# The Effects of Whole Body Vibration on Peripheral Cardiovascular Function

**By:**

**Mahmoud S. M. A. Gholoum**

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**Heriot Watt University**

**School of life Sciences**

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# Abstract

Exposure to acute bouts of whole body vibration (WBV), which can be employed as a novel form of exercise, has been reported to increase local skeletal muscle blood flow. However, the mechanism for this effect remains unclear. Therefore, this research aimed to explore the mechanism that would explain the effect of vibration on the peripheral cardiovascular function.

Initially, the aim was to investigate the potential mechanism of the effect of WBV on the systemic blood flow, since there are currently no studies reporting any systemic effects of WBV on blood flow. The results did not demonstrate any systemic effects on blood flow (i.e. forearm blood flow) in response to acute unloaded and loaded squats with WBV. It was concluded that it was difficult to identify the effects of vibration on systemic cardiovascular function because, most likely due to the higher exercise intensity, skeletal muscle activation resulted in a decrement in blood flow from a distal site (i.e. forearm) to the main site (i.e. lower limb).

Through the development of experimental methods involving applying vibration passively to the lower limbs, which avoids any influence of direct skeletal muscle activation and focuses solely on the mechanism inducing effects, it was demonstrated that ankle systolic blood pressure and ankle brachial pressure index substantially decreased in the post-vibration period. It was concluded that vibration has a direct effect on the peripheral cardiovascular function via increased vasodilatation; however, the mechanism underlying this effect remained unresolved.

The effects of different durations of passive vibration on the peripheral circulation were also investigated and the results demonstrated that a longer duration of passive vibration (i.e. 8 minutes) resulted in a significantly higher lower leg blood flow during the recovery period than a shorter duration (i.e. 1, 2 and 4 minutes) of passive vibration. These data provide evidence for a greater effect of WBV occurring with a longer duration on the peripheral cardiovascular function, caused by the vasodilatation response throughout the recovery period. However, there might be a minimum effect of skeletal muscle activation occurring with a longer duration of passive vibration that leads to a direct response to localised heating.

Furthermore, the thesis attempted to distinguish the effects of passive vibration on skeletal muscle activation from those on the peripheral vascular system. An experiment was designed in which passive vibration was applied with and without circulatory occlusion, to examine whether there was any underlying skeletal muscle activation. It was found that vibration with intact circulation produces more heat than the control, no vibration and occlusion, and occlusion plus vibration conditions. These effects were reflected by the higher skin temperature observed during exposure to vibration, and continuing into recovery. These data provide evidence that passive vibration does not appear to induce an increase in muscle activity. The data also suggest that the mechanism of the rise in skin temperature in response to passive vibration exposure is due to a vasodilatation that occurred in the lower limb via inducing an increase in shear stress at the blood vessels wall and led to an increase in circulating blood flow during exposure that continues into recovery.

Overall, the results obtained demonstrate that vasodilatation occurs during and after vibration exposure and appears to be a process that is independent of skeletal muscle activation. It is postulated that the stimulus is a direct effect on the blood vessels via inducing an increase in shear stress that results in an increased vasodilatation, thereby increasing blood flow. Hence, these observations demonstrate that vibration stimulus has a direct effect on the muscle vascular bed as a primary effect and that there is no carry over effect into the systemic circulation. Thus, the results of this thesis indicate that vibration induced enhancement in the peripheral circulation could be using as a training stimulus and also could have a beneficial effect in assisting recovery routines from exertion.

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# Glossary of Abbreviations

| | |
|---|---|
| ABPI | Ankle Brachial Pressure Index |
| ANOVA | Analysis of Variance |
| ASBP | Ankle Systolic Blood Pressure |
| AVC | Arm Vascular Conductance |
| BM | Body Mass |
| BP | Blood Pressure |
| bpm | Beats Per Minute |
| BS | British Standards |
| BSBP | Brachial Systolic Blood Pressure |
| cm | Centimetres |
| EMG | Electromyography |
| FBF | Forearm Blood Flow |
| g | Gravity |
| HR | Heart Rate |
| Hz | Hertz |
| ISO | International Standard Organization |
| Kg | Kilograms |
| $LBSk_{temp}$ | Leg Bone Skin Temperature |
| LLBF | Lower Leg Blood Flow |
| LLVC | Lower Leg Vascular Conductance |
| $LMSk_{temp}$ | Leg Muscle Skin Temperature |
| L-NMMA | L-$N^G$-Monomethyl Arginine |
| m | Metres |
| MAP | Mean Arterial Blood Pressure |

| | |
|---|---|
| min | Minutes |
| mm | Millimetres |
| mmHg | Millimetres of Mercury |
| RMS | Root Mean Square |
| s | Seconds |
| SD | Standard Deviation |
| SEM | Standard Error of the Mean |
| WBV | Whole Body Vibration |
| ° | Degree |
| °C | Degree Celsius |
| > | Greater-Than |
| < | Less-Than |
| % | Percent |

