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The Effects of Whole-Body Vibration on Specific Neural and Mechanical Properties of Muscle during Maximal Isometric Knee Extension

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "The Effects of Whole-Body Vibration on Specific Neural and Mechanical Properties of Muscle During Maximal Isometric Knee Extension" submitted by Matthew Jordan in partial fulfillment of the requirements for the degree of Master of Science in Exercise Physiology.

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ABSTRACT

The purpose of this investigation was to examine the acute effects of whole-body vibration on specific neural and mechanical properties of muscle during a maximum voluntary contraction (MVC) of isometric knee extension with 90 degrees of knee flexion.

Twenty-four healthy, strength trained males were recruited for this randomized cross-over design investigation. The vibration treatment consisted of 3 sets of 60 seconds at a frequency of 30 Hz on a commercially available vibration platform (NEMES-Bosco). The control treatment procedure was identical except that no vibration was administered. Subjects performed these protocols on alternate days in a randomized manner. Electromyography (EMG), muscle inhibition, peak torque during MVC and resting twitch torque were recorded using an interpolated twitch technique. In each testing session, two baseline measurements were recorded. This was followed by the intervention (i.e. vibration treatment or control treatment), and then the two post-intervention measurements. The trial with the highest torque value during MVC was used for analysis. The change in torque during MVC, the change in muscle inhibition, the change in resting twitch torque, and the change in potentiation of the resting twitch torque following MVC were calculated by the difference between the baseline value and the post-intervention value. Subsequently, the mean difference of the changes between the two testing sessions was analyzed using a two sample t-test.

Vibration treatment did not enhance muscle contractility and there was no observable post-activation potentiation. Also, vibration treatment did not improve muscle activation or torque production during the MVC. However the increase in muscle inhibition was significantly smaller following the vibration treatment. The mean increase (± SE) in muscle inhibition was 3.881 ± 1.345% following the control treatment and 0.056 ± 1.509% following the vibration treatment. This was paralleled by a decrease in torque during MVC of 19.47 ± 4.640 Nm following the control treatment and 4.323 ± 3.888 Nm following the vibration treatment. It appears that the vibration treatment may have provided a "protective effect". This may be due to attenuation of peripheral fatigue processes or psychological factors.

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DEDICATION

To my wife, my family, and my close friends... thank you.

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LIST OF DEFINITIONS AND SYMBOLS

Ia Afferents: Primary sensory nerve ending of the muscle spindle

II Afferents: Secondary sensory nerve ending of the muscle spindle

TVR: Tonic Vibration Reflex
(Muscle reflex response to vibration due to the stimulation of the primary endings of the muscle spindle)

MVC: Maximum voluntary contraction

H-Reflex: Hoffman-Reflex

Hz: Frequency of vibration (cycles • $second^{-1}$)

CNS: Central nervous system

HAVS: Hand arm vibration syndrome

MI: Muscle inhibition

ITT: Interpolated twitch torque

RTT: Resting twitch torque

RTT_{post}: Resting twitch torque following the MVC

$RTT_{post\text{-}treat}$: Resting twitch torque following the treatment

POT_{treat}: Potentiation caused by the treatment

POT: Post-activation potentiation from the MVC

TQ: Torque during MVC

RM: Repetition maximum

(The maximum weight that can be lifted concentrically for a given number of repetitions)

π: The effect of period in the linear additive model for the statistical evaluation of a cross-over design.

τ: The effect of treatment in the linear additive model for the statistical evaluation of a cross-over design.

γ: The effect of carry-over in the linear additive model for the statistical evaluation of a cross-over design.

CHAPTER 1: INTRODUCTION

Background

The effects of vibration on the human body have been documented for many years. In fact, a drive along a rough road was once prescribed for individuals suffering from kidney stones due to the therapeutic effects of the bumpy ride (Griffin, 1996). Many positive effects of vibration on the human body have also been reported in clinical and physiotherapeutic settings in which vibration has been used for pain management and to elicit muscle contractions in spastic and paretic muscles (Johnston et al., 1970; Liebermann & Issurin, 1997). At present several research groups are investigating the use of whole-body vibration in the treatment and prevention of osteoporosis (Rittweger et al., 2000).

The biological reaction to vibration is dependent on the frequency, magnitude, duration and type of vibration (Griffin, 1996). When used appropriately, the complex interaction of the human body with vibration may provide very useful effects although vibration can also pose a health risk. The negative effects of vibration on the human body are most often observed in the work place through exposure to large vibration loads or chronic exposure to vibration (Wasserman et al., 1991). In this environment, exposure to vibration has been shown to damage several biological structures and functions including peripheral nerves, blood vessels, joints and proprioception. Studies investigating the effects of vibration on living organisms also report changes in endocrine function, cardiovascular function, respiratory responses, central nervous system (CNS) patterns, and metabolic processes (Griffin, 1996).

The physiological hazards of vibration have led to occupational standards designed to limit exposure to harmful vibration in the workplace (Mester, et al., 1999). While standards do exist to limit exposure to occupational vibration there are no standards to limit exposure to vibration in the athletic environment, yet sports such as alpine skiing, sailing, in-line skating and horse-back riding are known to have a significant vibration load.

Recently, the use of vibration for improving the training regimes of athletes has been investigated (Rittweger, 2000). Vibration has been used during strength training movements such as elbow flexion (Bosco et al., 1999a), and whole-body vibration training has been performed with the use of mechanically driven vibration platforms (Bosco et al., 2000). In both of these circumstances, the vibratory wave has been propagated from distal to proximal links of muscle groups, and the subject has often been required to perform voluntary muscle contractions throughout the exposure to vibration (Issurin et al., 1994). Also, during the period of vibration electromyogram (EMG) activity increases significantly (Rittweger et al., 2000).

Investigations into the effects of vibration training have indicated that vibration applied to the upper extremities during a three-week training period has led to increased maximal strength in the seated row (Issurin et al., 1994), and in the post-vibratory period, vibration applied to the elbow flexors has been shown to improve power output in elbow flexion (Bosco et al., 1999a). Also, investigations into the effects of acute whole-body vibration training have demonstrated a significant improvement in power output during the post-vibratory period, and significant changes in the resting hormonal profiles of men (Bosco et al., 1999b; Bosco et al., 2000).

Several hypotheses have been proposed to explain the acute improvements in power output following vibration training. These hypotheses include improved muscle activation,

and the potentiation of different muscle reflexes (Liebermann & Issurin, 1997; Issurin & Tenenbaum, 1999). Conversely, other investigators have reported that in the post-vibratory period, the improvements in maximal power output were associated with decreased muscle activation, and this has led to the speculation that acute vibration training improved neuromuscular efficiency (Bosco et al., 2000).

Based on the limited research it would appear that there are acute benefits to whole-body vibration training which may augment the performance of athletes in speed and strength sports. Yet, the specific physiological mechanisms behind these benefits remain unclear. It is crucial that a clear understanding of the basic neuromuscular effects of vibration training be obtained in order to accurately assess the potential benefits and implications of this training method.

The evaluation of the acute effects of whole-body vibration on muscle activation, and the contractile properties of muscle would provide an indication of the basic neuromuscular effects of vibration training. This can be accomplished using the interpolated twitch technique (Suter & Herzog, 2001). This technique involves the application of a series of maximal electrical stimulations to a relaxed muscle (i.e. resting twitches), and the superposition of a maximal electrical stimulation during an MVC (i.e. interpolated twitch). The ratio between the interpolated twitch force and the resting twitch force has been referred to as muscle inhibition, and this provides a measure of muscle activation (Suter & Herzog, 2001). Also, analysis of the change that occurs in the resting twitch force when it is preceded by a conditioning activity (e.g. an MVC or vibration) provides information on the contractile properties of the muscle (Sale, 2002). An increase in resting twitch force following a conditioning activity has been termed post-activation potentiation. An investigation into the effects of whole-body vibration on the parameters

measured using the interpolated twitch technique would provide information on the neural and mechanical changes that occur in muscle in response to whole-body vibration. To this end, important information on the basic neuromuscular effects of acute whole-body vibration training may be gained.

The purpose of this investigation therefore, is to evaluate the acute effects of whole-body vibration training on specific mechanical and neural properties of muscle using the interpolated twitch technique during an MVC of isometric knee extension with 90 degrees of knee flexion.

Statement of Research Hypotheses

a) It is expected that compared to the control treatment, the vibration treatment will increase the potentiation of resting twitch torque following the MVC.

b) It is expected that the vibration treatment will potentiate resting twitch torque.

c) It is expected that compared to the control treatment, the vibration treatment will decrease muscle inhibition during the MVC.

d) It is expected that compared to the control treatment, the vibration treatment will increase torque production during the MVC.

CHAPTER 2: REVIEW OF THE LITERATURE

An Overview of the Area

Vibration is defined as oscillatory motion (Griffin, 1996). In the human environment whole-body vibration occurs in several instances including in motorized vehicles (e.g. cars, trucks, motorcycles), marine ships (e.g. boats, submarines), aircraft, buildings and from industrial equipment (e.g. cranes, fork-lifts).

The vibration in these different instances can vary considerably depending upon three main factors. Firstly, vibration can vary according to the waveform of the oscillation (Figure 1).

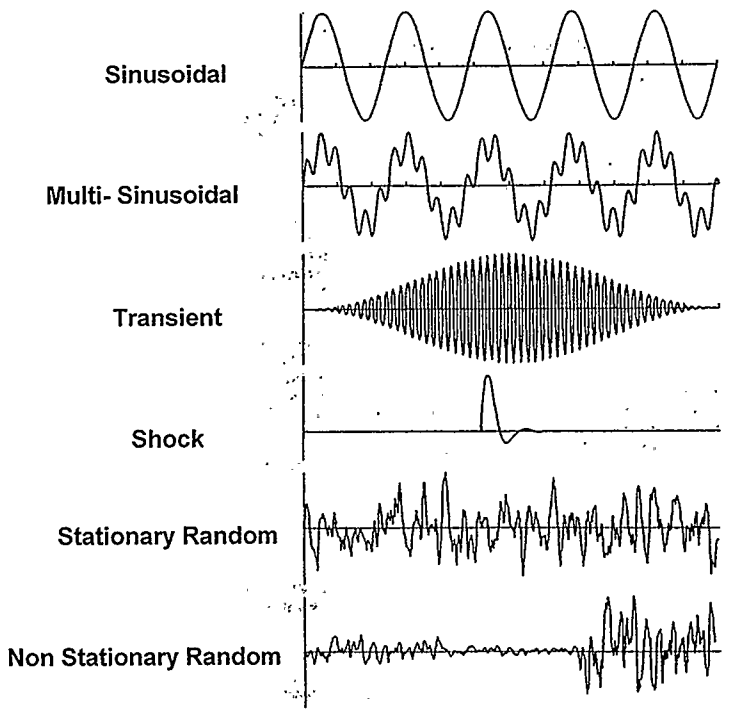


Figure 1: Different vibration waveforms (Adapted from Griffin, 1996, p. 6).

Vibration can also vary according to the frequency and the magnitude (Griffin, 1996). The frequency, which is usually measured in Hertz (Hz), refers to the repetition rate of the vibration, and is an important factor in determining the biological effects of vibration (Griffin, 1996). The magnitude of the vibration refers to the size of the oscillation and is represented either as the acceleration (i.e. g or $m \cdot s^{-2}$) or as the displacement (e.g. mm, cm, m).

The interaction of the human body with vibration is complex and is dependent on the vibration characteristics (Griffin, 1996). The physiological reaction to vibration is also dependent upon the environmental conditions, the intra-subject variability and the inter-subject variability. Some of the factors that affect intra-subject variability include the orientation of the subject (e.g. sitting in moving vehicle while facing forwards vs. facing sideways), the body position (e.g. sitting vs. standing) and the body posture (e.g. stiff posture vs. relaxed posture). The inter-subject variability is affected by the size of the individual (e.g. children vs. adults), body dynamics (e.g. the amount of power that can be absorbed by the body), age, gender and the psychological preparedness of the individual. A final parameter that must be considered when describing the potential effects that vibration may have on the human body is the duration of the exposure (Griffin, 1996).

Health and Performance Benefits of Vibration

Exposure to vibration has long been known for its healing effects and health benefits. Vibration is used to help clear the lungs in patients with respiratory problems, to improve mobility and muscle function in athletes, to help those suffering from rheumatoid arthritis, to treat the stumps of amputated limbs and to improve muscle function in spastic and paretic individuals (Griffin, 1996). Vibration may also provide health benefits to

members of the general population who are at risk for bone loss (Flieger, et al., 1998). Initial research performed by Flieger et al. (1998) has demonstrated that mechanical stimulation in the form of low intensity whole-body vibration was effective in reducing post-ovariectomy bone loss in animals. This finding may give way to an alternative method for developing bone mass in humans.

Vibration also represents a novel stimulus for the development of the physiological qualities that relate to the expression of muscle force. Traditionally this has been accomplished using different types of strength training protocols that involve the use of jumps, sprints and exercises with added resistance. In order to better understand how vibration training may improve the development of the physiological qualities associated with muscle force production, two of these qualities must first be described. The first quality is explosive ability, which is often referred to as speed strength (Schmidtbleicher, 1985). Using a force versus time curve of a muscle contraction the different characteristics of speed strength can be illustrated (Figure 2). Two of the characteristics that relate to speed strength are starting strength and explosive strength. Starting strength refers to the increase in force at the start of a force versus time curve, and explosive strength refers to the maximum rate of force development, or the ability of the neuromuscular system to continue to develop the already initiated muscle force (Schmidtbleicher, 1985).

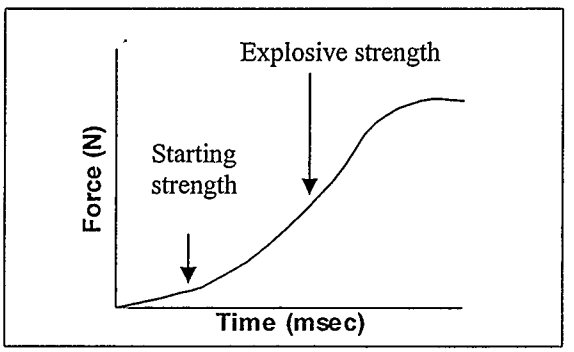


Figure 2: Hypothetical force versus time curve.

The second quality that relates to the expression of muscle force is maximal strength. Maximal strength is the maximum force that can be developed by a muscle or muscle groups (Zatsiorsky, 1995). It is also specific to the type of muscle contraction (i.e. isometric contraction, eccentric contraction and concentric contraction) (Figure 3).

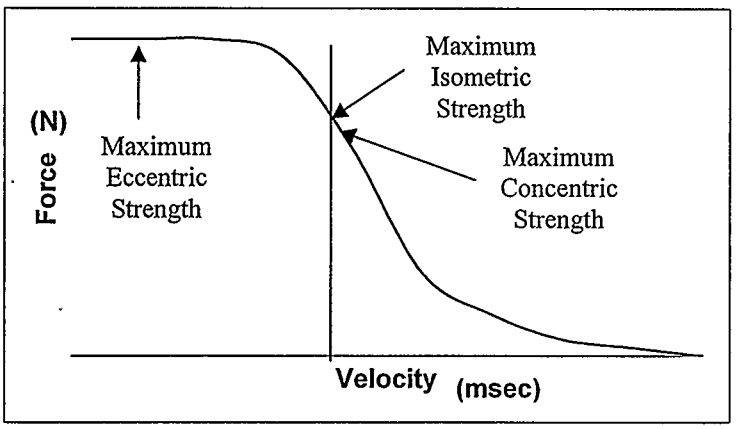


Figure 3: Hypothetical force versus velocity curve illustrating three different types of muscle contraction.

Speed strength and maximal strength are controlled by several neural factors which can be divided into two categories: intermuscular coordination and intramuscular coordination (Young, 1995). Intermuscular coordination is ability of an individual to efficiently control multiple muscles and muscle groups in order to produce a powerful movement. This quality is influenced by the activation of synergist muscles, and the inhibition of antagonist muscles (Young, 1993). Intramuscular coordination refers to the ability of an individual to maximally activate his or her muscle, and is controlled by the synchronization of motor unit firing, the rate of motor unit firing, and the number of motor units recruited during a contraction. Speed strength and maximal strength are also affected by the reflexive action of the muscle spindles, and the Golgi tendon organs.

It has been postulated that vibration training improves intramuscular coordination by increasing motor unit activation and the synchronization of motor unit firing (Liebermann & Issurin, 1997; Issurin & Tenenbaum, 1999). The vibration induced enhancement of muscle activation is thought to occur because of several neuromuscular changes including the activation and potentiation of different reflexes. The increased muscle activation caused by vibration training may augment the development of explosive ability and maximal strength, and if this is the case, may be helpful in the training regimes of athletes.

Biological Interaction with Vibration

The Effects of Vibration on Skeletal Muscle

High frequency vibration induces a reflex muscle contraction termed the tonic vibration reflex (TVR) (Bishop, 1974). The TVR has been shown to exist in every skeletal muscle except for the tongue and facial muscles, and can be elicited in individuals of all ages. In order to better understand the TVR, it is helpful to describe the basic structure of the muscle spindle and its response to muscle stretch (Figure 4). The muscle spindle is composed of two intrafusal muscle fibre types which include the nuclear chain fibre and the nuclear bag fibre (McComas, 1996). The ends of the intrafusal muscle fibres are innervated by the fusimotor axons (γ-motoneurons). Activation of the γ-motoneurons results in the contraction of the intrafusal muscle fibres, and this increases the sensitivity of the muscle spindle to stretch.

The intrafusal muscle fibres also have two afferent nerves that include the group Ia afferent nerve or the primary ending, and the group II afferent nerve or the secondary ending (McComas, 1996). When a muscle is stretched, the Ia afferents respond with a

large burst of activity while the stretch is occurring (dynamic response), and when the new muscle length has been attained the Ia afferents provide a sustained response (static response). Conversely, the group II afferents provide only a static response to muscle stretch. In response to a muscle stretch, the group Ia afferents, and the group II afferents deliver information to the brain and spinal cord causing a reflexive contraction of homonymous motor units. This reflex contraction has been termed the stretch reflex.

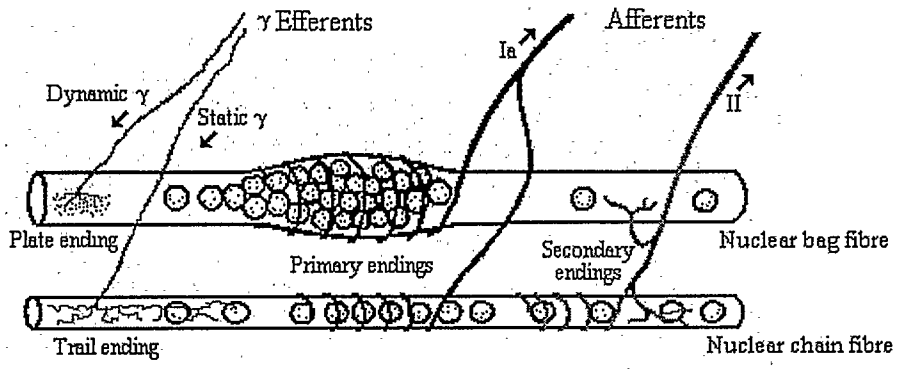


Figure 4: Structure of the muscle spindle.

Vibratory stimulation of a muscle excites the Ia afferents of the muscle spindle which excites homonymous motor units (Claus et al., 1988). In contrast, the Golgi tendon organs, and the group II afferents from the muscle spindle are relatively unresponsive to vibration. Analysis of EMG data reveals that when a muscle is exposed to vibration there is immediate muscle activity, and this provides evidence of a monosynaptic component to the TVR (Bishop, 1974). Tension continues to be developed in the exposed muscle for 20 to 25 seconds reaching a peak force that is only a fraction of the tension developed during a maximal voluntary contraction. This indicates that only a small portion of the motoneuron pool has been recruited during the TVR. EMG analysis further reveals that after cessation

of the vibration, muscle activity persists for a short period of time, providing evidence of a polysynaptic component to the TVR.

Along with EMG analysis, further evidence on the nature of the TVR is obtained from the following experimental evidence. Firstly, the TVR can not be elicited in a denervated muscle indicating that the TVR is dependent on neuromuscular mechanisms (Bishop, 1974). Secondly, the TVR is abolished in a muscle that has lost its afferent nerve supply indicating the dependency of the TVR on sensory feedback from the muscle. Finally, the TVR in the agonist muscle is suppressed by vibration and electrical stimulation of the antagonist muscle. This demonstrates that sensory signals from the antagonist muscle act on the same motoneuron pool as the signals caused by vibration of an agonist muscle.

The TVR is also affected by higher motor centres. This observation can be based on the following evidence: (1) the TVR can be elicited in the decerebrate and cerebellectomized cats but is abolished once the spinal cord is severed and (2) the administration of barbiturates depresses the TVR but does not depress the stretch reflex. In the latter instance the administration of barbiturates would depress small reticular neurons and interneurons and would only affect a polysynaptic reflex and not a phasic monosynaptic reflex. These observations also provide evidence that the TVR has a polysynaptic component in addition to a monosynaptic component.

