Hz, an assumption that needs further investigation. In addition to high frequencies, muscle demand from a task performed under WBV does impact the amount of muscular activity as higher physical demand leads to an increased activity. Finally, WBV does not positively or negatively impact task time-to-fatigue. When setting the exercise time in the design of the WBV training protocol, vibration must not become a variable to consider when considering vibration impact on time-to-fatigue. With the user's safety in mind, time should be set according to the training objective.

PRACTICAL APPLICATION

The present findings indicate frequency to be the main vibration parameter to have an effect on muscle activity. Significant increase in muscle activity is expected with higher rather than lower frequencies. Body position on the vibration platform is equally important as creating a large physical demand on specific muscles makes those muscles prone to increased muscle activity under WBV.

From this study, when designing a WBV training program with the aim of increasing muscle activity, strength and conditioning coaches should use frequencies around 30Hz, and set the amplitude to a comfortable level for the user. With regards to physical task time, coaches must not be concerned with any time alteration from vibration exposure as this study demonstrated no significant effect on time-to-fatigue. However, the user's physical health and safety is important; thus harmful physical effects from vibration should still be considered when choosing the vibration exercise time.

CONCLUSION

This study helped clarify the effects of WBV mechanism on the human body. The results suggest frequency to be the main vibration parameter to impact overall muscle activity. Muscle activity increased with increasing vibration frequency. On review of the current WBV and local (peripheral) vibration literature, 80 Hz is suggested to be the optimal frequency setting to reach maximal muscle activity amplitude from vibration stimuli; a suggestion that needs further investigation [22]. This frequency appears to be favoured as muscle spindles and motor units demonstrate maximum sensitivity to frequencies of that level. This study also adds to the evidence that increased physical demand on the muscle exposed to vibration affects muscle activity. In this study, results showed a greater increase in muscle activity in the muscles highly required by the physical task when compared to those less needed while under WBV.

This study found no vibration effect on time-to-fatigue. Also, the results of the pilot study on the effects of WBV on the rate of muscle fatigue suggested no vibration effect due to lack of statistical power. Data analysis was also proposed as to be a main factor for insignificant results as more robust analysis was considered. A joint analysis of EMG spectrum and amplitude seem to be a good strategy to identify muscle fatigue related to WBV [81].

Based on this study alone, it is not possible to affirm that exposure to WBV, or vibration training, results in significant neuromuscular change. The nature of the study was not to evaluate directly the effects of vibration on muscle strength and/or power. For this reason, the value of using vibration in human training remains questionable. However, further investigation using suggested optimal frequency settings examining the effects of WBV on muscle fibre type change, and neural pathways and neuron excitability are suggested.

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APPENDIX A

Ethics Committee Approval

UNIVERSITÉ Concordia UNIVERSITY

CERTIFICATION OF ETHICAL ACCEPTABILITY
FOR RESEARCH INVOLVING HUMAN SUBJECTS

Name of Applicant:	Dr. Richard DeMont
Department:	Exercise Science
Agency:	NA
Title of Project:	The acute effect of vertical whole-body vibration on rate of muscle fatigue and perceived exertion in sub-maximal isometric contraction
Certification Number:	UH2009-079

Valid From: July 21st 2009 to: July 21st 2010

The members of the University Human Research Ethics Committee have examined the application for a grant to support the above-named project, and consider the experimental procedures, as outlined by the applicant, to be acceptable on ethical grounds for research involving human subjects.

Dr. James Pfaus, Chair, University Human Research Ethics Committee

APPENDIX B

Consent to Participate in the Study

CONSENT TO PARTICIPATE IN:

The Acute Effect of Vertical Whole-Body Vibration on Rate of Muscle Fatigue and Perceived Exertion in Submaximal Isometric Contraction

This is to state that I agree to participate in a program of research being conducted by Mylène Saucier from the Exercise Science Department of Concordia University (***contact info***: mylen_02@hotmail.com) under the supervision of Dr. Richard DeMont (***contact info***: (514)848-2424 ext 3329, *rgdemont@gmail.com*)

A. Purpose of the Experiment

I have been informed that the purpose of the research is to obtain measures related to the rate of muscle fatigue under vertical Whole-Body vibration while holding a one leg squat position on a vibration platform. This research study is an important step in the understanding of the effect of vertical whole-body vibration on the human body.

B. Procedures

I understand that I am volunteering to participate in this study which will be carried out in the CONCAVE laboratory. There will be three data collecting sessions lasting approximately two hours, with one week between each session. All procedures will be explained to my satisfaction. The electrical activity of six muscles from my leg and two muscles from my trunk will be measured by a passive measure called electromyography (EMG). To do this pairs adhesive sensors will be attached to my skin, after it has been cleaned. Shaving of body hair might also be necessary. I will then do a one leg squat until exhaustion while standing on a vibration platform. After a 10 minute rest, I will repeat this activity ten times. Each session will include either three or four squats, so I will return after one week, twice.

C. Risks and Benefits

To our knowledge there is no risks linked to this study. You will be screened for the following conditions, and if absent, you will be declared fit to participate in the study: acute or chronic back injury, acute inflammation in the musculoskeletal system, acute migraine attack, acute or chronic musculoskeletal injury in the dominant leg, acute thrombosis, and recent surgery. (The manufacturer of the vibration platform also cautions against, cancer, epilepsy, gallstones, kidney or bladder stones, open wounds in the dominant leg, pregnancy, rheumatoid arthritis & arthropathy, and diabetes.)

All procedures are completely non-invasive. It is possible you will experience minor skin irritation from the tape holding the EMG equipment in place. Do to the squatting leg exercise and vibration nature of this study, the is a small possibility of minor effects including irritation or itchiness to the skin of the foot in contact with the vibration platform, nausea and dizziness, quick but temporary fall of blood pressure, and hypoglycaemia (if diabetic). Muscle soreness is possible following the experiment. ***These are unlikely temporary side effects with no known long term risk, but please inform the experimenter if you feel any discomfort.*** A certified athletic therapist will be present during the testing procedures. There are no direct benefits or compensation from your participation in this study. This research will aid both the rehabilitation and fitness communities.

D. Conditions of Participation

- I understand that I am free to withdraw my consent and discontinue my participation at anytime without negative consequences.
- I understand that my participation in this study is CONFIDENTIAL (i.e., the researcher will know, but will not disclose my identity)
- I understand that the data from this study may be published.

I HAVE CAREFULLY STUDIED THE ABOVE AND UNDERSTAND THIS AGREEMENT. I FREELY CONSENT AND VOLUNTARILY AGREE TO PARTICIPATE IN THIS STUDY.

Name (please print)

____

SIGNATURE

____

If at any time you have questions about your rights as a research participant, please contact Kyla Wiscombe, Research Ethics Assistant, Concordia University, at (514)848-2424 x4888 or by email at <kwiscomb@alcor.concordia.ca>.

Appendix C

Borg Scale – Rating of Perceived Exertion

0	**Nothing at all**
0.5	**Very, very weak**
1	**Very weak**
2	**Weak**
3	**Moderate**
4	**Somewhat strong**
5	**Strong**
6	
7	**Very strong**
8	
9	
10	**Very, very strong**

Table 9
Borg Scale – Borg, E. (2006)