# Publications

**1.** Gholoum, M., Thin, A. G., Mitchell, A., Gilbertson, C. & Ball, D. 2012. Potential Systemic Shear-Stress Inducing Effect of Whole Body Vibration. *7th Annual Postgraduate Conference 2012, Heriot-Watt University,* 6th June 2012, Edinburgh, UK. – Poster Presentation.

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# Chapter 1 - Introduction

## 1.1. Introduction

There is growing interest in the use of whole body vibration (WBV) for physical training (Delecluse et al., 2005, Cochrane and Stannard, 2005) and rehabilitation medicine (Ebersbach et al., 2008, Bautmans et al., 2005). WBV is a novel form of exercise which involves standing on a vibrating platform and is reported to have potential effects on several physiological systems, namely modulating skeletal, muscular, endocrine, nervous and vascular systems (Prisby et al., 2008). Recently, WBV has become more available and widely used in gyms and medical centres.

Workers subject to occupational vibration, who work in industries such as mining and construction, forestry and agriculture, and public utilities, who are exposed to prolonged periods of high frequency vibration exceeding 70 hertz (Hz) e.g. with handheld power tools, are reported to be prone to potential injuries (Bovenzi, 2005, Merriman and Jackson, 2009, Brooke-Wavell and Mansfield, 2009, Totosy de Zepetnek et al., 2009b, Wilcock et al., 2009, Jordan et al., 2005, Cochrane, 2011, Dolny and Reyes, 2008). However, exposure of the body to lower frequencies of vibration, below 60 Hz, for short periods of time of less than 10 minutes, may have potentially beneficial effects on the force and power production of the human musculoskeletal system (Bosco et al., 2000, Torvinen et al., 2002b, Cardinale and Bosco, 2003, Rittweger, 2010). Moreover, several studies have demonstrated improvements in neuromuscular performance and mechanical strength following WBV training (Delecluse et al., 2003, Fagnani et al., 2006, Roelants et al., 2006) and there is also some evidence to suggest it could be useful in the treatment and prevention of age related loss of muscle and bone mass (Blottner et al., 2006, Verschueren et al., 2004). These beneficial effects have led the scientific community to be interested in vibration as an exercise modality (Bosco et al., 1999a, Bosco et al., 1999b, Bosco et al., 2000, Cochrane et al., 2004, Cochrane and Stannard, 2005, Cormie et al., 2006, Necking et al., 1996, Rittweger et al., 2000, Kerschan-Schindl et al., 2001, Torvinen et al., 2002a, Torvinen et al., 2002b). However, the notion that vibration exercise could have beneficial effects on the human body is relatively new and needs further in-depth investigation.

A vibration device is a mechanical stimulus characterised by an oscillatory motion. These oscillating vibrations can induce physiological responses through stimulating short fast changes in the length of muscle and tendon, which is called a tonic vibration reflex (Cardinale and Bosco, 2003, Jordan et al., 2005). Through repeating this cycle of

the tonic vibration reflex, the muscle stiffens in an attempt to dampen out the effect of vibration, thereby enhancing skeletal muscle activity. Vibration machines produce an unusual and unfamiliar sensation to the entire body, but most people enjoy a session of vibration. This sensation is most likely due to spinal reflexes and muscle activation via the tonic vibration reflex.

Furthermore, the process of dampening out the effects of these vibrations within the muscle results in a transformation of mechanical energy into heat. This indeed was the case in several studies, with a reported increase in skin and muscle temperatures observed after acute vibration exposure (Cochrane et al., 2008, Hazell et al., 2008, Cochrane et al., 2010, Lohman et al., 2012).

In recent years it has been suggested that exercise using WBV can be attractive as an alternative exercise modality for improving skeletal muscle activity and subsequently enhancing muscle performance (Bosco et al., 2000, Torvinen et al., 2002b, Cardinale and Bosco, 2003). The mechanism is thought to involve neurogenic potentiation, involving spinal reflexes and muscle activation through the tonic vibration reflex. It is suggested that WBV can be an effective complement to traditional exercise forms for healthy, athletes, the aged and health compromised individuals (Cochrane, 2011).