Vibration may also enhance maximal voluntary contractions in a fatigued state (Bongiovanni & Hagbarth, 1990). In order to explore the effects of vibration on force output in a fatigued state, the effect of the γ-motoneurons on maximal voluntary contractions should be examined. It has been shown that activation of the γ-motoneurons increases the excitability of the Ia afferents and this leads to a concomitant excitation of the

α-motoneurons (Hagbarth et al., 1986). An investigation by Hagbarth and co-authors (1986) demonstrated the importance of γ-motoneurons in maximal force production. A partial peroneal nerve block affecting only γ-motoneurons was induced in four healthy subjects with a diluted solution of the local anaesthetic prilocaine. The effects of the partial nerve block on EMG and force output were recorded. The de-activation of the γ-motoneurons resulted in a significant decrease in the EMG and force of the dorsiflexors during voluntary contractions. Hagbarth et al. (1986) concluded that γ-motoneuron discharge and the increased excitability of the Ia afferents was an important component in maintaining α-motoneuron firing rate during maximal voluntary force production.

In situations in which fatigue is present, vibration can counteract the reduced drive of the γ-motoneurons by increasing the excitability of the Ia afferents. Bongiovanni and Hagbarth (1990) evaluated the effects of vibration on maximal voluntary contractions of the dorsiflexors in five healthy subjects. Vibration (frequency = 150 Hz, amplitude = 1.5 mm) was applied to the tendons of the ankle dorsiflexors and force measurements were recorded using a strain gauge attached to a foot plate. EMG was recorded with surface electrodes placed over the tibialis anterior muscle. In addition to examining the effects of vibration on force output in a fatigued state, Bongiovanni and Hagbarth (1990) also observed the effects of vibration on force output when recovering from a partial peroneal nerve block that was induced by the injection of prilocaine.

Three conditions were utilized to observe the effects of vibration on fatigued and non-fatigued muscle. The first condition included a series of maximal voluntary contractions in a non-fatigued state alternated with contractions performed with exposure to vibration. The second condition required the subject to perform a maximal voluntary contraction under the same conditions as the first although the sequence was preceded by a

fatiguing and prolonged maximal voluntary contraction. In the final condition, vibration was applied for 20 seconds while fatigue developed during a one-minute maximal voluntary contraction.

High frequency vibration in a non-fatigued state did not have a significant effect on motor output during a maximal voluntary contraction. Vibration did however compensate for the reduction in motor output in a fatigued state when the exposure was preceded by a prolonged maximal voluntary contraction (i.e. 4 minutes). As discussed previously, the contribution of γ-motoneuron firing and the increased excitability of the Ia afferents to maximal force output are significant (Hagbarth et al., 1986). Bongiovanni and Hagbarth (1990) hypothesized that in a fatigued state, vibration compensated for the decreased γ-motoneuron drive by exciting the Ia afferents and this resulted in the reflexive excitation of the α-motoneurons and greater force output.

The investigators also examined the effects of vibration on force output during recovery from a partial peroneal nerve block by testing the subject's ability to maximally activate the dorsiflexors as the effects of the anaesthetic wore off. During the recovery from the nerve block it was found that vibration increased force output when the subject had regained about 20% of their normal dorsiflexion force but had no effect on force output when dorsiflexion force was less than 10% of normal values. It was postulated that the peroneal nerve block prevented activation of the smaller motoneurons (i.e. γ-motoneurons) reducing the excitability of the Ia afferents and the reflexive activation of the α-motoneurons. The lowered excitatory input to the α-motoneurons decreased motor output in the maximal force tasks. When vibration was applied though muscle force production increased. Again, Bongiovanni and Hagbarth (1990) speculated that vibration activated the Ia afferents, and this increased muscle force production.

The strength of the TVR and the effects of vibration on voluntary contractions have been demonstrated to be dependent on the frequency of vibration (Siggelkow et al., 1999). Over a limited range, the Ia afferents of the muscle spindle responds to increasing vibration frequency with a 1:1 discharge rate (i.e. for every unit of increase in frequency, there is a corresponding unit of increase in spindle ending discharge). The response of the TVR takes the form of an inverted 'U' shape indicating that there is an optimal vibration frequency to elicit the TVR (Martin & Park, 1997). The TVR tends to increase relative to the vibration frequency up to a maximum of about 100 Hz (Martin & Park, 1997). At frequencies greater than 100 Hz though, Ia afferent discharge may be impaired. Bongiovanni and co-workers (1990) found that vibration at a frequency of 150 Hz (amplitude = 1.05 mm) suppressed motor output during sustained maximal voluntary contractions of the ankle dorsiflexors in 25 healthy subjects. At a frequency of 150 Hz, it was speculated that the vibration limited the subject's ability to generate and maintain high motor unit firing rates.

Subsequently, Siggelkow and co-authors (1999) examined the effects of three different vibration frequencies (80 Hz, 120 Hz and 160 Hz) on motor evoked potentials. Vibration was applied with an electromagnetic stimulator to the extensor muscles of the forearm in ten healthy subjects. The electromagnetic stimulator was placed over the extensor carpi radialis muscle. Motor evoked potentials were recorded using surface EMG electrodes. The authors found that while the 80 Hz and 120 Hz frequencies augmented motor evoked potentials, the highest frequency of 160 Hz was ineffective. This was attributed to a drop in the response rate of the Ia afferents. In addition to the drop in the response rate of the Ia afferents, the failure for augmentation in motor evoked potentials could have occurred due to other neurological mechanisms. These mechanisms would

include inhibitory polysynaptic mechanisms from mechanoreceptors and skin receptors, or central inhibitory factors.

The vibration frequency has also been shown to affect motor unit synchronization (Martin & Park, 1997). It has been reported that the TVR results from motor unit activity synchronized and unsynchronized with the vibration frequency. Martin and Park (1997) examined the effects of vibration frequency on EMG activity and motor unit synchronization in flexor and extensor muscles of the forearm in ten healthy human subjects. Vibration was applied to the tendons of the forearm flexors with an electromagnetic vibrator and grip strength was measured using a hand grip dynamometer. Motor unit synchronization was determined using the index of synchronization. The index of synchronization was calculated by the percentage of the area of the spectral peaks at the vibration frequency and at the first subharmonic frequency over the total power of the power density spectrum. The absence of artefacts was verified before each stage of the experiment.

At frequencies below 100 Hz, the strength of the TVR tended to increase with increasing vibration frequency (Martin & Park, 1997. The increase in the TVR was a result of greater motoneuron depolarization due to the increased firing rate of the Ia afferents with the increased frequency of vibration. Furthermore, at frequencies below 100 Hz, harmonic synchronization of motor unit firing occurred, and frequencies greater than 150 Hz tended to induce less EMG activity and less motor unit synchronization. It was concluded that EMG activity and motor unit synchronization were dependent on the frequency of vibration, and the authors postulated that at high frequencies the decrease in TVR and EMG was due to the failure of the Ia afferents to discharge in a 1:1 synchronous fashion to the vibration frequency.

In addition to examining the effects of vibration frequency on motor unit synchronization Martin and Park (1997) also evaluated the degree of pre-contraction on the strength of the TVR. Initially the subjects were required to perform a maximal voluntary contraction for the hand grip and the subjects were trained to maintain voluntary contractions at 10 and 20% of the maximal voluntary contraction. The TVR and EMG increased significantly over resting levels when the muscles were contracted at 10% of the maximal voluntary contraction. At 20% of the maximal voluntary contraction similar effects occurred although there was no significant difference compared with the 10% contraction.

A similar investigation performed by Park and Martin (1993) examined the effects of vibration frequency and the level of pre-contraction on the TVR in ten healthy college students. An electromagnetic vibrator was used to apply vibration to the flexor muscles of the forearm, and EMG was recorded using surface electrodes. Vibration was applied at 40, 80, 100, 120, 150 and 200 Hz, and pre-contraction of the grip was performed at 0, 10 and 20% the maximum voluntary contraction.

This investigation revealed that the strength of the TVR grew with increasing vibration frequency up to 150 Hz, after which the TVR decreased with increasing vibration frequency. This finding was consistent with previous research, and the authors concluded that the Ia afferents of the muscle spindle were able to respond in a 1:1 harmonic fashion with increasing frequency of vibration up to a maximum of between 100 and 150 Hz but at vibration frequencies greater than 150 Hz, the Ia afferents did not respond in a synchronous fashion and the firing rate was impaired. The TVR also increased with the voluntary contractions at 10% of the maximal voluntary contraction but failed to increase with voluntary contractions at 20% of the maximal voluntary contraction. The authors

speculated that at 10% of the maximal voluntary contraction, greater γ-motoneuron drive may have increased the muscle spindle responsiveness to stretch resulting in a larger TVR. It is also possible that at 10% of the maximum voluntary contraction that the improved accessibility of the Ia afferents to the α-motoneurons could have resulted in the increased TVR.

In addition to the level of pre-contraction and vibration frequency, the strength of the TVR may be affected by several factors related to the position of the body during vibration (Bishop, 1974). The strength and rate of force development of the TVR has been shown to change according to body temperature, the position of the head, and other reflexes such as the tonic neck reflex, and the body righting reflexes. An investigation by Rohmert and co-authors (1989) examined the effects of vibration on muscles of the upper extremity in three different body postures in a sample of six male subjects. The subjects were put into three different positions in order to simulate positions that would be held in the work place when operating vibrating hand tools. Rohmert and co-authors (1989) found that exposure to vibration significantly increased EMG in arm and shoulder muscles compared to the positions without vibration. Despite not quantifying muscle force, the authors found that positions in which there was increased muscle activation and increased muscle length accentuated the effects of vibration on muscle (Rohmert et al. 1989).

The Effects of Vibration on the Stretch Reflex and H-Reflex

In response to a sharp tendon tap, the Ia afferents of the muscle spindle deliver information to the brain and spinal cord causing a reflexive contraction of homonymous motor units (McComas, 1996). This reflex contraction has been termed the stretch reflex.

The Hoffman-Reflex (H-Reflex) is the electrical equivalent to the stretch reflex, and occurs when the Ia afferents are depolarized during electrical nerve stimulation.

Vibration causes inhibition of the stretch reflex and the H-Reflex (Archangel et al., 1971). This has been referred to as the "Vibration Paradox"; that is vibration induces the TVR but inhibits the stretch reflex and the H-reflex (Desmedt & Godaux, 1978). An investigation performed by Claus and co-authors (1988) attempted to resolve this issue by examining the effects of transcranial magnetic stimulation on the muscle response from the abductor digiti minimi muscle during exposure to vibration in six healthy subjects. Vibration was applied using an electromagnetic mechanical stimulator and compound muscle action potentials (CMAP's) were recorded using surface electrodes placed on the right hand of the subject. The latency and the amplitude of the first negative deflection of the CMAP were measured. The results indicated increased CMAP's during exposure to vibration. The authors concluded that the vibration enhanced the excitability of α-motoneurons to the descending pyramidal impulses and that the inhibition of the stretch reflex and H-reflex were due to inhibition of the Ia afferents as the CMAP's would have decreased during vibration had this not been the case.

In the post-vibratory period the stretch reflex is potentiated (Archangel et al., 1971). The exact mechanism that explains the potentiation of the stretch reflex is unclear. One possible explanation is that following the vibration induced firing in the presynaptic fibres the motoneuron was potentiated for a period of several minutes (Archangel et al., 1971). This potentiation may be a result of the enhancement of the pre-synaptic impulses and the increased availability of neurotransmitters. A second explanation is disinhibition (Archangel et al., 1971). It is possible that once the vibration has ceased the α-motoneuron pool is relieved of autogenous inhibition from the force sensitive Golgi tendon organs. In

contrast to the stretch reflex, the H-reflex does not display potentiation in the post-vibratory period (Archangel et al., 1971). In fact, following vibration the H-reflex can remain totally depressed for up to 15 seconds and it will show a gradual recovery to normal values over a period of about 100 seconds.

An investigation performed by Van Boxtel (1986) examined the effects of vibration (frequency = 100 Hz) on the H-reflex and stretch reflex of the soleus muscle in 74 healthy subjects. Subjects were seated in a semi-reclined position with their feet strapped to a foot plate designed to record isometric twitch tension. The EMG potentials of the H-reflex and the stretch reflex were recorded using surface EMG electrodes, and the H-reflex was elicited using 1-ms square current pulses delivered to the tibial nerve by a nickel-silver cathode. A mechanical tendon tap device elicited the stretch reflex. The strength of the tendon tap was 4.5 kg and was monitored by a force transducer and accelerometer throughout the experiment.

During the exposure to vibration, the H-reflex of the plantar flexors was significantly more inhibited than the stretch reflex ($p < 0.001$) (Van Boxtel, 1986). In the post-vibratory period though, the stretch reflex displayed a mark potentiation and the H-reflex displayed a gradual recovery to normal values. The dissimilar responses of the H-reflex and the stretch reflex have been shown to occur as a result of the reflexive afferent volleys that are induced by the vibration and the motoneuron pool that is recruited during an H-reflex and a stretch reflex.

In addition to central transmission factors the different response of the stretch reflex and the H-Reflex to vibration may be attributable to the widespread excitation of cutaneous receptors and the concomitant excitation of the stretch reflex pathways (Van Boxtel, 1986). Vibration induces pre-synaptic inhibition of the soleus H-reflex leading to suppression of

the H-reflex but in contrast the pre-synaptic inhibition of the stretch reflex could be partly compensated for by increased oligosynaptic excitation of the Ia afferents due to increased activity of interneurons during vibration (Morin et al., 1984). If this were the case then the vibration induced depression of the stretch reflex would be less than the depression of the H-reflex. A final explanation offered by Van Boxtel (1986) is that in addition to the depolarization of the Ia afferents vibration may have resulted in the depolarization of the Ib afferents. Van Boxtel (1986) reported that during vibration it is possible that the changes in the balance between the post-synaptic Ia and Ib effects may influence the H-reflex and stretch reflex differently resulting in a discrepancy between their magnitudes.

While the reasons for the dissimilar responses between the H-reflex and the stretch reflex are difficult to identify the important conclusion is that vibration affects the H-reflex and the stretch reflex differently. Further differences exist in the response of the stretch reflex and H-reflex to the vibration amplitude. In fact the depression of the H-reflex is related to the amplitude of vibration but is independent of the frequency (Martin et al., 1986). An investigation performed by Martin et al. (1986) examined the effects of vibration on the H-reflex response of the plantar flexors in nine healthy subjects. The subjects were seated in a chair with their feet attached to a foot pedal designed to record isometric twitch tension of the plantar flexors. EMG was recorded using surface electrodes and vibration was applied to the plantar flexors with an electromagnetic vibrator. The vibration amplitude and acceleration was recorded using piezoelectric accelerometer fixed inside the head of the electromagnetic vibrator. Vibration was applied at frequencies of 20, 50, 80 and 110 Hz. Tests were carried out in three different series. In the first series, the peak amplitude of the acceleration was kept constant, in the second series the displacement

remained constant, and in the third series subjects were tested with four different displacements at a constant frequency of vibration.

This investigation revealed that a constant amplitude of vibration resulted in equal depression of the H-reflex for frequencies increasing from 20 Hz to 110 Hz. The inhibition of the H-reflex increased though as the amplitude increased at a constant frequency. The authors could not accurately explain the reason for this observation but they postulated that the number of receptors stimulated by the vibration remained unchanged when the amplitude was held constant but if the frequency remained constant as the amplitude increased there was maximal pre-synaptic inhibition of the H-reflex.

Summary of the Effects of Vibration on Skeletal Muscle

In summary, muscle vibration stimulates the Ia afferents of the muscle spindle which causes the contraction of homonymous motor units and this results in the TVR. EMG increases as a result of the TVR and analysis of the EMG data has revealed that the TVR has a monosynaptic and a polysynaptic component. Evidence for the complexity of the TVR can be observed in the decerebrate cat, and in cats having undergone cerebellectomy as the TVR can still be elicited until the spinal cord is severed.

Vibration also results in the inhibition of the stretch reflex and the H-reflex during the exposure period (Van Boxtel, 1986). The depression of the H-reflex has been shown to be greater than the depression of the stretch reflex although the exact mechanism for this difference is difficult to identify. In the post-vibratory period the stretch reflex displays a marked potentiation in contrast to the H-reflex which displays a gradual recovery up to normal values over a period of about 100 seconds (Archangel et al., 1971). During the exposure period, the depression of the H-reflex is greater as the amplitude of the vibration

increases at a constant frequency but the depression remains unchanged if the amplitude is held constant while the vibration frequency increases.

The studies that examine the effects of the frequency of vibration, level of pre-contraction of the muscle and position of the body provide an indication of the dependency of the TVR on these parameters (Park & Martin, 1993; Martin & Park, 1997; Rohmert et al., 1989). Figure 5 provides a summary of the effects of vibration on skeletal muscle and indicates how the different parameters may affect the TVR.

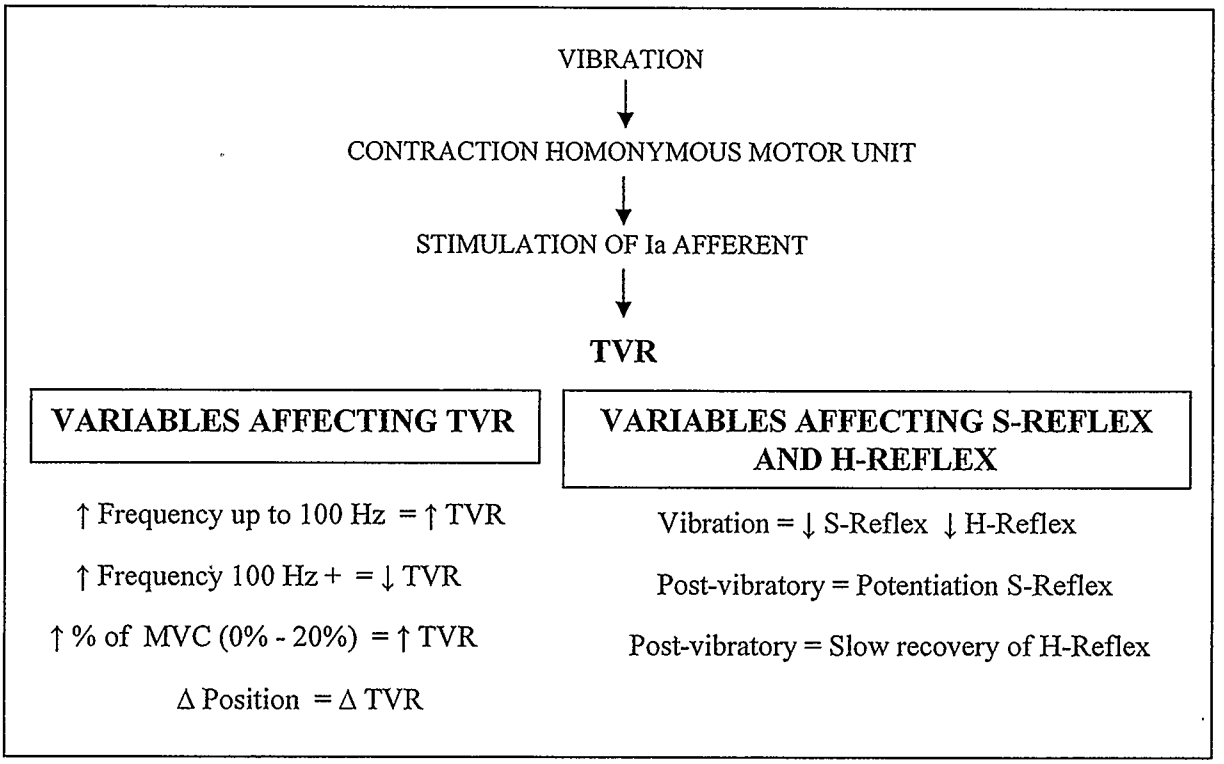


Figure 5: A summary of the effects of vibration on skeletal muscle, and the effects of vibration parameters and level of pre-contraction on muscle response.

Physiological Hazards Associated with Vibration Exposure

While vibration can be used as a rehabilitative tool or for improving the training regimes of athletes, there is substantial evidence on the negative consequences of vibration

on the human body (Griffin, 1996). The specific physiological effects of vibration can be considered under the following categories: (1) cardiovascular function (2) respiratory function (3) endocrine and metabolic function (4) motor processes (5) sensory processes (6) central nervous system (7) skeletal changes. Some reports on the adverse affects from exposure to vibration include severe chest pain and gastrointestinal bleeding in an individual exposed to vibration at frequencies of 10 and 25 Hz ranging in magnitude from ± 3 g to ± 10 g. In animal studies in which high magnitudes of vibration have been used there are reports of lung damage, gastrointestinal bleeding, and heart haemorrhage causing death in the exposed animals.

The research on the physiological responses to hazardous vibration is vast but in this review only a few categories will be considered. Much of the evidence on the adverse effects of vibration on humans has been gathered from the workplace (Liebermann & Issurin, 1997). For example, exposure to vibration from the operation of hand tools can cause hypertrophy of blood vessel walls and narrowing of the lumen of arterioles, damage to the musculo-skeletal system (Futasuka et al., 1983), and neurological disorders (Harada & Griffin, 1991). Armstrong and co-authors (1987) examined the effects of vibration at frequencies ranging between 20 and 160 Hz in 108 quarry workers. While the comparison of the two groups was not significant, Armstrong et al. (1987) concluded that high levels of hand vibration were associated with certain pathological conditions such as tendonitis, and chronic nerve dysfunction.

Excessive exposure to hand vibration can lead to a disorder referred to as "hand-arm vibration syndrome (HAVS)" (Wasserman et al., 1991). This disorder is often observed in miners who operate jack-leg-type drills (Wasserman et al., 1991). In these instances, miners can be exposed to hand vibration for up to three hours per day. Patients

exhibiting HAVS present with neurological dysfunction in the hands, and in later stages of this disease vascular dysfunction. Wasserman and co-authors (1991) examined 134 mine workers who operated jack-leg-type drills. Forty-nine subjects qualified for the analysis based on the absence of confounding variables and related medical conditions. Of the 49 miners 17% displayed vascular dysfunction, and 24% displayed neural dysfunction. The authors concluded that while the prevalence of HAVS was low in comparison to similar studies, exposure to vibration emitted from jack-leg-type drills was still unsafe (Wasserman et al., 1991).

The severity of disease from exposure to vibration is a function of the total exposure time (Miyashita et al., 1983). Miyashita and co-workers (1983) examined the prevalence of vibration induced pathology in a group of 266 chain saw operators. The subjects were divided into four groups depending on the amount of exposure (total operating time). The group with less than 2000 hours of exposure reported symptoms of tingling, numbness and mild pain. The group with 2000-5000 hours of exposure displayed circulatory dysfunction including Raynaud's syndrome. In workers with 5000-8000 hours of exposure serious functional changes in the body were noted, and those workers with over 8000 hours of exposure suffered severely from functional and organic changes (e.g. vertigo, irritability, sleeplessness, and other autonomic disturbances).

Along with vibration induced neural and vascular dysfunction, vibration has also been shown to hinder proprioception (Cordo et al., 1995). It has been well documented that vibration applied to tendons or muscles results in segmental kinaesthetic illusions (Ribot-Ciscar et al., 1998). Cordo and co-workers (1995) examined the effects of vibration on the perception of limb kinematics of the elbow using several different vibration frequencies. It was found that at a frequency of 20 Hz there was biased perception of the arm in the flexion

direction, 30 Hz produced no effect, and 40 or 60 Hz biased the perception of the arm in the extension direction. Furthermore, it was found that errors in limb placement with higher frequency vibration depended on the velocity of movement, and that the bias of perception was dependent on the timing of the application of the vibratory stimulus. Similar investigations examining the ability of blindfolded subjects to perform a position-matching task have also concluded that vibration causes significant alignment errors (Rogers et al., 1985).

It has been postulated that the disturbance in proprioception is due to increased input from the Ia afferents following the vibration which induces an illusory type feeling on the location of the limb in space (Cordo et al., 1995). The stretch sensitivity of muscle spindles has also been shown to change following exposure to vibration (Ribot-Ciscar et al., 1998). Ribot-Ciscar and co-authors (1998) proposed that the decreased sensitivity of the muscle spindles could explain the poor position-matching ability of 11 healthy subjects following a 30 second exposure to vibration at a frequency of 80 Hz. Immediately following vibration, subjects displayed depression in spindle responsiveness to stretch that led to the perception of the limb feeling less stretched than its actual position. The post-vibratory depression of spindle sensitivity lasted for only a few seconds following vibration but the disturbance in proprioception persisted for up to a few minutes.

Several physiological hazards have also been associated with whole-body vibration (Fritz, 2000). Whole-body vibration has been shown to alter sensory motor control, postural regulation, spinal reflexes, and cardiac and respiratory rhythms (Martin et al., 1984). For example, exposure to whole-body vibration below a frequency of 1 Hz has been shown to induce motion sickness due to sensory mismatch (Seidel, 1988). At frequencies greater than 1 Hz, an increase in activity of the back muscles has been shown to occur

(Seidel, 1988). Seidel (1988) demonstrated that an increase in frequency from ultra-low (e.g. 0.315 Hz) to low (e.g. 5 Hz) resulted in significantly greater EMG activity in the back muscles. The visco-elastic properties of the musculoskeletal system and the activation of peripheral muscle receptors were proposed as mechanisms responsible for the increased back muscle activity.

Several biomechanical models have been developed to describe the effects of vibration stress on the human body (Fritz, 1998). Short term exposure to whole-body vibration can adversely affect vegetative and organic function, and vibration exposure over several years may contribute to low back pain, and other musculo-skeletal injuries. Epidemiological studies provide evidence for an increased risk of injury and disease mainly to the lumbar spine and the connected nervous system as a result of long duration exposure to high intensity whole-body vibration (Fritz, 2000). Whole-body vibration of the type and magnitude produced by motor vehicles, airplanes, and construction have been linked to low back pain, and studies on animals have suggested that changes in the neurons of the dorsal root ganglion may be responsible for vibration induced low back pain (McLain & Weinstein, 1994).

Currently there is insufficient evidence to show a quantitative relationship between vibration exposure and risk of health effects. Several factors such as the vibration frequency, vibration intensity, and the posture of the body have been shown to alter the reaction of the human body to whole-body vibration (Kitazaki & Griffin, 1998). Kitazaki and Griffin (1998) examined the effect of body posture on the resonance behaviour of the human body and found that posture and body motions adversely affected the prediction of forces causing injury from whole-body vibration. They concluded that the forces

experienced during whole-body vibration were not well predicted by simple biodynamic models.

An accepted standard to assess risk between exposure to whole-body vibration and disease is based on the frequency-weighted acceleration and daily exposure time (ISO 2631-1). It should be mentioned though that assessment of risk in this manner has been shown to overestimate the effects of vibration at frequencies greater than 5 Hz (Fritz, 2000).

Summary of the Physiological Hazards Associated with Vibration Exposure

Scientific research has demonstrated that several health risks are associated with long-term exposure to vibration. The health risks include vascular and neural dysfunction, back pain, tendonitis, and disturbances in proprioception. Models that have attempted to describe the effects of vibration on the human body have been unsuccessful or have been limited in their application. The difficulty in modelling the effects of vibration on the body is mainly due to the complexity of the interaction between the vibratory stimulus and changes in body posture and the level of muscle contraction. The important conclusion that can be drawn from the research is that health risks are associated with exposure to vibration but the risk is a function of the frequency and amplitude of vibration, the resulting forces from the movement of the body mass and the duration of the exposure

The Effects of Vibration Training on Performance

Chronic Training Effects of Vibration Training

While vibration training has yet to make an official presence in the resistance training programs of athletes, it appears that this modality of training may have the potential to elicit a chronic training effect. An investigation performed by Issurin and co-authors (1994) examined the chronic training effects of vibration on muscle force production in the seated row. Twenty-eight physical education students were divided into three training groups. Group one performed the seated row with vibration (frequency = 44 Hz, amplitude = 3mm), group two performed the seated row without vibration and the third group served as a control. The vibration treatment group and the group using conventional training methods performed the same exercises and used the same loading parameters during the three-week training period which included six sets to failure with loads increasing from 80 to 100% of the subject's 1RM, and a 2.0-3.5 minute rest interval between sets. Pre- and post-training measurements were made in the seated row exercise. After a three-week training period, the vibration training group had a statistically significant increase in strength of 49.8% in the seated row compared with a16.1% increase in strength for the group using conventional training methods.

Based on these results, it was concluded that vibration training resulted in a significant training advantage over the conventional training method. Issurin and co-workers (1994) proposed that neural mechanisms were primarily responsible for the significant improvements in strength observed in the group treated with vibration. It was postulated that vibration excited muscle receptors and Ia afferents, and the increased discharge from the Ia afferents resulted in greater motor unit recruitment. Furthermore, it was reported that at a frequency of 44 Hz, it was possible that motor unit synchronization

improved which led to greater force production during training and a better overall training effect.

The fact that Issurin and co-authors (1994) did not evaluate the effects of vibration training on the neuromuscular apparatus was a major criticism of their study. It is probable that the gains in strength observed in their study were due to a neural mechanism as the loading parameters of six sets to failure with progressively increasing loads up to 1RM would probably not have induced significant muscle hypertrophy in a three-week training period (Poliquin, 1991). Although vibration has been shown to induce hypertrophy in Type I muscle fibres in rats (Necking et al., 1996), it is unlikely that an increase in muscle mass was responsible for such significant gains in strength. Also, without a test to assess muscle activation (e.g. interpolated twitch technique) it is very difficult to ascertain the extent to which neural factors were responsible for the significant strength improvements in the group treated with vibration. Thus, the conclusions that attribute the vibration induced strength gains to neural factors (i.e. increased motor unit synchronization and increased recruitment of motor units) may be unfounded. Furthermore, the investigators failed to control the total work performed by the subjects. The loading parameters as indicated in the methodology states that the subjects performed six sets to failure with progressively increasing loads from 80 to 100% of the subject's 1RM. It is possible that the subjects may have performed more or less repetitions per set depending on their training history and motivation. If the subjects in the vibration treatment group were encouraged to perform more repetitions per set than the non-vibration treatment group, then a greater amount of work would have been performed and this could have affected the results. It is important to establish whether the improvement in strength over the 3-week training study was due to a

greater total amount of work performed when exposed to vibration or if the improvement was due to other factors.

In addition to the studies that have examined the effects of vibration on strength gains during upper body movements, research has been performed on the physiological adaptations to whole-body vibration in athletic movements. Bosco and colleagues (1998) evaluated the effects of whole-body vibration (frequency = 26 Hz, amplitude = 10 mm) on the jumping ability of 14 physically active subjects. Subjects were randomly divided into two groups. The experimental group was given the vibration treatment over a period of ten days and the control group maintained normal daily activities without exposure to vibration. The vibration treatment consisted of five sets of whole-body vibration lasting 90 seconds with a 40 second rest interval. The duration of the sets were increased by five seconds over the ten-day period up to a maximum of two minutes per set. In Set 1 subjects stood on the vibration platform with the ankles plantar flexed. Set 2 was performed in a half-squat position. Set 3 the subjects were in a half-squat position with the feet externally rotated. Set 4 the subject stood on the right foot with the knee flexed to 90 degrees, and in Set 5, subjects stood on the opposite foot in the same position.

Subjects were tested prior to and following the ten-day exposure to whole-body vibration. Testing procedures included a ten-minute warm up on a cycle ergometer, and light stretching for the quadriceps and triceps surae muscles. The testing protocol included a countermovement jump and five-seconds of continuous jumping. Flight time and contact time of the jumps were recorded using a resistive platform connected to a digital timer with an accuracy of ± 0.001 seconds. For the countermovement jump subjects descended to a knee angle of 90 degrees and jumped maximally while keeping the hands on the hips.

During five-seconds of continuous jumping subjects were instructed to maximize jumping effort, and minimize knee flexion and contact time during the contact phase.

Ten-days of vibration training resulted in a significant increase in jump height during five-seconds of continuous jumping but no improvement in jump height for the countermovement jump. The control group did not show improvement in jumping ability for either the five-seconds of continuous jumping or the countermovement jump.

The fact that whole-body vibration led to an improvement in five-seconds of continuous jump but not the countermovement jump may help to elucidate the effects of whole-body vibration on jumping performance. Compared to the five-seconds of continuous jumping, the countermovement jump was characterized by a slower eccentric contraction and a longer ground contact phase, and, along with previous research performed by Bosco and Viitasalo (1982) which concluded that EMG activity during the eccentric phase of a countermovement jump was small in comparison with drop-jumping exercises, this may indicate that vibration affects specific neural and reflex pathways (e.g. stretch reflex) which might contribute more to performance during short duration stretch-shorten cycle activity. Based on these findings, the authors concluded that whole-body vibration elicited positive changes in neural mechanisms (e.g. stretch-reflex potentiation, increased threshold of firing of the Golgi-tendon organs, improved synchronization of firing of the motor units, and improved co-contraction of synergist muscles) (Bosco et al., 1998).

Finally, a longitudinal study performed over 21 days by Spitzenpfeil and co-workers (1999) investigated the effects of vibration training on the performance of one highly trained alpine skier. The training was divided into six phases and in the first, third and fifth phases vibration training was performed (frequency = 24 Hz, amplitude = 2.5 mm). The subject performed a variety of exercises during the 21-day training cycle

including single leg squats (both with and without dumbbells), lunges, and various jumping movements. In the alternate training phases the same loading parameters and exercises were used as in the vibration training phases but there was no exposure to vibration. The investigators examined the effects of vibration training on creatine kinase, urea, heart rate, lactate, EMG and muscle force measured in the leg muscles using an isometric leg press. Each parameter was measured on each day of the three vibration training phases over the 21-day training cycle.

The results from this study show a significant increase in urea and creatine kinase on the vibration training days compared with the non-vibration training days indicating that the subject had experienced considerable physical strain. In addition, over the first two vibration training phases, the investigators reported a decrease in the force production measured on the isometric leg press but a 43% increase in isometric strength was observed in the final vibration training phase. Vertical jump also increased from 38.9 cm at the beginning of the 21-day training cycle to 47.8 cm after 14 days of training. These findings were contrary to previous results which indicated that no significant improvements in strength or jumping ability occurred with vibration training. It was hypothesized that the additional load (i.e. the dumbbells), which was not used in previous studies, may have increased the tension in the muscle during the vibration training and resulted in the improvements in performance not observed in previous investigations.

Acute Effects of Vibration Training

An investigation performed by Liebermann and Issurin (1997) examined the acute effect of vibration (frequency = 44 Hz, amplitude = 3 mm) during elbow flexion on the perception of effort in 41 male athletes. The 41 athletes were split into four groups. The

first group consisted of Olympic level athletes, the second group consisted of National level athletes, the third group comprised junior athletes, and finally the fourth group included amateur athletes and physical education students. The subjects began by performing a 1RM in an elbow flexion exercise. Following the 1RM test, the subjects performed four sets of single repetitions at 30, 60, 90 and 100% of their 1RM with and without vibration. Using a Borg scale to gauge perception of effort, Liebermann and Issurin (1997) reported that all subject groups except for the group consisting of the junior athletes perceived their effort to be less when performing the repetitions with vibration. Furthermore, all groups lifted significantly more weight for the 1RM when exposed to vibration. It was proposed that the increase in the load lifted for a 1RM while exposed to vibration was obtained in part by the sensation that the load being lifted was lighter.

In order to understand how vibration might alter the sensation of effort it is important to consider the mechanism by which the brain perceives muscular effort. During voluntary muscular contractions, muscle force is perceived by the central nervous system by one of three mechanisms (Cafarelli, 1982). The first mechanism is a feedback mechanism which operates by afferent flow that is received from the peripheral receptors in the joints, tendons (e.g. Golgi tendon organs), and the muscles (e.g. muscle spindles). A second mechanism by which force is perceived is the feedforward mechanism. In this instance, a copy of the motor outflow that leaves the motor cortex is transmitted to the sensory cortex. The feedforward component provides information referable to the muscular system, and is responsible for sensations such as the "phantom limb" that is perceived by amputees. Finally there can be a combination of the feedback and feedforward components. In this instance, afferent inflow from the peripheral receptors is compared with the feedfoward copy from the motor cortex.

It is possible that the decreased sensation of effort observed by Liebermann and Issurin (1997) could be explained in part by a reduced feedforward element from the motor cortex. During exposure to vibration, the increased activity of the Ia afferents may have reduced the central feedforward element making any force generated partially or entirely during exposure to vibration feel like less force than during a normal contraction (Cafarelli, 1988). The difficulty in making this conclusion is the uncertainty in the degree to which the feedforward element affects the perception of force during exposure to vibration.

It is also unclear how a decreased perception of effort would have positively affected the elite athlete group. It would be expected that maximal voluntary force production for elite athletes would be a governed by a biological limit and not a limit based on the sensation of effort. If the elite athlete group was capable of fully activating their muscle then the vibration treatment should not have resulted in the recruitment of previously inactive motor units and a significant difference in maximal strength.

After examining the training effects and cognitive events associated with the increase in muscle force production caused by vibration, Issurin and Tenenbaum (1999) examined the acute and residual effects of vibration on power during elbow flexion in elite and amateur athletes. Power during elbow flexion was measured by the use of two probes (marking the ends of the subject's range of motion) that were placed on the vertical struts of the elbow flexion machine. A magnet was placed on the weight stack, and as the weight stack moved between the two probes electrical signals were generated allowing the elbow flexion movement to be timed. The product of force and velocity were used to calculate power.

Twenty-eight male athletes were divided into two groups. The first group consisted of elite athletes who regularly participated in powerful movements, and the second group

consisted of amateur athletes who engaged in explosive movements less often than the elite athlete group. Initially both groups were allowed a controlled warm up and the 1RM was then determined on the elbow flexion machine. Both groups performed two series of three sets of maximal elbow flexion movements at a load of 65-70% of the 1RM during which power output was measured. In one series, exposure to vibration occurred during the second set, and in the other series, vibration was not used for any of the three sets. The subjects were allowed 8 to 15 minutes rest between the two series of elbow flexion. The vibration treatment resulted in a significant gain in power for both groups ($p < 0.001$), 10.4% for the elite athlete group, and 7.9%, for the amateur athlete group. Furthermore, the elite group displayed a significantly greater gain in power than the less trained amateur group ($p < 0.04$). There were no significant residual effects of vibration on explosive strength.

Issurin and Tenenbaum (1999) concluded that the vibration treatment increased power output in elite and amateur athletes and that the gains in maximal power were greater in the elite athlete group than in the less well-conditioned amateur athletes. They postulated that the greater gains in maximal power for the elite athletes were most likely due to a higher sensitivity of muscle receptors and the central nervous system to stimulation. The acute effects of vibration on power output were attributed to stimulation of α-motoneurons by the increased firing of the Ia afferents that resulted in the recruitment of previously inactive motor units.

Unfortunately, the investigators failed to perform any diagnostic measurements that would explain how vibration affected muscle activation therefore it is difficult to identify the exact mechanism that led to an improved power output during elbow flexion. The validity and reliability of the power ergometer also poses a problem. The researchers failed

to mention if the power ergometer was properly calibrated prior to the measurement of power and they also failed to specify the sampling frequency of the power ergometer. Both of these parameters must be controlled and evaluated prior to the data collection to ensure accurate interpretation of the results.

A similar investigation evaluating the acute effects of vibration on the upper body was performed by Bosco et al. (1999a). Vibration treatment was applied to the arms of 12 international level boxers. Power output was recorded using a digital encoder that measured movement time. A signal was emitted by the encoder every 3mm of displacement. EMG was recorded using bipolar surface electrodes that were secured to the skin with a suit in order to diminish movement artefact.

Baseline mechanical power for both arms was evaluated by performing maximal elbow flexion with an additional load equal to 5% of the subject's body mass. The subjects were allowed five attempts with 60-second rest intervals in between trials, and a five-minute rest interval between each arm. After the initial testing, one arm was randomly treated with vibration (frequency = 30 Hz, amplitude = 6 mm) for five-minutes, and the other arm served as a control. After the vibration treatment, each limb was re-tested according to the initial protocol.

EMG in the biceps brachii muscles on the treated arm increased significantly during the vibration treatment compared to the pre-treatment value. Furthermore, in the post-vibratory period, the arm treated with vibration displayed a significant increase in power output over the pre-treatment values but this was paralleled by a significant decrease in EMG activity ($p < 0.01$). This effect was attributed to improved neuromuscular efficiency of the elbow flexors. In this instance, the term neuromuscular efficiency was defined as an increase in power output and decrease in EMG during elbow flexion. This term has also

been used to describe the adaptations to long-term resistance training whereby EMG activity will decrease with a given force production (Hakkinen et al., 1985). It is possible that the vibration treatment in this experiment resulted in an improved neuromuscular efficiency associated with maximal power output of the elbow flexors.

Based on the results, it is difficult to determine the mechanism by which vibration affected the elbow flexors in the post-vibratory period. While the investigators demonstrated that EMG activity in the biceps brachii increased during exposure to vibration it is still difficult to ascertain the reason for a decrease in EMG and an increase in power output in the post-vibratory period. If vibration enabled the subject to better activate their muscle then this should have resulted in greater EMG in the post-vibratory period. One possible explanation of this finding is that the vibration treatment resulted in movement of the EMG electrodes despite the efforts of the researchers to control for this. Basmajian and Deluca (1985) explain that movement of the EMG electrodes in relation to the active muscle fibres during a muscle contraction can affect most of the spectrum of the EMG signal (p. 88). If in this investigation vibration caused the EMG electrodes to shift then the EMG data would have been adversely affected.

In a subsequent investigation, Bosco and co-workers (1999b) evaluated the acute effects of whole-body vibration (frequency = 26 Hz, amplitude = 10 mm) on lower body power output in a group of six female volleyball players. Power output was evaluated on a dynamic leg press. The load on the leg press was linked to an encoder that interfaced with an electronic microprocessor. The encoder transmitted a signal from the load every 3mm of displacement.

The subjects were allowed a controlled warm up that consisted of five minutes of cycling on a cycle ergometer and five minutes of static stretching for the quadriceps and

triceps surae muscles. The subjects were then tested with extra loads of 70, 90, 110 and 130 kg. The test was performed separately for each leg. After the initial test, one leg was randomly assigned to the vibration treatment. The vibration treatment included ten minutes on a vibration platform with the ankle plantar-flexed and the knee flexed to 100 degrees. Prior to the vibration treatment, no significant differences were found between the two legs of any subjects. After vibration, the exposed leg displayed a significant improvement in average force, average velocity, and average power developed with all loads ($p < 0.05$-0.005).

The authors concluded that the increased power output observed in the treated leg was most likely due to changes in neural mechanisms (Bosco et al., (1999b). Unfortunately EMG was not measured nor did they perform any other diagnostic measurement to evaluate muscle activation. It is possible that a vibration induced change in the neural drive (e.g. motor unit firing rate, motor unit synchronization, number of motor units recruited, and potentiation of the stretch reflex) was responsible for the improvement in power output although more scientific evidence is required to confirm this hypothesis.

In addition to the improvements in power output, whole-body vibration can also affect hormonal profiles in men. Bosco and co-workers (2000) evaluated the hormonal responses in a group of 14 male subjects to ten minutes of whole-body vibration (frequency = 26 Hz, amplitude = 4 mm). Explosive power was also evaluated using a countermovement jump and maximal dynamic leg press. Initially, resting blood samples were drawn to evaluate the concentration of serum total testosterone, cortisol, and growth hormone. Prior to the vibration treatment baseline measurements were made in the countermovement jump and maximal dynamic leg press with a load of 160% of the subject's body mass.