It is well known that skeletal muscle blood flow increases significantly during activation of muscle (Green et al., 2002). Data from electromyography (EMG) measurements support the notion that vibration exposure increases skeletal muscle activity (Cardinale and Lim, 2003, Abercromby et al., 2007a, Hazell et al., 2007). Therefore, it is postulated that, if vibration exposure increases skeletal muscle activity, this should increase blood flow to the activated muscle bed. Furthermore, it has been demonstrated that if exercise involves a substantially large muscle group and is at a sufficiently high intensity, it would be expected to have an effect on the whole cardiovascular system (Green et al., 2002).

Indeed, previous studies have reported a measurable cardiovascular response (skeletal muscle blood flow), when subjects are exposed to WBV (Hazell et al., 2008, Lythgo et al., 2009, Kerschan-Schindl et al., 2001, Stewart et al., 2005, Herrero et al., 2011b, Herrero et al., 2011a); however, there are little, if any, data indicating the potential enhancement effects of WBV on the peripheral cardiovascular function. Hence the mechanism of the effect of WBV on the peripheral circulation is not very well

understood. These days, vibration exercise is widely used for exercising and physical therapy, but it appears that this new model of exercise is still largely unexplored by the scientific community to understand the in-depth the effects of vibration on the peripheral blood flow, which is the aim of this current thesis.

In studying the use of WBV, there is interest in detecting the potential vasodilatory effects of vibration, which enhance the peripheral blood flow and thus may be helpful in enhancing recovery from exertion and also to have potential as a novel training stimulus. Therefore, using vibration is of interest for its potential mechanism that enhances skeletal muscle blood flow. Since there is currently no study identifying the mechanism of the effect of WBV on the peripheral cardiovascular function, it would be beneficial to investigate this area to obtain a greater degree of understanding.

## 1.2. Definition of Vibration

Vibration is defined as a mechanical wave characterised by oscillatory motion that can cause a transfer of energy from one object to another. Human vibration has been studied extensively in relation to many aspects, such as physics, mathematics, engineering, medicine, physiology, statistics, psychology, and ergonomics (Li et al., 2005, Hayne, 1981, Bogadi-Sare, 1993, Cimino, 1999, Cooperrider, 2013, Fuermaier et al., 2014, Guasch and Cortés, 2009, Johanning, 1997, Krinidis and Chatzis, 2008, Maikala and Bhambhani, 2008, Schenk, 1995, Tustin and Jariwala, 2005, Zingoni, 2014). The human environment can transmit vibration to the whole body or through the hand to the body from different instances, such as industrial equipment (e.g. forklifts, cranes), buildings, aircraft, motorised vehicles (e.g. motor cycles, trucks, cars), and marine ships (e.g. submarines and boats). Exposure to vibration from these instances can cause a considerable variety of sensations, due to the different characteristics of their vibration.

Furthermore, there are different types of waveforms of oscillatory motion e.g. sinusoidal, multi-sinusoidal, transient, shock, stationary random and non-stationary random (Griffin, 1996). Therefore, the waveform may be presented in a random or deterministic form. Typically, the vibration humans are exposed to in most sports is a random waveform, for instance, the vibration felt by a skier during a downhill. In contrast, the vibration produced by the WBV platform that is transmitted to the human body is a pre-determined waveform (Jordan et al., 2005). This form of vibration device can produce oscillations and repeat them at an identical time interval. The vibration stimulus wave can be varied according to frequency and amplitude.

### *1.2.1. Mechanical Forces of Vibration*

Vibration indicates an oscillatory motion displacement with an alternating change in velocity (i.e. frequency) and displacement (i.e. amplitude). The frequency is the repetition rate of the oscillation cycles per second and measured in Hz. The amplitude is the vertical displacement of the oscillatory motion and measured in millimetres (mm). Changes in vibration frequency or amplitude will define the changes in acceleration (i.e. gravitational force) transmitted to the body. The acceleration is the maximum speed of the oscillatory motion and measured in metre per second squared ($m \cdot s^{-2}$) or gravity (g). Furthermore, when both frequency and amplitude are set at the maximum, the greatest acceleration will occur. The factors of frequency, amplitude (displacement) and duration

of exposure can play a role in the intensity of vibration exposure and directly influence the entire body.

The vibration exposure level can be quantified in several ways, such as peak-to-peak, peak, average and root mean square (RMS). The peak-to-peak value is the difference between the maximum positive and the maximum negative amplitudes of a waveform. The peak value is the maximum value attained either as a positive or negative wave that occurring on a waveform. The average value is the sum of the waves divided by number of waves. The RMS value of a set of values is the square root of the average value of the squares of the original values of the quantity, taken over the continuous waveform. The RMS acceleration is the variable most commonly used in engineering to express vibration. However, most studies in physiology and biomechanics express vibration exposure as the displacement and frequency or gravitational acceleration.