The vibration treatment resulted in a significant improvement in mechanical power output and countermovement jump height but a decrease in EMG activity for the knee extensors during dynamic leg press. The whole-body vibration treatment also resulted in a significant increase in testosterone and growth hormone, and a significant decrease in cortisol (Bosco et al., 2000).

The decrease in cortisol observed by Bosco and co-authors (2000) may indicate that vibration training did not elicit a large physiological stress response as cortisol is associated with a generalized stress response and has also been shown to elicit catabolic actions on muscle proteins (Kraemer, 1988). This finding contradicts previous research performed by Spitzenpfeil and colleagues (1999) in which vibration training appeared to induce significant stress on muscle tissue as inferred from the increase in creatine kinase.

It is possible that the increased growth hormone and testosterone as a result of whole-body vibration may improve the physiological conditions for muscle growth and development. Growth hormone is essential for normal growth of skeletal muscle and is involved in a wide variety of biological actions to maintain normal structure and function (Kraemer, 1988). Testosterone possesses anabolic properties by inducing the synthesis of mRNA inside the muscle cell and testosterone also possesses anti-catabolic effects (Loebel & Kraemer, 1998). Testosterone inhibits muscle glycogen breakdown, and displaces glucocorticoids from its attachments to receptors in muscle. Testosterone and growth hormone have also been shown to increase following resistance training protocols (Kraemer, 1988). If vibration training does have the potential to elicit a substantial anabolic effect then it may serve as a recovery tool following intense training. Further research would be required to confirm the validity of this hypothesis.

Finally, in an experiment similar to the one described in this thesis, the short-term effects of whole-body vibration on maximal voluntary and involuntary knee extensor force were investigated (de Ruiter et al., 2003). Twelve untrained subjects participated in this investigation. Baseline measurements for maximum force and rate of force development were made during voluntary and involuntary muscle contractions over a two-day period. On the second testing day, the baseline measurements were followed by the vibration treatment (5 sets of 60 seconds, frequency = 30 Hz, amplitude = 8mm). Post-treatment measurements were made in the recovery period and 10 subjects continued with a two-week vibration training protocol. Measurements were repeated for the training group three days following the final training session. In addition to the rate of force development and maximal force development during the voluntary and involuntary muscle contractions, de Ruiter et al. (2003) also determined voluntary activation (%) which was defined as:

$$\textbf{Voluntary Activation} = \frac{\text{Force during Maximum Voluntary Contraction}}{\text{Force during Maximal Electrical Stimulation}} \text{ X } 100\%$$

This investigation revealed that vibration did improve performance during the voluntary and involuntary muscle contractions. In fact there was a 7% decline in force production during the maximal voluntary contraction 90 seconds following the vibration treatment. The decline in force in the maximum voluntary contraction was relatively larger than the decline in force observed during the involuntary contraction. This was reflected in a decrease in voluntary activation from 95% to 90% which led the conclusion that the subjects' ability to activate their muscle had declined following the vibration treatment. The statistically significant depression in force production remained up to 3 hours

following the vibration treatment. Furthermore, the vibration treatment did not appear to have an effect on maximal rate of force development during the voluntary or involuntary contractions. Finally, the two-week vibration training period did not improve any of the parameters measured in this investigation.

While this investigation failed to demonstrate an improvement in muscle activation and performance following the vibration treatment, there are two main concerns that arise with the methodology that can lead to uncertainty in these results. Firstly, the procedure used to evaluate muscle activation is troublesome due to a relatively small sample size of untrained subjects (de Ruiter et al., 2003). It is well accepted that the assessment of muscle activation using electrical stimulation requires repeat measurements and a homogeneous sample size with a relatively large number of subjects to accurately assess muscle activation (Suter & Herzog, 2001). Secondly, de Ruiter et al. (2003) evaluated muscle activation using the central activation ratio which was calculated by the force produced in the voluntary contraction divided by the maximum force during an 80 ms involuntary contraction. The central activation method has been shown to be very problematic (Behm et al., 2001). An investigation performed by Behm and co-authors (2001) demonstrated that linear regression estimations of the central activation ratio resulted in very erroneous values for muscle activation. A more suitable technique would have been the interpolated twitch ratio which calculates muscle activation relative to the potentiated resting twitch torque.

Cardiovascular Effects of Vibration Training

In addition to the neural and hormonal effects of whole-body vibration, the cardiovascular and metabolic effects of whole-body vibration are of importance in

evaluating the usefulness of this training modality. Rittweger and colleagues (2000) examined the effects of exhaustive whole-body vibration exercise in a group of 40 healthy subjects, and compared the results with exhaustive cycle ergometry. Initially subjects performed a maximal incremental cycle ergometer test. Pre- and post-vibration measurements were made on the following parameters: arterial blood pressure, ECG and heart rate, $\dot{V}O_2$ and CO_2 delivery using a Metamax system, perceived exertion using a Borg scale, and blood lactate concentration with blood samples obtained from the finger tip were recorded.

On the second and third testing days, subjects performed exhaustive vibration exercise (frequency = 26 Hz, amplitude = 10.5 mm) with an additional load of 40% of body mass for males and 35% of body mass for females. After 30 seconds of standing, subjects performed slow moving squats (i.e. 6 seconds eccentric phase, 6 seconds concentric phase). In addition to the values obtained on the initial testing day, jump height, cutaneous laser Doppler flow over the triceps surae muscles and foot, and ten seconds of MVC of the knee extensors were recorded.

During the exposure to vibration there was a significantly smaller increase in heart rate compared with the maximal cycle ergometry test ($p < 0.05$), and there was no significant difference in the recovery heart rates after maximal cycle ergometry exercise and exhaustive vibration exercise. $\dot{V}O_2$ uptake was also significantly lower during vibration exercise compared with maximal cycling and the mean blood lactate concentration was significantly lower after the exhaustive vibration exercise. Systolic blood pressure increased more during maximal cycle exercise but diastolic blood pressure was significantly decreased after the vibration exercise. After exhaustive vibration exercise there was a significant decrease in jump height and knee extensor torque during the MVC

compared with pre-exercise values. Finally subjects perceived the vibration exercise to be more fatiguing than the maximal cycle ergometry exercise, and the perceived exertion was higher in the first vibration exercise session.

The investigators concluded that exhaustive vibration exercise did not have a significant cardiovascular effect, and that the fatigue that was experienced during exhaustive vibration exercise was most likely caused by the neuromuscular system and not by the same mechanisms that triggered fatigue during cycle ergometry (Rittweger et al., 2000).

Summary of the Effects of Vibration Training on Performance and the Human Body

Vibration has been used in many different settings to improve recovery from injury and to enable patients with motor dysfunction to regain motor ability. In an athletic setting the use of vibration during resistance training leads to an increased muscle force production, greater explosive strength, and increased power output. These improvements occur immediately following the vibration treatment and after a short vibration training block (i.e. ten days – three weeks). Whole-body vibration also induces significant changes in the resting hormonal profiles of men.

Vibration can compensate for decreased γ-motoneuron drive by exciting the Ia afferents and this can result in greater muscle activation in a fatigued state (Bongiovanni & Hagbarth, 1990). Based on the literature it can also be concluded that vibration of a muscle leads to the excitation of the Ia afferents, causing the Ia afferents to fire for each cycle of the vibration up to a maximum frequency of about 150 Hz (Burke et al., 1976a&b). The excitation of the Ia afferents stimulates α-motoneurons and excites homonymous and synergistic muscle fibres and this response has been referred to as the TVR. The strength

of the TVR is dependent on the vibration frequency and amplitude, and also the level of pre-contraction in the muscle.

Vibration also depresses the stretch reflex and the H-reflex (Van Boxtel, 1986). During the post-vibratory period though there is a marked potentiation of the stretch reflex while the H-reflex recovers gradually over a period of about 100 seconds. The vibration induced stimulation of the Ia afferents can compensate for the decreased intrafusal muscle drive during a fatigued state leading to excitation of α-motoneurons. In the post-vibratory period, vibration has been associated with a decrease in EMG associated with maximal power outputs. This finding has been described as an improvement in neuromuscular efficiency (Bosco et al., 2000). It is possible that in the post-vibratory period the stretch reflex may be potentiated and the threshold of firing of the Golgi tendon organs may be increased leading to an improvement in performance during ballistic movements although contrary to the findings, an increase in EMG would be expected in this instance (Bosco et al., 1998).

In addition to the motor effects, vibration may also affect the perception of effort during maximal contractions (Liebermann & Issurin, 1997). The use of vibration during a strength training movement causes a decreased perception of effort in the amount of force required to exert a maximum effort compared to a conventional movement. The perception of effort may be related to the age of the athlete with older athletes perceiving a greater difference in effort between contractions with vibration than contractions without vibration. It is postulated that the perception of needing less force to move a load is related to a diminished feedforward outflow from the motor cortex to the sensory cortex.

Several improvements can be made on the investigations that examine the effects of vibration on power output and strength. It is unclear whether vibration improves the ability

of a subject to perform greater work during a training period or if the improvements in performance are due to other reasons. It is crucial that a training study attempt to control the total work performed by the subjects as this variable can significantly affect the improvements in performance. Secondly the use of EMG during an exposure to vibration may be troublesome. EMG is highly sensitive to changes in position of the recording electrodes relative to the motor units being recorded. Finally the investigations that examine the effects of vibration on maximal strength in an acute setting should evaluate the ability of the subjects to activate their muscle.

Further research should also be done to understand the effects of different vibration protocols on performance. Of the studies reviewed in this paper, several different vibration protocols were used. Some investigations required the subject to perform voluntary movements with extra loads, some required voluntary movements without loads, and in some studies the subjects stood in a static position on the vibration platform. The studies also differed in the frequency and amplitudes of vibration and the length of exposure for the vibration treatment. None of the authors offer a rationale explaining why one protocol is superior to another. Furthermore, based on the fact that the TVR is influenced by the level of pre-contraction in the muscle and the position of the body it is important that the effects of variables such as level of pre-contraction, use of additional load, body position and frequency and amplitude of vibrations on performance be investigated.

Finally several pathological conditions are associated with exposure to vibration. The health risks associated with vibration exposure are most often observed in occupational settings. The severity of the symptoms that result from exposure to occupational vibration is a function of the total exposure to vibration and the intensity of the vibration. Several models have been developed to quantify the forces experienced by the body during

exposure to vibration although accurate modelling of the human body is extremely difficult. Tools such as the ISO 2631-1 may be useful in assessing the risk from exposure to vibration.

In conclusion the potential of vibration to enhance the training regimes of athletes appears quite promising. It is essential though that a thorough understanding of the implications of this type of treatment be acquired prior to its use in athletic situations. Future research should be undertaken with the aim of understanding the biological effects of vibration on muscle performance and also the effects of different vibration protocols on muscle performance.

Purpose of the Present Investigation

In consideration of the evidence in support of the acute benefits of vibration in athlete populations, and the lack of information on the exact biological mechanisms underlying these benefits, the purpose of the present investigation was to evaluate the acute effects of whole body vibration on specific mechanical and neural properties of muscle during an MVC of isometric knee extension. Furthermore, because of the variability in the protocols reported in vibration training research studies, the vibration protocol used in this investigation was very conservative, making this study a starting point in series of future investigations over which a systematic increase in the vibration load and dose will be administered.

CHAPTER 3: METHODOLOGY

Subjects

Twenty-four male subjects provided written informed consent to participate in this investigation. Subjects were recruited from the Faculty of Kinesiology at the University of Calgary. All subjects were healthy and had been involved in regular strength training for a minimum of two years prior to the start of the investigation. The subject characteristics were as follows (mean ± sd): age, 28.1 ± 3.3 years; height, 180.0 ± 6.7 cm; body mass, 82.8 ± 7.6 kg. The experimental protocol was approved by the Conjoint Faculties Research Ethics Board at the University of Calgary.

Study Design

The testing week was preceded by a two-week run-in period (Figure 6). The purpose of the run-in period was to control for the effects of outside physical activity. Furthermore, two days prior to each testing session the subject rested, abstaining completely from any physical activity.

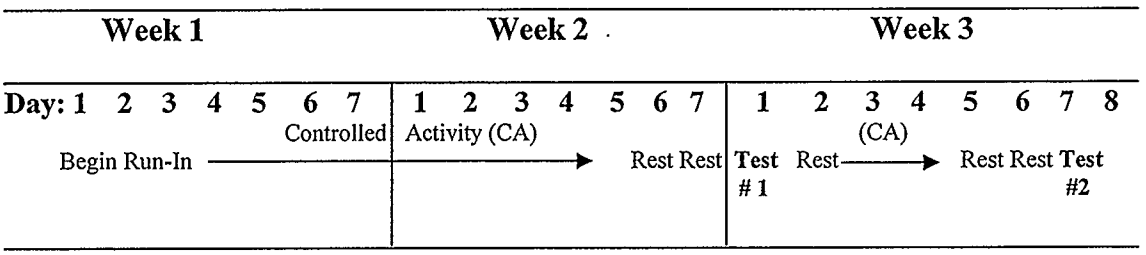


Figure 6: An overview of the three-week testing schedule.

Subjects performed the testing protocol twice over a one week time period; once with the vibration treatment and once with the control treatment. Subjects were randomly divided into one of two groups with the treatment order reversed for the second group (Figure 7). The first group received the vibration treatment in the first testing session and the second group received vibration treatment in the second testing session. The vibration treatment consisted of 3 sets of 60 seconds at a frequency of 30 Hz on a commercially available vibration platform (NEMES-Bosco). The control treatment procedure was identical except that no vibration was administered.

	Testing Day 1	Washout	Testing Day 2
Group I (n_{12})	**A**	**-------**	**B**
Group II (n_{12})	**B**	**-------**	**A**

A = Vibration treatment B = Control Treatment

Figure 7: Layout of the cross-over design (Adapted from Armitage et al., 2002).

Overview of the Testing Session

The following is an overview of the testing procedure. A schema representing the testing session is presented in Figure 8 of this document, and a detailed explanation of the exact testing procedure will follow this section.

Initial Preparation

Upon arrival, the subject was familiarized with the testing procedure. The subject was then prepared for testing; this included preparation of the subject's skin, fastening of the EMG electrodes, and adjustments were made to the Biodex in preparation for the MVC. Subjects

performed a series of warm up isometric knee extension repetitions on the Biodex which included 5 submaximal repetitions at 50% effort, 5 submaximal repetitions at 75% effort and 3 near maximal repetitions at 90% effort. The warm up also allowed the investigator to adjust and calibrate the EMG signal. The subject was then provided with a 10 minute rest interval while the electrical stimulation electrodes were fastened to the skin.

Baseline Measurements

The baseline measurements (i.e. EMG, torque during MVC, resting twitch torque, and muscle inhibition) were recorded using an interpolated twitch technique. There was a 12 minute rest interval between each of the baseline tests. A 25 minute rest interval separated the baseline measurements and the post-intervention measurements. The trial with the greatest peak torque during the MVC was used for further data analysis.

Post-Treatment Measurements

Three resting twitches were recorded immediately prior to the treatment. These resting twitches served as the reference twitches for the post-intervention measurements and allowed the effects of the treatment on the resting twitch torque to be evaluated. Following the three resting twitches, the subject was released from the Biodex and then stepped onto the vibration platform. The subject maintained a quarter squat position (knee angle measured at 130 degrees of knee flexion) with the heels slightly elevated for three sets of 60 seconds with a 60 second set rest interval at a frequency of 30 Hz (**Note:** The control treatment was administered in exactly the same method except there was no exposure to vibration). Following the treatment the entire interpolated twitch technique was performed. The post-treatment interpolated twitch technique was always performed exactly one-minute

following the final set of the treatment in order to accurately assess the effect of the treatment on resting twitch torque. This measurement was repeated a second time with a 20 minute rest interval separating the tests. The trial with the greatest peak torque during the MVC was used for further data analysis.

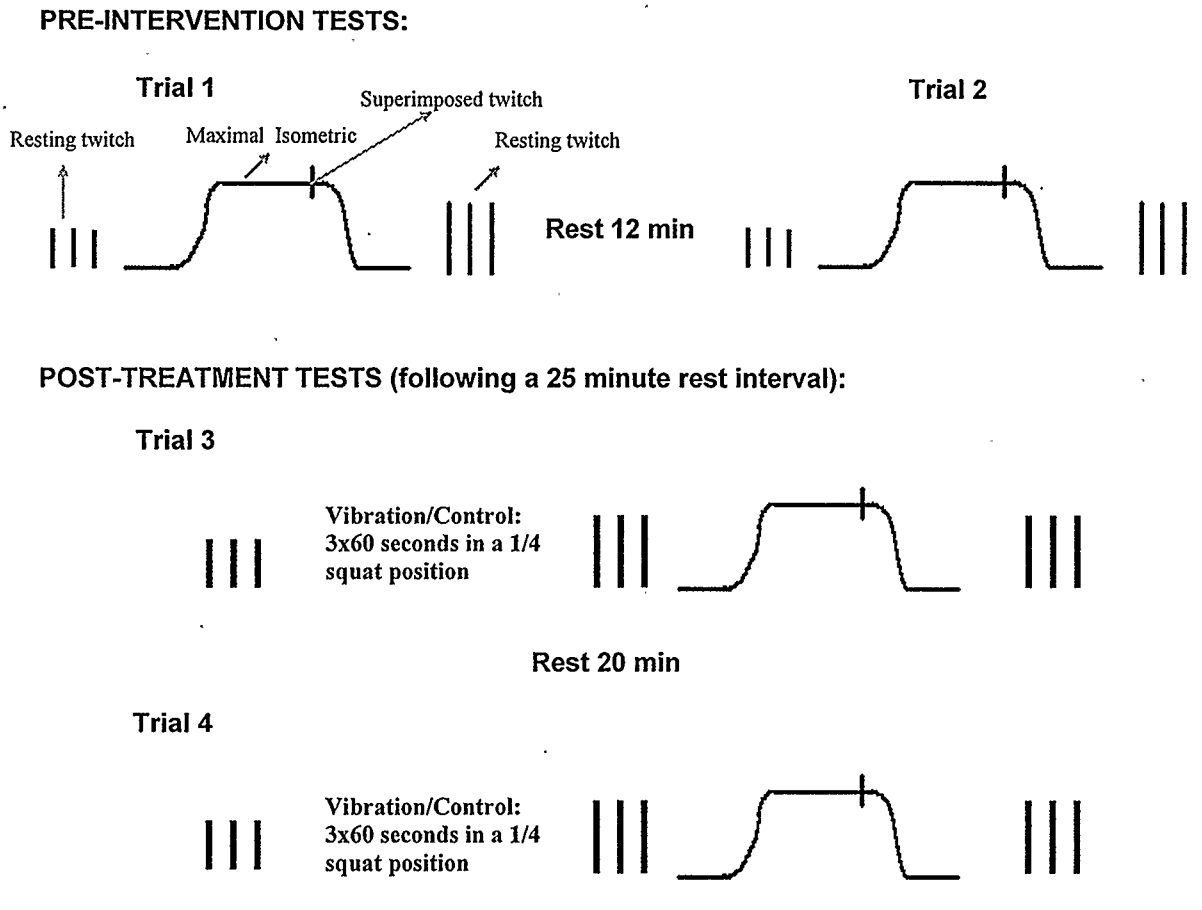


Figure 8: A schema of the study design.

The following outcome measures were evaluated using this above study design:

(1) EMG during MVC
(2) Peak torque during MVC
(3) Muscle inhibition during MVC
(4) Effect of treatment on resting twitch torque
(5) Effect of treatment on resting twitch torque following MVC

Procedure

Pre-Testing Procedure

Prior to the testing session the subjects were familiarized with the testing procedures. This included familiarization with the vibration platform and the maximal isometric knee extension on the Biodex.

Subject Preparation

The subject was seated in the Biodex dynamometer with the lateral epicondyle of the femur aligned with the axis of rotation of the dynamometer. The subject was strapped to the dynamometer with two belts crossing the chest and one belt crossing the hips. The knee angle was set at 90 degrees of knee flexion using a reference angle at full knee extension (i.e. 0 degrees knee flexion). The proximal and distal regions of the thigh were shaved and cleaned with isopropyl alcohol.

Electrical Stimulation

Standard carbon-impregnated rubber electrodes (4.5x10 cm) were coated with a conductive gel and were secured to the skin with adhesive tape above the femoral nerve, distal to the inguinal ligament and on the skin at the distal region of the quadriceps muscle. A doublet twitch lasting 0.8 ms was applied using a Grass S88 Muscle Stimulator in combination with an isolation unit approved for human use (Quincy, MA). Firstly, the voltage that resulted in the maximal resting twitch torque signal was determined. This was accomplished using an incremental stimulation protocol beginning at 20 Volts and ending at the voltage resulting in maximum resting twitch torque. The increment was 10 Volts per stimulation. The torque resulting from the electrical stimulations was sampled at 2000 Hz using an

analog-digital board, and was monitored and stored for further data analysis on an IBM personal computer. The voltage associated with the maximal resting twitch torque was used for all the interpolated twitch techniques throughout the testing session. The voltage resulting in maximal resting twitch torque was re-assessed on the second testing day using the above protocol.

Twitch Interpolation Technique

Three stimulations were given to the relaxed muscle. The average torque produced by the three stimulations was referred to as the resting twitch torque (RTT). It was defined by the following formula

$$\mathbf{RTT = (RTT_1 + RTT_2 + RTT_3)/3}$$

The subject then performed an MVC which was held for seven seconds. At the fourth second of the voluntary contraction another electrical stimulation was applied eliciting the interpolated twitch. Following the MVC three more stimulations were given to the relaxed muscle.

Quantifying Muscle Inhibition

Muscle inhibition (MI) during the MVC was calculated by dividing the interpolated twitch torque (ITT) by the resting twitch torque (RTT). This value was then multiplied by 100. It was defined by the following formula:

$$\mathbf{MI\ (\%) = (ITT/RTT)\ x\ 100}$$

The effect of the treatment on muscle inhibition was calculated by the baseline muscle inhibition subtracted by the post-treatment muscle inhibition resulting in the following

outcome measures: (i) Change in Muscle Inhibition on Day 1 (ΔMI_1) and (ii) Change in Muscle Inhibition on Day 2 (ΔMI_2), where,

$$\Delta MI_1 = \textbf{Baseline } MI_{day\ 1} - \textbf{Post-Treatment } MI_{day\ 1}$$

$$\Delta MI_2 = \textbf{Baseline } MI_{day\ 2} - \textbf{Post-Treatment } MI_{day\ 2}$$

Quantifying Effects of Treatment on Resting Twitch Torque

The effect of the treatment on the potentiation of the resting twitch torque (POT_{treat}) was calculated by dividing the post-treatment resting twitch torque ($RTT_{post\text{-}treat}$) by the pre-treatment resting twitch torque (RTT). This value was then multiplied by 100 and subtracted by 100. This resulted in the following outcome measures: (i) Post-Treatment Potentiation on Day 1 (POT_{treat1}) and (ii) Post-Treatment Potentiation on Day 2 (POT_{treat2}), where,

$$\textbf{POT}_{treat1} = (\textbf{RTT}_{post\text{-}treat}/\textbf{RTT x 100}) - \textbf{100}$$

$$\textbf{POT}_{treat2} = (\textbf{RTT}_{post\text{-}treat}/\textbf{RTT x 100}) - \textbf{100}$$

Quantifying Potentiation

Potentiation (POT) of the resting twitch torque (RTT) following MVC was calculate by the post-MVC resting twitch torque (RTT_{post}) divided by the pre-MVC resting twitch torque (RTT). This value was multiplied by 100 and subtracted by 100.

$$\textbf{POT} = (\textbf{RTT}_{post}/\textbf{RTT x 100}) - \textbf{100}$$

The effect of the treatment on the potentiation following MVC was determined by the baseline potentiation from the MVC subtracted by the post-treatment potentiation from the MVC. This gave the following outcome measures: (i) Change in Potentiation on Day 1 (ΔPOT_1) and (ii) Change in Potentiation on Day 2 (ΔPOT_2), where,

$$\Delta POT_1 = \textbf{Baseline } POT_{day\,1} - \textbf{Post-Treatment } POT_{day\,1}$$

$$\Delta POT_2 = \textbf{Baseline } POT_{day\,2} - \textbf{Post-Treatment } POT_{day\,2}$$

Quantifying Torque during MVC

Torque (TQ) signals were sampled at 2000 Hz using an analogue-to-digital board, and data was monitored and stored on an IBM personal computer for analysis. Torque during the MVC was calculated by averaging the torque signal over 500 msec immediately prior to the application of the interpolated twitch stimulation. The effects of the treatment on torque during the MVC was then determined by the baseline torque subtracted by the post-treatment torque resulting in the following outcome measures: (i) Change in Torque on Day 1 (ΔTQ_1) and (ii) Change in Torque on Day 2 (ΔTQ_2), where,

$$\Delta TQ_1 = \textbf{Baseline } TQ_{day\,1} - \textbf{Post-Treatment } TQ_{day\,2}$$

$$\Delta TQ_2 = \textbf{Baseline } TQ_{day\,2} - \textbf{Post-Treatment } TQ_{day\,2}$$

EMG

EMG was recorded during the interpolated twitch technique from the quadriceps muscles (i.e. vastus lateralis muscle, vastus medialis muscle and rectus femoris muscle). Self-adhesive bipolar AgCl electrodes of 1cm active diameter were secured to the skin and additional adhesive tape was applied to ensure the electrodes did not displace during the vibration treatment. Electrodes were placed in the estimated direction of the muscle fibres and the ground electrode was placed on the patella. Impedance was measured and the cut-off value was set at 5 kilo-ohms. A value above this threshold resulted in re-preparation of the skin and the application of new electrodes. EMG was sampled at 2000 Hz using an analogue-to-digital board, and data was monitored and stored on an IBM personal

computer. EMG was not analyzed statistically due to the large inter-session variability that can occur with EMG measurements. However, EMG was used as a qualitative measure of muscle activation.

Vibration Treatment and Control Treatment Protocol

A commercially available vibration platform (NEMES-Bosco System) was used for this experiment. The parameters used for this experiment are based on previous experiments in which the positive effects of whole-body vibration have been observed as well as on personal communication with the primary author of these experiments (Bosco et al., 1999b, personal communication Bosco, 2002). The frequency of the vibration was set at 30 Hz. A major limitation of this vibration platform is that the amplitude could not be controlled although merit was seen in using this particular platform as this type has been used in previous research, and is commonly used in training athletes.

During the treatment, the subject maintained a quarter squat position on the platform with the knee angle set at 130 degrees of knee flexion. Knee angle was quantified with the use of a goniometer. The treatment procedure was repeated three times with a 60 second rest interval between sets. The control treatment was performed in exactly the same manner except no vibration was applied.

Statistical Analysis

The following outcome measures were analyzed: Change in muscle inhibition (ΔMI), Change in Torque (ΔTQ), change in potentiation following MVC (ΔPOT), and the effects of the treatment on resting twitch torque (POT_{treat}). The outcome measures were evaluated by calculating the difference between the changes with the two treatment conditions. The calculations were as follows:

(i) Group 1 (Vibration Treatment on Day 1)

$$\Delta_{day1} - \Delta_{day2} = \textbf{Diff Group 1} \quad \textit{where,}$$

Δ_{day1} = Baseline Score – Post Vibration Score (VIBRATION TREATMENT)

and

Δ_{day2} = Baseline Score – Post Standing Score (CONTROL TREATMENT)

(ii) Group 2 (Vibration Treatment on Day 2)

$$\Delta_{day1} - \Delta_{day2} = \textbf{Diff Group 2} \quad \textit{where}$$

Δ_{day1} = Baseline Score – Post Standing Score (CONTROL TREATMENT)

and

Δ_{day2} = Baseline Score – Post Vibration Score (VIBRATION TREATMENT)

Evaluation of Treatment Effects

The treatment effects were evaluated by comparing the mean difference between days for Group 1 and Group 2 using a two-sample t-test.

$$t = \frac{(\bar{d}_1 - \bar{d}_2)}{SE(\bar{d}_1 - \bar{d}_2)}, \quad df = n_1 + n_2 - 2,$$

where

$$SE(\bar{d}_1 - \bar{d}_2) = \sqrt{\left[s^2_d \left(1/n_1 + 1/n_2\right)\right]}$$

and

$\bar{d}_1$ = Mean Δ between treatment 1 and treatment 2 for Group 1

$\bar{d}_2$ = Mean Δ between treatment 1 and treatment 2 for Group 2

s^2_d = Pooled within-groups estimate of variance, which is given by the formula:

$$s^2_d = \frac{(n_1 - 1)s^2_1 + (n_2 - 1)s^2_2}{n_1 + n_2 - 2}$$

Evaluation of Period Effects

The effects of period were evaluated using the following test statistic:

$$t = \frac{(\bar{d}_1 + \bar{d}_2)}{SE(\bar{d}_1 - \bar{d}_2)}, \quad df = n_1 + n_2 - 2,$$

where

$$SE(\bar{d}_1 - \bar{d}_2) = \sqrt{\left[s^2_d \left(1/n_1 + 1/n_2\right)\right]}$$

and

$\bar{d}_1$ = Mean Δ between treatment 1 and treatment 2 for Group 1

$\bar{d}_2$ = Mean Δ between treatment 1 and treatment 2 for Group 2

s^2_d = Pooled within-groups estimate of variance, which is given by the formula:

$$s^2_d = \frac{(n_1 - 1)s^2_1 + (n_2 - 1)s^2_2}{n_1 + n_2 - 2}$$

Evaluation of Carry-Over Effects

Carry-over effects were assessed using the following test statistic:

$$t = \frac{(\overline{S_1} - \overline{S_2})}{SE(\overline{S_1} - \overline{S_2})} \qquad , df = n_1 + n_2 - 2,$$

where

$$SE(\overline{S_1} - \overline{S_2}) = \sqrt{\left[s^2_S \left(1/n_1 + 1/n_2\right)\right]}$$

and

$\overline{S_1}$ = Mean sum of the response for treatment 1 and 2 for Group 1

$\overline{S_2}$ = Mean sum of the response for treatment 1 and 2 for Group 2

s^2_S = Pooled within-groups estimate of variance, which is given by the formula:

$$s^2_S = \frac{(n_1 - 1)s^2_1 + (n_2 - 1)s^2_2}{n_1 + n_2 - 2}$$

Derivation of the Statistical Formulas

The test statistics used to analyze this data are based on the assumption of an additive linear model defining the treatment effect, period effect and carry-over effect. Below is the arithmetic demonstrating how the test statistics permit each variable to be analyzed.

	Response Period 1	**Response Period 2**
Group I	$\mu + \tau_V + \pi_1$	$\mu + \tau_C + \pi_2 + \gamma_A$
Group II	$\mu + \tau_C + \pi_1$	$\mu + \tau_V + \pi_2 + \gamma_B$

where,

μ = mean, τ_V = response following vibration treatment τ_C = response following control treatment, π_1 = period effect from period 1, π_2 = period effect from period 2, γ_A = carry-over effect for treatment order vibration-control, γ_B = carry-over effect for treatment order control-vibration

Carry-Over Effect: (A difference of the sum of the two responses for Group 1 and 2)

$$\overline{S_1} - \overline{S_2} = (\mu + \tau_V + \pi_1 + \mu + \tau_C + \pi_2 + \gamma_A) - (\mu + \tau_C + \pi_1 + \mu + \tau_V + \pi_2 + \gamma_B)$$

$$= \gamma_A - \gamma_B$$

Period Effect: (The sum of the difference of the two responses for Group 1 and 2)

$$\overline{d_1} + \overline{d_2} = [(\mu + \tau_V + \pi_1) - (\mu + \tau_C + \pi_2)] + [(\mu + \tau_C + \pi_1) - (\mu + \tau_V + \pi_2)]$$

$$= [(\tau_V - \tau_C) + (\pi_1 - \pi_2)] + [(\tau_C - \tau_V) + (\pi_1 - \pi_2)]$$

$$= (\pi_1 - \pi_2) + (\pi_1 - \pi_2)$$

Treatment Effect: (A difference of the difference of the two responses for Group 1 and 2)

$$\overline{d_1} - \overline{d_2} = [(\mu + \tau_V + \pi_1) - (\mu + \tau_C + \pi_2)] - [(\mu + \tau_C + \pi_1) - (\mu + \tau_V + \pi_2)]$$

$$= [(\tau_V - \tau_C) + (\pi_1 - \pi_2)] - [(\tau_C - \tau_V) + (\pi_1 - \pi_2)]$$

$$= (\tau_V - \tau_C) - (\tau_C - \tau_V)$$

Statistical Significance and Statistical Power

An estimate of the statistical power was obtained using the results of a similar investigation (Bosco et al., 2000). The calculation was performed assuming the use of a two-sample ANOVA with repeated measures, and a sample size of 26 subjects. The estimated statistical power was 0.81. It should be mentioned that this power calculation was based on a controlled study design, and the type of design used in the present investigation was a randomized cross-over design. A randomized cross-over design provides more statistical power than a controlled study design (Hopkins, 2000), and this was the rational for using only 24 subjects in the present investigation. The level of statistical significance was set at alpha equal to 0.05.

CHAPTER 4: RESULTS

Effects of Vibration on Mechanical Properties of Muscle

Change in Potentiation of Resting Twitch Torque following MVC

The post-treatment potentiation following the MVC decreased following both the vibration treatment and control treatment. The mean change (± SE) in potentiation of resting twitch torque (RTT) following the MVC was -3.374 ± 1.565% for the control treatment and -2.335 ± 1.981% for the vibration treatment condition (Figure 9).

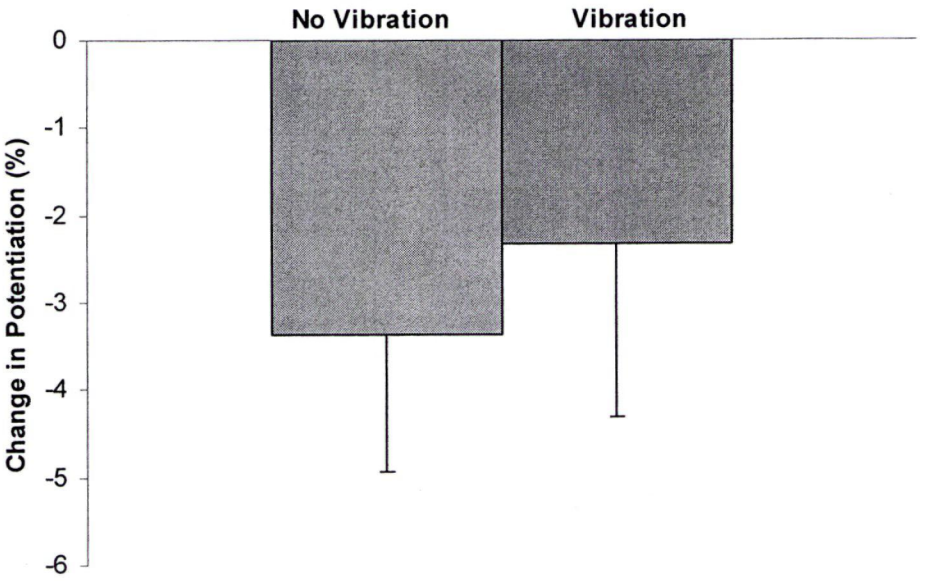


Figure 9: The effects of vibration treatment and control treatment on the change in potentiation following maximal isometric knee extension (Group 1 and 2 combined).

The mean difference (± SE) between days was 2.285 ± 4.006% for Group 1 and 4.363 ± 2.677% for Group 2 (Figure 10). There was no evidence of a treatment effect of vibration on the change in potentiation following the MVC ($p = 0.6705$).

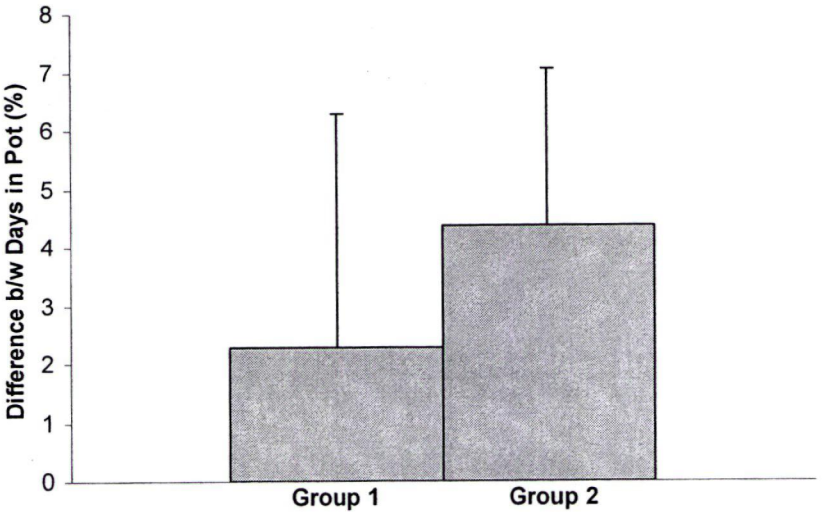


Figure 10: A comparison of the mean difference between days of the change in potentiation following maximal isometric knee extension for Group 1 and Group 2.

Change in Resting Twitch Torque following Treatment

Resting twitch torque decreased following the vibration treatment and the control treatment. The mean change (±SE) in resting twitch torque was -6.582 ± 1.284% following the control treatment and -5.475 ± 1.605% following the vibration treatment (Figure 11).

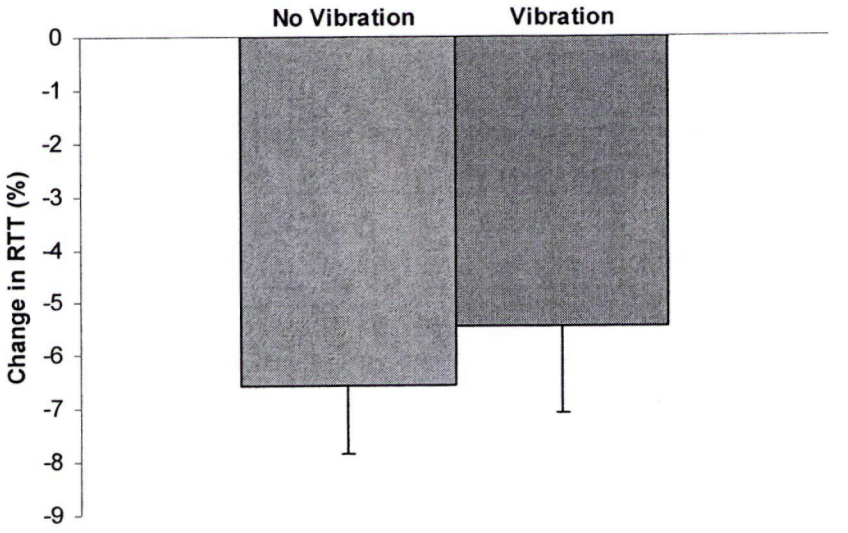


Figure 11: The effect of vibration treatment and control treatment on resting twitch torque (Group 1 and 2 combined).

The mean difference (± SE) between days was -0.8639 ± 2.640% for Group 1 and -3.077 ± 2.789% for Group 2 (Figure 12). There was no evidence of a treatment effect of vibration on resting twitch torque (p = 0.5703).

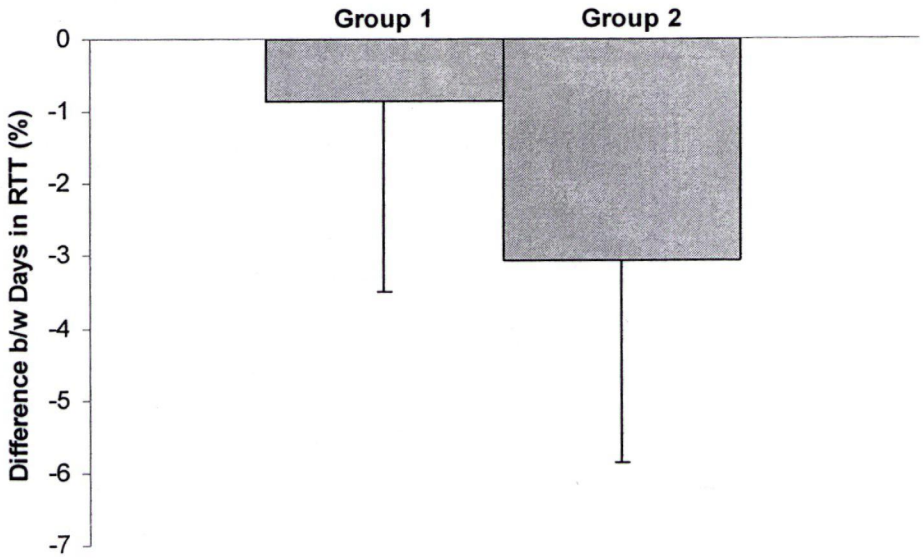


Figure 12: Comparison of mean difference between days of the effects of the treatment on resting twitch torque for Group 1 and Group 2.

Summary of Effects of Vibration on Mechanical Properties of Muscle

There was no evidence supporting the hypothesis that vibration would improve the contractile mechanisms of muscle. The lack of evidence existed for both the effects of the treatment on resting twitch torque and the potentiation following the MVC.

Effects of Vibration on Voluntary Activation of Muscle and Performance

Change in EMGrms during the MVC following Treatment

Post-treatment EMG during the MVC decreased in comparison to the baseline values following both the vibration treatment and the control treatment conditions. The mean change (± SE) in EMGrms was -0.1070 ± 0.0284 Volts following the control treatment and -0.0187 ± 0.0337 Volts following the vibration treatment (Figure 13).

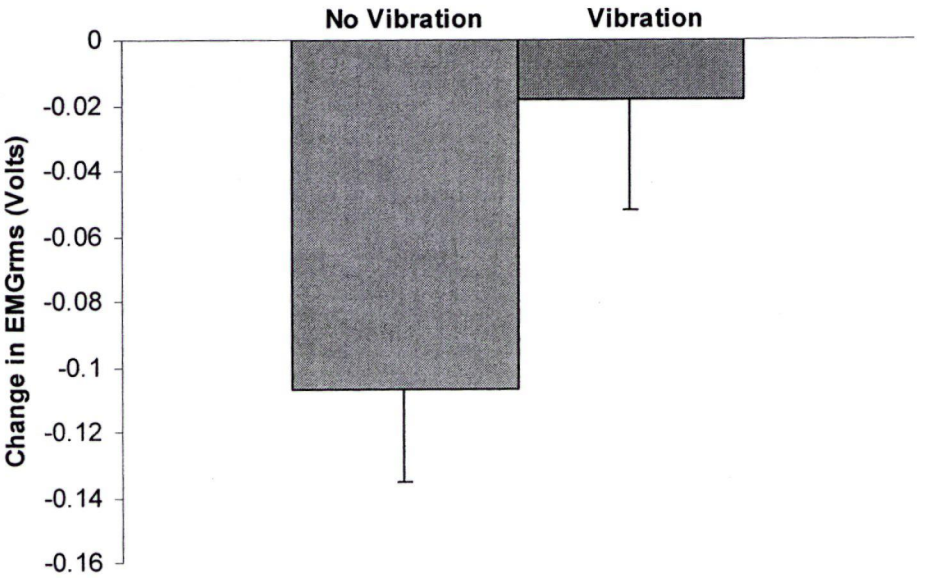


Figure 13: The effects of vibration treatment and control treatment on the change in EMGrms from the Vastus Lateralis muscle during maximal isometric knee extension (Group 1 and 2 combined).

The effect of the treatment on EMG was not analyzed statistically; it was used as a qualitative indication of muscle activation. The trend observed in the EMG data was consistent with the other findings in this experiment. That is, the decline in EMG on the vibration treatment day was smaller than the decline in EMG on the control treatment day.

Change in Muscle Inhibition following Treatment

Post-treatment muscle inhibition increased over the baseline measurement for both the vibration treatment and the control treatment conditions. The mean change (± SE) in muscle inhibition was 3.881 ± 1.345% following the control treatment and 0.056 ± 1.509% following the vibration treatment (Figure 14).

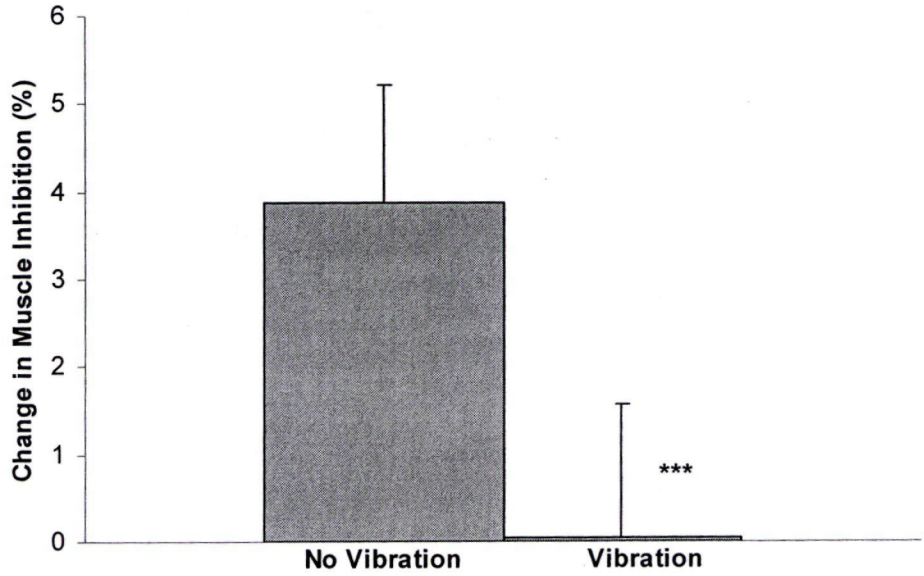


Figure 14: The effects of vibration treatment and control treatment on the change in muscle inhibition during maximal isometric knee extension (Group 1 and 2 combined). **Note:** The symbol *** indicates $p < 0.05$.

The mean difference (± SE) between days was 2.905 ± 1.424% for Group 1 and -4.743 ± 2.849% for Group 2 (Figure 15). There was evidence of a treatment effect of vibration on muscle inhibition ($p = 0.0252$).

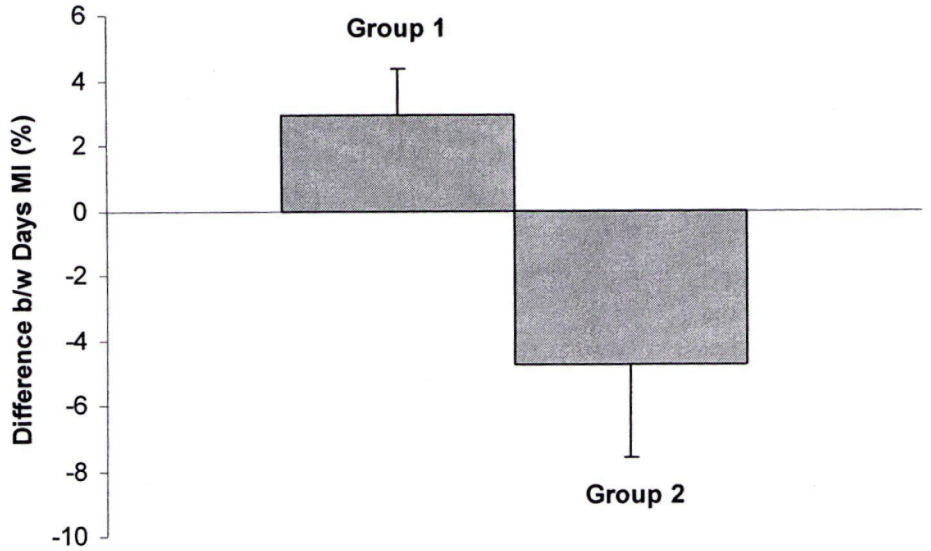


Figure 15: A comparison of the mean difference between days for the change in muscle inhibition during maximal isometric knee extension following treatment for Group 1 and Group 2.

There was no evidence of a carry-over effect ($p = 0.5717$), and no evidence of a period effect ($p = 0.5698$). The estimated treatment effect of vibration on the change in muscle inhibition during the MVC was 3.824%. That is, the vibration treatment resulted in a smaller change in muscle inhibition during the MVC in the order of 3.824%. The 95% confidence interval for the treatment effect is given by: 3.152% to 4.497%.

Change in Torque during the MVC following Treatment

Post-treatment torque during the MVC decreased compared to baseline values for both the vibration and control treatment conditions. The mean change (± SE) in torque was -19.47 ± 4.640 Nm (8.9%) following the control treatment and -4.323 ± 3.888 Nm (1.9%) following the vibration treatment (Figure 16a and 16b).

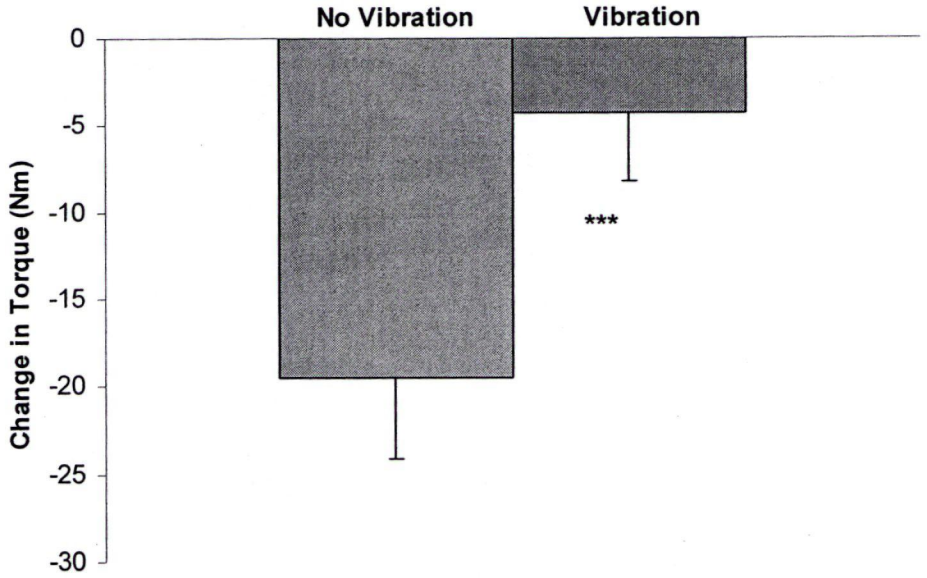


Figure 16a: The effects of vibration treatment and control treatment on the change in torque during maximal isometric knee extension (Group 1 and 2 combined). **Note:** The symbol *** indicates $p < 0.05$.

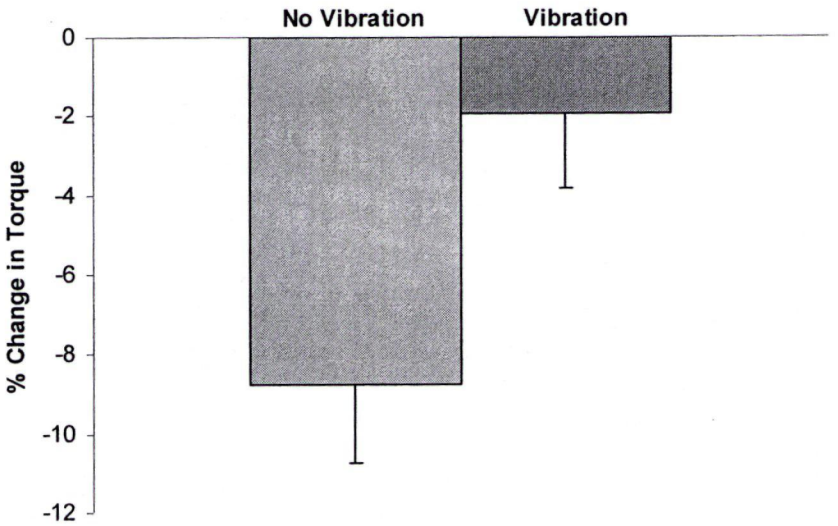


Figure 16b: The effects of vibration treatment and control treatment on the % change in torque during maximal isometric knee extension (Group 1 and 2 combined).

The mean difference (± SE) between days was -24.36 ± 8.062 Nm for Group 1 and 5.936 ± 6.951 Nm for Group 2 (Figure 17). There was evidence of a treatment effect of vibration on torque during the MVC ($p = 0.0094$).

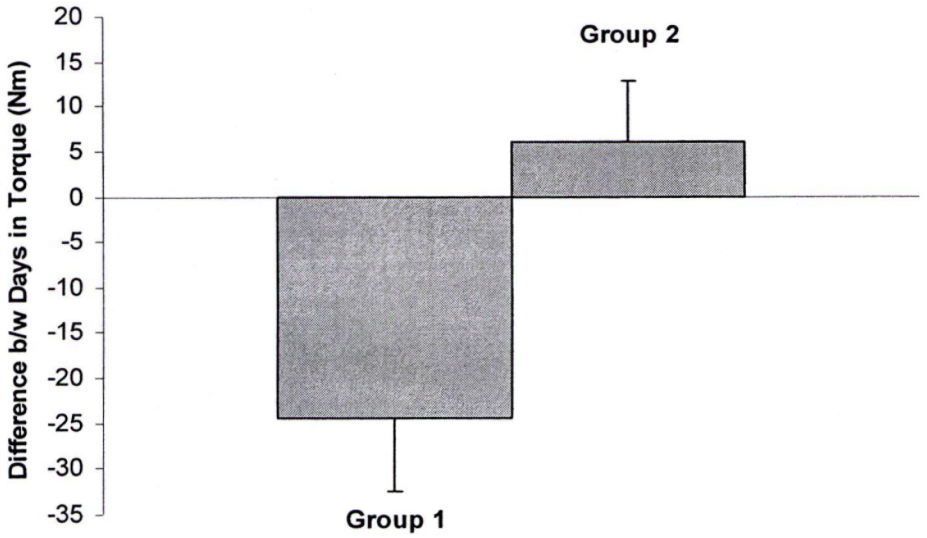


Figure 17: A comparison of the mean difference between days for the change torque during maximal isometric knee extension following treatment for Group 1 and Group 2.

There was no evidence of a carry-over effect ($p = 0.4775$), and no evidence of a period effect ($p = 0.0975$). The estimated treatment effect of vibration on the change in torque during the MVC was -15.17 Nm. That is, the vibration treatment resulted in a smaller change in torque during the MVC in the order of 15.17 Nm. The 95% confidence interval for this treatment effect is given by: -17.39 Nm to -12.90 Nm.

Summary of Effects of Vibration on Muscle Activation and Torque during MVC

There was no evidence to support an increase in activation of the quadriceps muscle and better performance during the MVC. However, the decrease in torque production and increase in muscle inhibition during the MVC over the testing session was significantly less with the vibration treatment ($p = 0.0094$, and $p = 0.0252$ respectively).

CHAPTER 5: DISCUSSION

The Effects of Vibration on Mechanical Properties of Muscle

The specific vibration exposure protocol imposed in this investigation did not enhance the mechanical contractility of the knee extensor muscles. This was evidenced by a decrease in the amount of potentiation following the MVC during isometric knee extension, and a decrease in resting twitch torque following the vibration treatment. While vibration has been shown to potentiate the stretch reflex (Archangel et al., 1971) the present finding is consistent with the lack of conclusive evidence in the scientific literature in support of a vibration induced mechanical potentiation of resting twitch torque.

However, the literature on vibration training does provide logical support for the hypothesis formulated in the present investigation that vibration might result in post-activation potentiation of the knee extensor muscles. Support for this hypothesis exists in an investigation performed by Bosco and co-authors (2000) in which an acute bout of vibration training resulted in increased jump performance but decreased EMG activity compared to baseline values. The improvement in jumping performance associated with decreased EMG activity was attributed to enhanced neuromuscular efficiency. If this finding was accurate and muscle activity had indeed declined while performance had improved, then a form of post-activation potentiation may have partially explained the improvement in performance.

The hypothesis in the present investigation postulated that a vibration induced post-activation potentiation would be similar in nature to the potentiation observed following different types of muscle conditioning activities (Sale, 2002). Some of these activities include a series of electrically induced muscle twitches, electrically induced tetanic

contractions, and maximal voluntary contractions. In these instances post-activation potentiation is attributable to mechanical changes in the muscle that result from the phosphorylation of the myosin regulatory light chains and an enhanced actin-myosin interaction (Sale, 2002).

There are two important factors that must be considered for interpreting the results of this investigation that suggested vibration treatment did not improve the mechanical properties of the knee extensor muscles. Firstly, an increase in the amount of potentiation following the MVC would have been expected if the vibration treatment had resulted in greater torque production during the MVC as a greater intensity in the conditioning activity may increase post-activation potentiation (Sale, 2002). Conversely it was found that on average, vibration treatment resulted in a 1.9% decrease in performance during knee extension compared to the baseline measurement. Furthermore, even if the vibration treatment had caused post-activation potentiation it is unlikely that this would have led to an improvement in performance during the MVC. This is primarily due to the limited influence that post-activation potentiation has on force production during maximal muscle contractions (Sale, 2002). Evidence suggests that post-activation potentiation only improves force production during low-frequency muscle contractions, and rate of force development during explosive muscle contractions (Sale, 2002).

Secondly, the amount of post-activation potentiation caused by the conditioning activity is strongly dependent on the contractile history and more specifically the strong interaction that occurs between low frequency fatigue and post-activation potentiation (MacIntosh & Rassier, 2002; Sale, 2002). An improvement in muscle function resulting from post-activation potentiation can be counteracted if the conditioning activity induces fatigue.

The balance between fatigue and post-activation potentiation is significant in interpreting the results from this investigation in which a 5.5% decline in resting twitch torque was observed following the vibration treatment, and a 6.6% decline in resting twitch torque was observed following the control treatment. The decline in resting twitch torque following both treatment conditions provides evidence that the testing procedure was sufficiently long to induce a mild low frequency fatigue in the knee extensor muscles. The relatively smaller decline in resting twitch torque following the vibration treatment though may be partially explained by a larger amount of post-activation potentiation from the exposure to vibration. Unfortunately, to confirm this possibility, resting twitch torque would have had to been monitored for several minutes following both of the treatment conditions, and this was not done in the present investigation.

The possibility of a vibration induced post-activation potentiation reinforces the importance in evaluating the exact loading parameters and vibration characteristics alongside the resulting effects on performance. Further investigation into the effects of vibration on the mechanical properties of muscle should carefully consider the duration of the vibration exposure in order to control for the effects of low frequency fatigue, and should also consider the timing and number of the measurements following the vibration treatment.

The Effects of Vibration on Neural Properties of Muscle and Performance

In this study, the vibration protocol did not increase muscle activation or improve performance during the MVC. However the vibration treatment did result in a smaller decrease in torque compared to the control treatment. This "protective effect" was evidenced by a 3.9% increase in muscle inhibition following the control treatment

compared to a 0.06% increase in muscle inhibition following the vibration treatment, and was paralleled with a decrease in performance during the MVC of 8.7% on the control treatment day and only1.9% on the vibration treatment day.

These results can be explained by one or a combination of the following factors: (1) improved motivation and psychological factors, and (2) attenuation of peripheral fatigue processes. The following section will discuss the implications associated with each of these factors.

Improved Motivation and Psychological Factors

A possible explanation of the present findings is an increase in motivation following the vibration treatment. In maximal effort activity, motivation can have a profound effect on performance (Zatsiorsky, 1995). In fact, Zatsiorsky (1995) reports that in elite weightlifters, competition maximums and training maximums can differ by as much as 12.5%. This difference is largely attributed to the heightened motivation and psychological arousal that occurs in the competition environment. In this investigation, it is possible that the testing protocol and the length of the testing session were sufficiently long to negatively affect subject motivation. As a result, the vibration treatment may have caused a placebo effect by improving subject motivation resulting in a smaller decline in performance than occurred following the control treatment.

The decline in motivation in this instance is related to fatigue of the central nervous system or central fatigue (McComas, 1996). Central fatigue encompasses the sensation of effort and motivation along with other factors related to descending motor pathways. An attenuation of central fatigue and improved motivation may partially explain the smaller decline in performance that was observed following the vibration treatment, but if this was

the only vibration induced effect, then this would provide a strong criticism of the few studies that attribute improvements in strength and explosive ability following vibration treatment to better muscle recruitment. While the present investigation does not definitively eliminate the role of enhanced muscle mechanics and neural factors following exposure to vibration the effects of the vibration treatment on motivation may have been significant, and must be considered when interpreting the results.

Attenuation of Peripheral Fatigue Processes

At the time of the post-treatment measurements, each subject in this investigation would have performed at least two 7-second maximal isometric contractions, at least 3-minutes of vibration exercise, and a minimum of 25 maximal electrical stimulations would have been administered. While this protocol was not expected to result in significant fatigue there was evidence of peripheral fatigue as resting twitch torque decreased following both the vibration and control treatment conditions. Vibration treatment resulted in a decrease in resting twitch torque of 5.5% and the control treatment resulted in a decrease in resting twitch torque of 6.6%.

An explanation of this result requires an understanding of fatigue processes in muscle. Fatigue is a complex process that is generally defined as a loss of force generating capability or an inability to sustain a specific intensity during exercise, and it can be of a central or peripheral origin (Strojnik & Komi, 1998). Peripheral fatigue can be further divided into high frequency fatigue which is associated with the impairment of action potential propagation over the muscle fibre sarcolemma or low frequency fatigue which is associated with the impairment of the steps involved in excitation-contraction coupling (MacIntosh & Rassier, 2002; Strojnik & Komi, 1998). Low frequency fatigue presents as a

depression in resting twitch force measured during electrical stimulation of a muscle, and this is most likely the type of fatigue observed in the present investigation.

The presence of low frequency fatigue following both the vibration and control treatments provides an argument in support of a vibration induced "protective effect". That is while low frequency fatigue was present following both of the treatment conditions, torque and muscle activation during the MVC declined to significantly lesser extent with the vibration treatment. The decline in performance during an isometric MVC is consistent with the evidence in the scientific literature. While several investigators have demonstrated an acute improvement in performance during dynamic and explosive lower body activity following vibration (Bosco et al., 1999b; Bosco et al., 2000), the results from other studies demonstrate a decline in performance during isometric knee extension following acute administration of vibration (Jackson et al, 2003; Kouzaki et al., 2000; de Ruiter et al, 2003; Rittweger et al., 2000). Of these investigations though, three used exhaustive or prolonged vibration protocols with exposure periods lasting up to 30 minutes (Jackson et al., 2003; Kouzaki et al., 2000; Rittweger et al., 2000). This is in contrast to the present investigation in which the total exposure to vibration was only six minutes.

The vibration protocol used in this investigation, and the resulting effect on performance during knee extension (i.e. decline of 1.9%), is comparable to the findings of de Ruiter and co-workers (2003). It was demonstrated that there was a decline in knee extensor force of 7% following five minutes of whole body vibration (frequency = 30 Hz, amplitude = 8 mm). De Ruiter and co-authors (2003) also observed a 5% decline in muscle activation.

Possible explanations for the relatively greater decline in performance and muscle activation compared to the present findings include the different methods by which muscle

activation was determined and the population on which the experiment was performed. De Ruiter et al. (2003) used the central activation ratio to evaluate muscle activation and the subjects included 12 untrained students (seven male), compared to the use of the interpolated twitch technique in this investigation and the use of well-trained male subjects, most of whom were former elite athletes. The central activation ratio has been shown to be less reliable than the interpolated twitch technique (Behm et al., 2001), and over a testing session, it is likely that the former elite athletes used in the present investigation would be able to provide more consistent and relatively greater MVC's. Finally, an investigation evaluating the effects of superimposed vibration during elbow flexion exercise provides evidence that vibration treatment elicits a comparatively greater effect on elite athletes than recreational athletes (Liebermann & Issurin, 1997).

In contrast to the present findings and the results from the investigation performed by de Ruiter et al. (2003), Torvinen and co-authors (2002) demonstrated a small, non-significant increase in performance during isometric leg press activity. Following four minutes of whole body vibration (frequency = 26 Hz, amplitude = 2 mm) Torvinen and co-authors (2002) observed a 1% increase in knee and hip extensor strength and a small decrease in EMG activity of the hip muscles. Using a cross-over design similar to the one used in this investigation, Torvinen et al. (2002) did not report a significant treatment effect of vibration on performance when compared to the control treatment. This is in contrast to the results of the present investigation indicating that muscle activation and performance declined to a lesser extent following the vibration treatment than the control treatment providing evidence of a significant treatment effect.

A possible explanation for the discrepancy in the present findings and the results of Torvinen and co-authors (2002) includes the use of a longer vibration protocol and use of a

greater number of baseline and post-treatment measurements in the present study. Also, the present investigation used a seven-second maximal isometric contraction during knee extension compared to the use of a shorter duration isometric contraction during leg press by Torvinen et al. (2002). Not only could the use of a shorter duration isometric MVC have resulted in less fatigue, but the choice to use isometric leg press over isometric knee extension would have involved more musculature of the lower body and it was also a more similar position to the one that was maintained on the vibration platform. If vibration does elicit movement specific effects then it is possible that the vibration induced effects would be more pronounced during isometric leg press rather than isometric knee extension.

Variability in Response to Vibration Training

The variability in the results between the present investigation and the investigations discussed above may be a reflection of the differences in vibration protocols. For instance, the difference between the vibration characteristics provides an example of just one of the potential factors that may affect the results of vibration training experiments. Unfortunately, the few researchers that have investigated the effects of vibration on performance have not accounted for many of these factors when interpreting their results. Two important factors that have the potential to affect the outcome of vibration training experiments include the vibration protocol and the specific movements that are tested following the vibration treatment. The following section will elaborate on these important variables and discuss how they may have affected the results in the present investigation.

Vibration Protocol

The variability in the vibration training protocols used by different investigators may be an important reason for the inconsistent results that are reported in the scientific literature. The vibration protocols can vary in the vibration characteristics (i.e. frequency and amplitude), the movement performed during the exposure to vibration, the duration of the exposure and the length of time between the cessation of the vibration treatment and the post-treatment measurements. Table 1 provides a brief summary of some of the differences in the vibration training protocols reported in the scientific literature.

Table 1: A comparison of vibration characteristics between different vibration training investigations.

Author	Frequency	Amplitude	Movement	Timing of Measurement	Loading Parameters
Bosco et al. (1999b)	26 Hz	10 mm	Isometric squat on 1 leg	Immediate	10x1min/1min rest
Bosco et al. (2000)	26 Hz	4 mm	Isometric squat	Immediate	10x1min/1min rest
Rittweger et al. (2000)	26 Hz	15 g	Exhaustive exercise with additional load and isometric squat	Immediate	Continuous to voluntary failure
Torvinen et al. (2002)	25 Hz – 40 Hz	2 mm	Multi-directional squatting movements	2 and 60 minutes after treatment	4 mins
De Ruiter et al. (2003)	30 Hz	8 mm	Isometric squat	1.5, 30, 60 and 180 minutes after treatment	5x1min/1min rest
Present Investigation	30 Hz	2 mm	Isometric squat	1 minute after treatment	2x(3x1min/1min rest)

As with all types of exercise designed to improve strength qualities, the exact loading parameters must be carefully determined, applied and then controlled in order to ensure the desired training effect. It is likely that different vibration protocols would elicit different physiological effects and as a result the exact vibration characteristics are of paramount importance when evaluating and interpreting the results of an investigation on the effects of vibration training.

Evidence in support of the need to account for inter-protocol differences in the vibration treatment can be obtained in the basic science literature on vibration. Firstly, the position of the body during the exposure to vibration and the degree of muscle contraction can affect the biological response to vibration (Griffin, 1996). Rohmert and co-authors (1989) reported different EMG responses in the shoulder muscles during exposure to vibration when the arm was placed in different positions. Also, results from an investigation performed by Martin and Park (1997) demonstrated that the reflex response to vibration increased as the degree of muscle contraction increased from 0% of MVC to 20% of MVC. Secondly, the biological response, and specifically the TVR is highly dependent on the frequency of the vibration (Griffin, 1996; Siggelkow et al., 1999). The TVR, the reflex response resulting from the stimulation of muscle spindles, has been shown to respond in a synchronous fashion with the frequency of vibration firing in a 1:1 ratio (Siggelkow et al., 1999). This response takes the form of an inverted 'U' shape indicating that there is an optimal vibration frequency to elicit the TVR (Martin & Park, 1997). The TVR tends to increase relative to the vibration frequency up to a maximum of about 100 Hz after which the TVR begins to decrease.

Thirdly, the duration of the vibration exposure can greatly affect muscle function. Evidence from an investigation on the effects of prolonged exposure to vibration suggests that during a sustained MVC of the dorsiflexors muscles, vibration counteracted fatigue in the initial phase of its application but prolonged vibration accentuated fatigue as evidenced by a large decrease in EMG activity (Bongiovanni et al., 1990). Furthermore, studies evaluating the effects of prolonged vibration (i.e. 30 minutes) on the quadriceps muscles reveal a significant decrease in force and muscle activation during an MVC (Jackson et al., 2003; Kouzaki et al., 2000).

The final parameter that varies between the different investigations is the timing of the post-treatment measurements following the vibration treatment. It is unclear whether or not the post-vibratory effects occur immediately following the vibration exposure, and if they exist, the degree to which they persist. Using the example of post-activation potentiation following a conditioning activity such as an MVC, it is clear that the decay of potentiation occurs in a logarithmic fashion and may decay to negligible amounts within minutes (Sale, 2002). Also, when considering the post-vibratory recovery of the stretch reflex and the H-reflex, it is clear that the stretch reflex will show potentiation within a few seconds while the H-reflex displays a gradual recovery over a period of approximately 100 seconds (Van Boxtel, 1986). Based on the potential for muscles responses such as post-activation potentiation to decay rapidly, and the time dependent response of the stretch reflex and the H-reflex in the post-vibratory period, the timing of the post-treatment measurements may be an important source of variation in the results between different investigations.

In summary, based on the parameters represented in Table 1, it is clear that vibration protocols used by investigators have varied according to the frequency, amplitudes, duration of exposure, the type of exercise during the exposure to vibration, and the timing of the post-treatment measurements. It is clear from the evidence provided above that all of these parameters have the capacity to greatly affect the biological response to vibration, and therefore the effects of vibration training on performance.

Movement Specific Effects of Vibration

In addition to the large potential that exists for the vibration protocol to affect the outcome of vibration training studies, it is also possible that vibration may elicit biological effects that are movement specific. While several investigations have demonstrated a post-vibratory improvement in dynamic and explosive activities (Bosco et al., 1998; Bosco et al., 1999b; Bosco et al., 2000), studies have also demonstrated a deterioration or negligible improvement in performance during isometric MVC's (de Ruiter et al. 2003; Torvinen et al., 2002; Rittweger et al., 2000).

While accurate comparisons between the results of these different investigations may be troublesome due to the large inter-protocol variability that exists in the vibration treatment, it may also be possible that the post-treatment effects of vibration treatment would augment performance only in explosive activity involving a stretch-shorten cycle and not maximal isometric activity. An investigation performed by Bosco and co-authors (1998) provides an indication of this possibility. The investigation revealed that 10 days of vibration training resulted in an improvement in jump height during 5 seconds of continuous jumping in which the subjects were asked to minimize ground contact time compared to a relatively smaller improvement in jump height during one maximal countermovement jump. In this instance, the 5 seconds of continuous jumping involved a short stretch-shorten cycle which may have been more greatly influenced by the stretch reflex and muscle stiffness. Further evidence in support of a specific post-vibratory improvement in explosive activity is obtained from the basic science literature. There is strong evidence that in the post-vibratory period there is a marked potentiation of the stretch reflex in the human plantar flexor muscles (Archangel et al., 1971; Van Boxtel, 1986).

In consideration of the evidence presented, it is possible that explosive activity involving a stretch-shorten cycle might be positively influenced to a greater degree by the potentiation of the stretch reflex than would an isometric MVC. The difficulty with this statement is ascertaining the degree to which the stretch reflex would contribute to performance during explosive activity. An investigation performed by Griffiths (1991) evaluating the effects of stretch on cat tendon and muscle reported that in response to stretch, tendon stretch exceeded muscle stretch except for situations in which high rates of stretch occurred. It was further concluded that for the muscle spindles and the stretch reflex to provide a useful signal in these situations the fusimotor system would have to be strongly activated. In consideration of the post-vibratory potentiation of the stretch reflex, it is possible that vibration treatment might increase the activation of the fusimotor system and create a physiological condition in which the stretch reflex could positively contribute to performance during explosive activity.

Conclusion and Summary

1. The specific vibration protocol used in this investigation did not enhance the mechanical properties of the knee extensor muscles during the MVC. However both the control treatment and the vibration treatment conditions did result in a decrease in resting twitch torque providing evidence of low frequency fatigue.
2. The specific vibration protocol used in this investigation did not decrease muscle inhibition or increase EMG activity in the knee extensor muscles during the MVC.
3. The specific vibration protocol used in this investigation did not increase torque production from the knee extensor muscles during the MVC.
4. This vibration protocol did result in a significantly smaller decrease in muscle activation and torque during the MVC compared to the control treatment providing and indication of a "protective effect". This "protective effect" may be due to a placebo effect resulting from improved motivation following the vibration treatment or it may be due to attenuated peripheral fatigue processes.
5. Future research must explore the effects of different vibration protocols which include careful attention to the following variables: frequency, amplitude, duration of exposure, type of exercise during the exposure, and timing of post-treatment measurements. Future research must also explore the possibility that the acute effects of vibration are movement specific. Future research should also consider the effects of vibration on the stretch reflex, muscle stiffness, and on performance during explosive activity involving the stretch reflex.
6. Finally, it is clear that vibration, if used improperly, can be very harmful to humans. The potential for harm must not be overlooked and must be considered in future

scientific research on vibration training and in its introduction into the training regime of athletes.

Recommendations for Future Research

This investigation has revealed two main focuses for future research. First, future research must be performed on the effects of different vibration protocols. A few of the parameters that must be considered include the vibration characteristics (i.e. frequency and amplitude), the duration of the exposure, the type of exercise performed during the exposure to vibration, and the time period between the cessation of the treatment and the post-treatment measurements.

Second, future research should focus on the effects of vibration on the stretch reflex, and investigations should include explosive movements involving a stretch shorten cycle. Investigations designed in this manner would be better able to evaluate whether or not the acute effects of vibration are movement specific.

REFERENCES

1. Arcangel, C. S., Johnston, R. & Bishop, B. (1971). The achilles tendon reflex and the H-response during and after tendon vibration. Physical Therapy. 51(8): 889-902.

2. Armitage, P., Berry, G. & Matthews, J.N.S. (2002). Statistical Methods in Medical Research 4th ed. London: Blackwell Science.

3. Armstrong, T. J., Fine, L.J., Radwin, R.G. & Silverstein, B.S. (1987). Ergonomics and the effects of vibration in hand-intensive work. Scandinavian Journal of Work and Environmental Health. 13: 286-289.

4. Basmajian, J.V., & Deluca, C.J. (1985). Muscles Alive: Their Function Revealed by Electromyography 5th Ed. Baltimore: Williams & Wilkins.

5. Behm, D., Power, K. & Drinkwater, E. (2001). Comparison of interpolation and central activation ratios as measures of muscle inactivation. Muscle and Nerve. 24: 925-934.

6. Bishop, B. (1974). Vibratory stimulation. Neurophysiology of motor responses evoked by vibratory stimulation. Physical Therapy. 54(12): 1273-1282.

7. Bongiovanni, L. G., & Hagbarth, K.E. (1990). Tonic vibration reflexes elicited during fatigue from maximal voluntary contractions in man. Journal of Physiology. 423: 1-14.

8. Bongiovanni, L. G., Hagbarth, K.E. & Stjernberg, L. (1990). Prolonged muscle vibration reducing motor output in maximal voluntary contractions in man. Journal of Physiology. 423: 15-26.

9. Bosco, C. (2002). Personal Communication. January 7, 2002.

10. Bosco, C., & Viitasalo, J.T. (1982). Potentiation of myoelectrical activity of human muscles in vertical jumps. Electromyography and Clinical Neurophysiology. 22: 549-562.

11. Bosco, C., Cardinale, M., Tsarplea, O. (1998). The influence of whole-body vibrations on jumping performance. Biology of Sport. 15(3): 157-164.

12. Bosco, C., Cardinale, M. & Tsarpela, O. (1999a). Influence of vibration on mechanical power and electromyogram activity in human arm flexor muscles. European Journal of Applied Physiology. 79: 306-311.

13. Bosco, C., Colli, R., Introini, E., Cardinale, M., Tsarpela, O., Madella, A., Tihanyi, J. & Viru, A. (1999b). Adaptive responses of human skeletal muscle to vibration exposure. Clinical Physiology. 19(2): 183-187.

14. Bosco, C., Iacovelli, M., Tsarpela, O., Cardinale, M., Bonifazi, M., Tihanyi, J., Viru, M., De Lorenzo, A. & Viru, A. (2000). Hormonal responses to whole-body vibration in men. European Journal of Applied Physiology. 81: 449-454.

15. Burke, D., Hagbart, K., Lofstedt, L. & Wallin, G.B. (1976a). The responses of human muscle spindle endings to vibration of non-contracting muscles. Journal of Physiology. 261: 673-693.

16. Burke, D., Hagbart, K., Lofstedt, L. & Wallin, G.B. (1976b). The responses of human muscle spindle endings to vibration during isometric contraction. Journal of Physiology. 261: 695-711.

17. Cafarelli, E. (1982). Peripheral contributions to the perception of effort. Medicine and Science in Sports and Exercise. 14(5): 382-389.

18. Cafarelli, E. (1988). Force sensation in fresh and fatigued human skeletal muscle. In K. B. Pandolf (Ed.), Exercise and Sport Sciences Reviews (Vol. 16). New York: MacMillan Publishing.

19. Claus, D., Mills, K.R. & Murray, N.M.F. (1988). The influence of vibration on the excitability of alpha motoneurons. Electroencephalography and Clinical Neurophysiology. 69: 431-436.

20. Cordo, P., Gurfinkel, V.S., Bevan, L. & Kerr, G.K. (1995). Proprioceptive consequences of tendon vibration during movement. Journal of Neurophysiology. 74(4): 1675-1688.

21. de Ruiter, C.J., van der Linden, R.M., van der Zijden, M.J.A., Hollander, A.P. & de Haan, A. (2003). Short-term effects of whole-body vibration on maximal voluntary isometric knee extensor force and rate of force rise. European Journal of Applied Physiology. 88: 472-475.

22. Desmedt, J.E., & Godaux, E. (1978). Mechanism of the vibration paradox: Excitatory and inhibitory effects of tendon vibration on single soleus muscle motor units in man. Journal of Physiology. 285: 197-207.

23. Flieger, J., Karachalios, Th., Khaldi, L., Raptou, P. & Lyritis, G. (1998). Mechanical stimulation in the form of vibration prevents postmenopausal bone loss in ovariectomized rats. Calcification Tissue International. 63: 510-514.

24. Fritz, M. (1998). Estimation of spine forces under whole-body vibration by means of a biomechanical model and transfer functions. Aviation, Space and Environmental Medicine. 68(6): 512-519.

25. Fritz, M. (2000). Description of the relation between the forces acting in the lumbar spine and whole-body vibrations by means of transfer functions. Clinical Biomechanics. 15: 234-240.

26. Futasuka, M., Pyykko, I., Farkkila, M., Korhonen, O. & Starck, J.P. (1983). Blood pressure, flow, and peripheral resistance of digital arteries in vibration syndrome. British Journal of Industrial Medicine. 40 434-441.

27. Griffin, M.J. (1996). Handbook of Human Vibration. Academic Press: London.

28. Griffiths, R.I. (1991). Shortening of muscle fibres during stretch of the active cat medial gastrocnemius muscle: the role of tendon compliance. Journal of Physiology. 436: 219-236.

29. Hagbarth, K. E., Kunesch, E.J., Nordin, M., Schmidt, R. & Wallin, E.U. (1986). Gamma loop contributing to maximal voluntary contractions in man. Journal of Physiology. 380: 575-591.

30. Hakkinen, K., Alen, M. & Komi, P.V. (1985). Changes in isometric force and relaxation time electromyographic and muscle fibre characteristics of human skeletal muscle during strength training and detraining. Acta Physiologica Scandinavica. 125: 573-585.

31. Harada, N., & Griffin, M.J. (1991). Factors influencing vibration sense thresholds used to assess occupational exposures to hand transmitted vibration. Journal of Industrial Medicine. 48: 185-192.

32. Hopkins, W. (2000). A New View of Statistics. http://www.sportsci.org/resource/stats/ancova.html

33. Issurin, V. B., Liebermann, D.G. & Tenenbaum G. (1994). Effect of vibratory stimulation training on maximal force and flexibility. Journal of Sport Sciences. 12: 561-566.

34. Issurin, V. B. & Tenebaum, G. (1999). Acute and residual effects of vibratory stimulation on explosive strength in elite and amateur athletes. Journal of Sport Sciences. 17: 177-182.

35. Jackson, S.W. & Turner, D.L. (2003). Prolonged muscle vibration reduces maximal voluntary knee extension performance in both the ipsilateral and the contralateral limb in man. European Journal of Applied Physiology. 88: 380-386.

36. Johnston, R. M., Bishop, B. & Coffey, G.H. (1970). Mechanical vibration of skeletal muscles. Physical Therapy. 50(4): 499-505.

37. Kitazaki, S., & Griffin, M.J. (1998). Resonance behaviour of the seated human body and effects of posture. Journal of Biomechanics. 31: 143-149.

38. Kouzaki, M., Shinohara, M. & Fukunaga, T. (2000). Decrease in maximal voluntary contraction by tonic vibration applied to a single synergist muscle in humans. Journal of Applied Physiology. 89(4): 1420-1424.

39. Kraemer, W. J. (1988). Endocrine responses to resistance exercise. Medicine and Science in Sports and Exercise. 20(5): S152-S157.

40. Liebermann, D. G., & Issurin, V. (1997). Effort perception during isotonic muscle contractions with superimposed mechanical vibratory stimulation. Journal of Human Movement Studies. 32: 171-186.

41. Loebel, C. C., & Kraemer, W.J. (1998). A brief review: testosterone and resistance exercise in men. Journal of Strength and Conditioning Research. 12(1): 57-63.

42. MacIntosh, B.R. & Rassier, D.E. (2002). What is fatigue? Canadian Journal of Applied Physiology. 27(1): 42-55.

43. Martin, B.J. & Park, H.S. (1997). Analysis of the tonic vibration reflex: influence of vibration variables on motor unit synchronization and fatigue. European Journal of Applied Physiology. 75: 504-511.

44. Martin, B. J., Roll, J.P. & Gauthier, G.M. (1984). Spinal reflex alterations as a function of intensity and frequency of vibration applied to the feet of seated subjects. Aviation, Space and Environmental Medicine. 55(1): 8-12.

45. Martin, B. J., Roll, J.P. & Gauthier, G.M. (1986). Inhibitory effects of combined agonist and antagonist muscle vibration on H-Reflex in man. Aviation, Space and Environmental Medicine. 57: 681-687.

46. McComas, A. J. (1996). Skeletal Muscle Form and Function. Champaign, Il: Human Kinetics.

47. McLain, R.F. & Weinstein, J.N. (1994). Effects of whole body vibration on dorsal root ganglion neurons: changes in neuronal nuclei. Spine. 19(13): 1455-1461.

48. Mester, J., Spitzenpfeil, P., Schwarzer, J. & Seifriz, F. (1999). Biological reaction to vibration- implication for sport. Journal of Science and Medicine in Sport. 2(3): 211-226.

49. Miyashita, K., Shiomi, S., Itoh, N., Kasamatsu, T. & Iwata, H. (1983). Epidemiological study of vibration syndrome in response to total hand-tool operating time. British Journal of Industrial Medicine. 40: 92-98.

50. Morin, C., Pierrot-Deseilligny, E. & Hultborn, H. (1984). Evidence for presynaptic inhibition of muscle spindle Ia afferents in man. Neuroscience Letters. 44: 137-142.

51. Necking, L. E., Lundstrom, R., Lundborg, G., Thornell, L. & Friden, J. (1996). Skeletal muscle changes after short term vibrations. Scandinavian Journal of Plastic and Reconstructive Hand Surgery. 30: 99-103.

52. Park, H.S. & Martin, B.J. (1993). Contribution of the tonic vibration reflex to muscle stress and muscle fatigue. Scandinavian Journal of Work and Environmental Health. 19: 35-42.

53. Poliquin, C. (1991). Training for improving relative strength. Sports. 11(7).

54. Ribot-Ciscar, E., Rossi-Durand, C. & Roll, J.P. (1998). Muscle spindle activity following muscle and tendon vibration in man. Neuroscience Letters. 258: 147-150.

55. Rittweger, J., Beller, G. & Felsenberg, D. (2000). Acute physiological effects of exhaustive whole-body vibration exercise in man. Clinical Physiology. 20(2): 134-142.

56. Rogers, D. K., Bendrups, A.P. & McDonald, M.L. (1985). Disturbed proprioception following a period of muscle vibrations in humans. Neuroscience Letters. 57 147-152.

57. Rohmert, W., Wos, H., Norlander, S. & Helbig, R. (1989). Effects of vibrations on arm and shoulder muscles in three body postures. European Journal of Applied Physiology. 59: 243-248.

58. Sale, D. (2002). Post-activaiton potentiation: role in human performance. Exercise and Sport Sciences Review. 30(3): 138-143.

59. Schmidtbleicher, D. (1985). Strength training part II: Structural analysis of motor strength qualities and its application to training. SPORTS. W-4.

60. Seidel, H. (1988). Myoelectric reactions to ultra-low frequency and low-frequency whole body vibration. European Journal of Applied Physiology. 57: 558-562.

61. Siggelkow, S., Kossev, A., Schubert, M., Kappels, H., Wolf, W. & Dengler, R. (1999). Modulation of motor evoked potentials by muscle vibration: the role of vibration frequency. Muscle & Nerve. 22: 1544-1548.

62. Spitzenpfeil, P., Schwarzer, J., Fiala, M. & Mester, J. (1999). Strength training with whole body vibration- single case studies and time series analysis. In Parisi, P., Pigozzi, F., Prinzi, G. (eds). Sport Science in Europe. Proceedings of the 4th Annual Conference of the European College of Sport Science. Rome, 613.

63. Strojnik, V. & Komi, P. (1998). Neuromuscular fatigue after maximal stretch-shortening cycle exercise. Journal of Applied Physiology. 84(1): 344-350.

64. Suter, E. & Herzog, W. (2001). Effect of number of stimuli and timing of twitch application on variability in interpolated twitch torque. Journal of Applied Physiology. 90: 1036-1040.

65. Torvinen, S., Sievanen, H., Jarvinen, T.A.H., Pasanen, M., Kontulainen, S. & Kannus, P. (2002). Effect of 4-min vertical whole body vibration on muscle performance and body balance: a randomized cross-over study. International Journal of Sports Medicine. 23: 374-379.

66. van Boxtell, A. (1986). Differential effects of low-frequency depression, vibration-induced inhibition, and post-tetanic potentiation of H-Reflexes and tendon jerks in the human soleus muscle. Journal of Neurophysiology. 55(3): 551-568.

67. Wasserman, D. E., Behrens, V.J., Pelmear, P.L., Ilka, R., Reynolds, D.D., Doyle, T.E., Samueloff, S. & Goff, R.J. (1991). Hand-arm vibration syndrome in a group of U.S. uranium miners exposed to hand-arm vibration. Applied Occupational Environmental Hygiene. 6(3): 183-187.

68. Young, W. (1993). Training for speed/strength: heavy vs. light loads. National Strength and Conditioning Association Journal. 15(5): 34-42.

69. Young, W. (1995). Strength qualities: What they are and what they mean to the coach. Strength and Conditioning Coach.

70. Zatsiorsky, V. (1995). Science and Practice of Strength Training. Champaigne: Human Kinetics.

APPENDIX A: STATISTICAL CALCUATIONS EFFECTS OF TREATMENT ON POTENTIATION FOLLOWING MVC

(Note: All statistical calculations performed using Intercooled Stata Version 6.0)

Mean Change in Potentiation following MVC:

Group	Obs	Mean	Std. Err.	Std. Dev.	[95% Conf.	Interval]
0	24	3.373702	1.56522	7.667983	.1357969	6.611607
1	24	2.334769	1.980561	9.70273	-1.762334	6.431872

0 = Control Treatment **1 = Vibration Treatment**

Assessment of Treatment Effects:

Group	Obs	Mean	Std. Err.	Std. Dev.	[95% Conf.	Interval]
1	12	2.284787	4.006259	13.87809	-6.53293	11.1025
2	12	4.362654	2.677412	9.274826	-1.530289	10.2556
combined	24	3.323721	2.366266	11.59229	-1.571273	8.218715
diff		-2.077866	4.818573		-12.07098	7.915243

Degrees of freedom: 22

Ho: mean(1) - mean(2) = diff = 0

Ha: diff ~= 0
t = -0.4312

P > |t| = 0.6705

APPENDIX B: STATISTICAL CALCULATIONS FOR THE EFFECTS OF TREATMENT ON RESTING TWITCH TORQUE

Mean Change in Resting Twitch Torque following Treatment:

Group	Obs	Mean	Std. Err.	Std. Dev.	[95% Conf.	Interval]
0	24	-6.581892	1.284205	6.291296	-9.238473	-3.925311
1	24	-5.475303	1.605429	7.864965	-8.796387	-2.15422

0 = Control Treatment **1 = Vibration Treatment**

Assessment of Treatment Effects:

Group	Obs	Mean	Std. Err.	Std. Dev.	[95% Conf.	Interval]
1	12	-.8638964	2.640407	9.146638	-6.675393	4.9476
2	12	-3.077074	2.789345	9.662576	-9.216382	3.062234
combined	24	-1.970485	1.892337	9.270521	-5.885083	1.944112
diff		2.213177	3.840859		-5.752276	10.17863

Degrees of freedom: 22

Ho: mean(1) - mean(2) = diff = 0

Ha: diff ~= 0
t = 0.5762

P > |t| = 0.5703

APPENDIX C: STATISTICAL CALCULATIONS FOR THE EFFECTS OF TREATMENT ON EMG

Mean Change in EMG following Treatment:

Group	Obs	Mean	Std. Err.	Std. Dev.	[95% Conf.	Interval]
0	24	.1069625	.0284532	.1393919	.0481025	.1658225
1	24	.0187083	.0336786	.1649909	-.0509612	.0883779

0 = Control Treatment **1 = Vibration Treatment**

APPENDIX D: STATISTICAL CALCULATIONS FOR THE EFFECTS OF TREATMENT ON MUSCLE INHIBITION

Mean Change in Muscle Inhibition following Treatment:

Group	Obs	Mean	Std. Err.	Std. Dev.	[95% Conf.	Interval]
0	24	-3.880709	1.345234	6.590274	-6.663537	-1.097881
1	24	-.0564367	1.508608	7.390639	-3.17723	3.064356

0 = Control Treatment **1 = Vibration Treatment**

Assessment of Treatment Effects:

Group	Obs	Mean	Std. Err.	Std. Dev.	[95% Conf.	Interval]
1	12	2.905265	1.423679	4.931769	-.228231	6.038761
2	12	-4.743279	2.849306	9.870284	-11.01456	1.528
combined	24	-.9190071	1.749842	8.57244	-4.538831	2.700817
diff		7.648545	3.185185		1.042875	14.25421

Degrees of freedom: 22

Ho: mean(1) - mean(2) = diff = 0

Ha: diff ~= 0
t = 2.4013

P > |t| = 0.0252

Assessment of Period Effects:

t(22) = -0.5770509

Pr(|T| >= .5770509) = 0.5698

Assessment of Carry-Over Effects:

Group	Obs	Mean	Std. Err.	Std. Dev.	[95% Conf.	Interval]
1	12	-5.329417	3.881517	13.44597	-13.87258	3.213743
2	12	-2.544874	2.907318	10.07125	-8.943838	3.85409
combined	24	-3.937146	2.389207	11.70468	-8.879596	1.005305
diff		-2.784543	4.849605		-12.84201	7.272923

Degrees of freedom: 22

Ho: mean(1) - mean(2) = diff = 0

Ha: diff ~= 0
t = -0.5742

P > |t| = 0.5717

APPENDIX E: STATISTICAL CALCULATIONS FOR THE EFFECTS OF TREATMENT ON TORQUE DURING MVC

Mean Change in Torque following Treatment:

Group	Obs	Mean	Std. Err.	Std. Dev.	[95% Conf.	Interval]
0	24	19.46941	4.637577	22.71939	9.875856	29.06297
1	24	4.322611	3.888091	19.04768	-3.720517	12.36574

0 = Control Treatment **1 = Vibration Treatment**

Assessment of Treatment Effects:

Group	Obs	Mean	Std. Err.	Std. Dev.	[95% Conf.	Interval]
1	12	-24.35738	8.062193	27.92826	-42.10215	-6.612613
2	12	5.936228	6.951206	24.07968	-9.363273	21.23573
combined	24	-9.210576	6.088749	29.82866	-21.80611	3.384961
diff		-30.29361	10.6451		-52.3702	-8.217015

Degrees of freedom: 22

Ho: mean(1) - mean(2) = diff = 0

Ha: diff ~= 0

t = -2.8458

P > |t| = 0.0094

Assessment of Period Effects:

t(22) = -1.730482

Pr(|T| >= 1.730482) = 0.0975

Assessment of Carry-Over Effects:

Group	Obs	Mean	Std. Err.	Std. Dev.	[95% Conf.	Interval]
1	12	28.55043	9.900258	34.2955	6.76011	50.34075
2	12	19.03362	8.685521	30.08753	-.0830817	38.15032
combined	24	23.79202	6.516321	31.92332	10.31199	37.27206
diff		9.51681	13.17017		-17.79645	36.83007

Degrees of freedom: 22

Ho: mean(1) - mean(2) = diff = 0

Ha: diff ~= 0
t = 0.7226

P > |t| = 0.4775

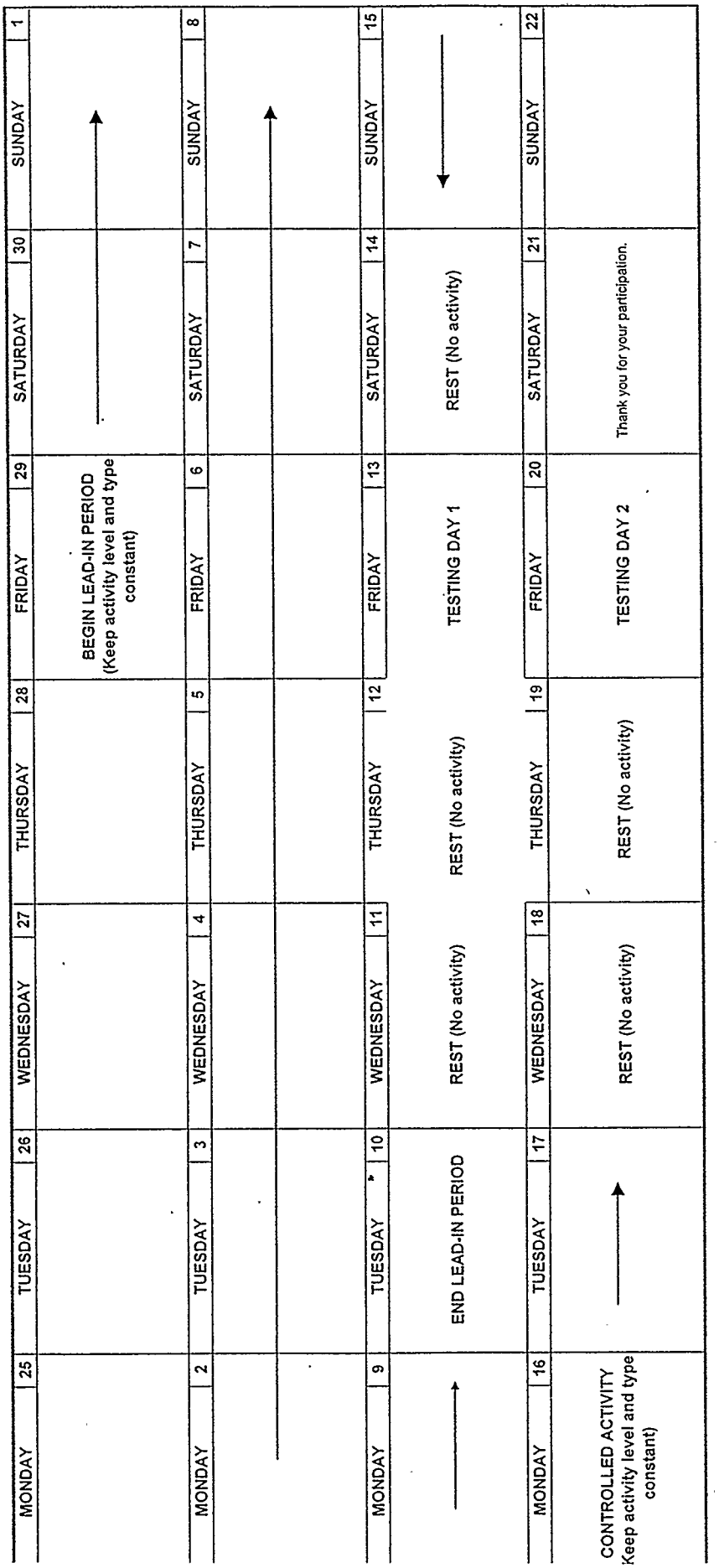
APPENDIX F: INDIVIDUAL TESTING SHEET

NAME:		EMAIL:	
SUB. ID		PHONE:	
GRP No.			
D/O/B:			
WEIGHT:			
HEIGHT:			

I/C YES NO

TESTING DAY 1					TESTING DAY 2				
EMG	VL	VM	RF	GR	EMG	VL	VM	RF	GR
AMPLIF.					AMPLIF.				
PLACEMENT					PLACEMENT				
STIM					STIM				
MAX. VOLT.					MAX. VOLT.				
TORQUE					TORQUE				
AMPLIF.					AMPLIF.				

APPENDIX G: TESTING SCHEDULE WITH RUN-IN PERIOD



APPENDIX H: INFORMED CONSENT

HUMAN PERFORMANCE LABORATORY

INFORMED CONSENT FORM

University of Calgary
Faculty of Kinesiology
Human Performance Laboratory

INFORMED CONSENT FORM

Project Title: The Effects of Whole-Body Vibration on Specific Neural and Mechanical Properties of Muscle during Maximal Isometric Knee Extension

Investigators: Stephen R. Norris, PhD. & Matthew Jordan, MSc. Candidate

This consent form, a copy of which has been given to you, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more details about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this form carefully and to understand any accompanying information.

Purpose

The purpose of this research project is to evaluate the acute effects of whole-body vibration training on neuromuscular function, specifically evoked muscle force potentiation, muscle inhibition, torque, and muscle electrical activity (EMG) during isometric knee extension with 90 degrees of knee flexion. All of these measures evaluate the function of your quadriceps muscles and the neural structures which affect quadriceps function.

A secondary purpose of this research project is to begin to understand how whole-body vibration training may be integrated into the training programs of elite athletes.

Explanation of Subject's Involvement

As a participant in this study you are required to undergo the following procedures. Please note that all procedures will be thoroughly explained to you several times before having to perform them.

The Run-In Period

Prior to the one-week testing period you will be required to participate in a run-in period lasting two weeks. The purpose of the run-in period is to ensure that your regular daily physical activity does not interfere with the testing period. During this period you will be asked to not change any loading or training parameter in your daily physical activity regime or engage in any additional strenuous or maximal activity that may compromise the results of this study. In addition you will be required to take two days of complete rest before each testing session and one rest day following the first testing session. Figure 1 below details the run-in period and testing period.

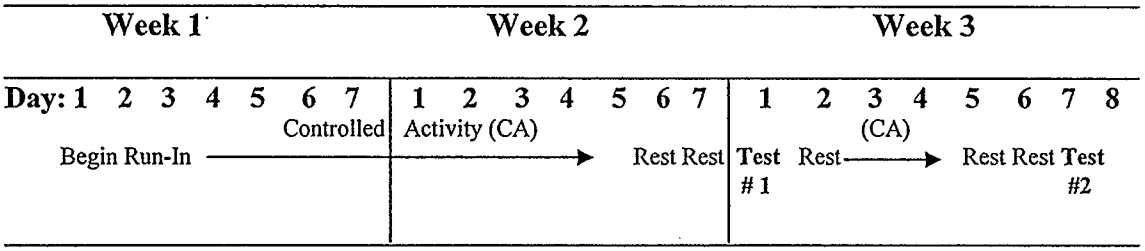


Figure 1: An overview of the three-week testing schedule.

The Testing Sessions

You will be asked to attend two testing sessions lasting approximately 90 minutes. Each testing session will be separated by 7 days.

In one of the testing sessions you will be required to stand on a vibration platform in a half-squat position with your heels slightly elevated off the platform. The vibration platform is commercially available and has been documented and used in several scientific studies published in peer reviewed journals. This vibration platform has also been used to train athletes. During this testing session you will be exposed to whole-body vibrations while maintaining the half-squat position. The platform will vibrate in the vertical direction at a frequency of 30 Hz and the displacement of the vibration is equal to 1 mm. You will maintain the half-squat position for 3 sets of 60 seconds with a 60 second rest interval between sets.

In the other session you will be required to stand on a vibration platform in a half-squat position with your heels slightly elevated off the platform. In this testing session there will be no exposure to the vibration. You will maintain the half-squat position for 3 sets of 60 seconds with a 60 second rest interval between sets.

There will be one of two orders for the treatment. You may receive the vibration treatment on the first testing day and not on the second day or you may receive the vibration treatment on the second testing day and not the first day. The given treatment will be performed a total of two times per testing session with a long rest interval separating the treatments.

In both testing sessions you will perform a series of maximum isometric knee extension tests before and after the treatments described above. The maximum isometric knee extension will be performed with 90 degrees of knee flexion and the contraction will be held for 7 seconds. You will be required to perform 2 contractions before the treatment and 2 contractions after the treatment. Each contraction will be separated by a long rest interval.

During the muscle contractions we will use the "twitch interpolation technique" which measures your ability to fully activate your quadriceps muscle. This technique requires that a series of electrical stimulations be applied to your muscle. To do this, two padded electrodes will be placed on the upper and lower part of the muscle and fixed to the skin with tape. In addition, disposable electrodes will be attached in order to measure muscle activity (EMG) and reflex response in the affected muscle groups. No penetration of the skin by needles is required. Also, force produced will be measured with a strength measuring device.

Risk and Discomforts

The risks involved are minimal. There might be some discomfort of post test joint or muscle pain of short duration. There is some potential for minor muscle strain. The electrical stimuli applied are very brief and may feel unusual and slightly uncomfortable. Voltage control during stimulation is ensured by an isolation unit approved for human use, which will shut off if the applied voltage exceeds 220 V.

The whole-body vibration training protocol being used is a protocol similar to those used in other recent whole-body vibration training studies except the total exposure time has been significantly reduced to only 3 sets of 60 seconds. The risks of whole-body vibration training are minimal. You can expect the whole-body vibration training to cause a feeling of fatigue in your thigh and calf muscles similar to the fatigue felt from riding a bicycle or performing leg weights with a low to moderate load. This fatigue may persist for up to 24 hours following the testing session. In addition the whole-body vibration training may cause a temporary and short term dilation of the blood vessels in your feet and legs giving you an itchy feeling. This effect is commonly experienced in subjects who are exposed to whole-body vibration training and does not pose a serious health concern. It is also common for subjects to feel dizzy or light headed after the first exposure to whole-body vibration training. These feelings are temporary and will subside with more treatments. Finally the strain of this type of whole-body vibration training on cardiovascular function is minimal. The changes that occur in cardiovascular function caused by whole-body vibration training are similar to those experienced during low to moderate exercise.

Research Related Injury

In the event that you suffer injury as a result of participating in this research project, no treatment or compensation will be provided for you by the University or the Researchers. You still have all your legal rights. Nothing said here about treatment or compensation in any way alters your right to recover damages.

Benefits to be Expected

This study will assist the researchers in understanding the acute effects of whole-body vibration training on muscle function. The results from this study may lead to superior training methods for the development of strength and power, and for dampening abilities especially for athletes who are exposed to a large vibration load in their sport (e.g. alpine skiing, in-line skating). Further, the results of this study will mark the beginning of extensive research into the effects of whole-body vibration training, a training modality that may be extremely beneficial in the preparation of elite athletes.

Personal Information

Information obtained during this research project is confidential. It will not be released without your written consent. The information however, may be used for statistical analysis or scientific purposes with your right to privacy retained. To prevent the invasion of privacy through a digital medium, all computerized data will be saved on a password protected hard drive. All passing of information between computers will be done only with the use of floppy disks or CD-ROM eliminating the need of a network transfer of information. The main data file will be locked in a filing cabinet. Three years following the final day of data collection all files will be destroyed. Files saved on disk will be erased and hard copy files will be shredded. Identification of subjects through publication will be prevented by the use of the Subject ID Codes.

Freedom of Consent

Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to participate as a subject. In no ways does this waive your legal right nor release the investigator, sponsors or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation. If you have further questions concerning matters related to this research, please contact:

Matthew Jordan (Ph. 220-2157) or Dr. Stephen Norris (Ph. 220-7005)

If you have any questions concerning your rights as a possible participant in this research, please contact the Office of Medical Bioethics, Faculty of Medicine, University of Calgary, at 220-7990.

_____ _____

Participant Date

_____ _____

Investigator Date

_____ _____

Witness Date

A copy of this consent form has been given to you to keep for your records and reference.

UNIVERSITY OF CALGARY

FACULTY OF MEDICINE

Office of Medical Bioethics
Heritage Medical Research Building/Rm 93
Telephone: (403) 220-7990
Fax: (403) 283-8524

2002-06-06

Dr. S.R. Norris
Faculty of Kinesiology
University of Calgary
KN B 211
Calgary, Alberta

Dear Dr. Norris:

RE: The Effects of Whole-Body Vibration on Specific Neural and Mechanical Properties of Muscle During Maximal Isometric Knee Extension
Student: Mr. Matthew Jordan **Degree: MSc**

Grant-ID: 16527

The above-noted thesis proposal and the consent form have been submitted for Committee review and found to be ethically acceptable. Please note that this approval is subject to the following conditions:

(1) a copy of the informed consent form must have been given to each research subject, if required for this study;
(2) a Progress Report must be submitted by 2003-06-06, containing the following information:
  (i) the number of subjects recruited;
  (ii) a description of any protocol modification;
  (iii) any unusual and/or severe complications, adverse events or unanticipated problems involving risks to subjects or others, withdrawal of subjects from the research, or complaints about the research;
  (iv) a summary of any recent literature, finding, or other relevant information, especially information about risks associated with the research;
  (v) a copy of the current informed consent form;
  (vi) the expected date of termination of this project;
(3) a Final Report must be submitted at the termination of the project.

Please note that you have been named as a principal collaborator on this study because students are not permitted to serve as principal investigators. Please accept the Board's best wishes for success in your research.

Yours sincerely,

Christopher J. Doig, MD, MSc, FRCPC
Chair, Conjoint Health Research Ethics Board

c.c. Dr. W. Herzog (information)
Mr. Matthew Jordan