The peak acceleration transmitted to the human body during exposure to vibration, can be determined using the equation

$$a_{Peak} = \omega^2 A$$

(Rittweger, 2010, Cochrane, 2011)

where $a_{Peak}$is peak acceleration ($m \cdot s^{-2}$), $\omega$ is angular frequency (Hz) and $A$ is peak-to-peak amplitude (mm). The angular frequency can be calculated with the formula

$$\omega = (2\pi f),$$

(Rittweger, 2010, Cochrane, 2011)

where $\omega$ is angular frequency (Hz), $\pi$ is pi = 3.14159 and $f$ is frequency (Hz). The RMS acceleration is the most relevant mathematical method of determining the vibration level. The equation of RMS acceleration which can be used to define the vibration level is

$$a_{RMS} = \frac{a_{Peak}}{\sqrt{2}}$$

(Rittweger, 2010)

where $a_{RMS}$ is RMS acceleration (m·s⁻²) and $a_{Peak}$ is peak acceleration (m·s⁻²). The RMS acceleration can also be calculated by another equation

$$a = \frac{d(2\pi f)^2}{2g\sqrt{2}}$$

(Wilcock et al., 2009)

where $a$ is acceleration (g), $d$ is maximal peak-to-peak displacement (m), $\pi$ is pi = 3.14159, $f$ is frequency (Hz), and $g$ is gravity (9.81 m·s⁻²). The result from these RMS acceleration equations are a metric measure relative to the Earth's gravitational field (g force), where 1 g is the acceleration due to the Earth's gravitational field or 9.81 m·s⁻². The calculation of RMS acceleration is very important to be used for establishing the safety limits of vibration, which are defined by International Standard Organization (ISO 2631-1) and British Standards (BS 6841) as discussed below.

## 1.3. Natural Stimulation on the Body

During daily activity and all sporting activities the human body reacts with and to the external environment and experiences externally applied forces such as an absorption of the shock via the foot pronation and flexion of the knee when the heel hits the ground during running or walking. These forces can also generate vibrations and oscillations within the tissues of the body (Cardinale and Wakeling, 2005). For example, the effect of sporting activities such as hitting a ball with a stick or racket can induce vibration.

The impact of vibration on the tissues of the human body varies depending on a variety of types of activities (Cardinale and Wakeling, 2005). Activities such as riding a bike during a downhill can generate vibrations on the arms, whereas a skiing activity during a downhill run can produce vibrations on the skier's body. It has been demonstrated that the oscillations within the tissues of the human body are minimised or removed via the dampening of vibrations by a maximally activated muscle (Wakeling et al., 2002). These tissues can dampen vibrations and oscillations via tissue stiffness, which causes an increase in muscle stiffness and mass (Boyer and Nigg, 2007). Furthermore, the skeletal muscles for each cross bridge between the actin and myosin myofilaments generates some stiffness, where the tissue stiffness can be increased with increases in skeletal muscle activity (Cardinale and Bosco, 2003).

It has been suggested that in order to tolerate more vibration energy within the human body, an increased activity of skeletal muscle can occur via dampening of an external vibration by skeletal muscle (Ettema and Huijing, 1994). Moreover, a study conducted by Dye (1996) demonstrated that the human body requires a period of time to adapt to a load and thus, maybe, to vibration. Overall, it is clear that there are beneficial effects from natural vibration on the tissues of the human body and therefore this beneficial effect might also occur with exposure to WBV, if it is used as an exercise modality.

### *1.3.1. Risks of High Frequency Vibration > 70 Hz*

Since the modern industrial revolution, workers in many occupations are now subjected to different types of oscillatory motions (i.e. vibration) that did not exist in the past. This vibration can be transmitted to the workers via hand-held power tools, hand-transmitted vibration and seats of various transportation vehicles (e.g. trains, buses, tractors, cars, trucks, heavy machinery, forklifts, aircraft or helicopters).

It should be borne in mind that being exposed to vibration improperly and indiscriminately carries the risk of harmful effects on the human body (Merriman and Jackson, 2009). Most studies have observed that workers experiencing occupational vibration, who are exposed to large vibration loads or have chronic vibration exposure from different types of machinery, are likely to experience negative effects on their health (Bovenzi, 2005, Merriman and Jackson, 2009, Brooke-Wavell and Mansfield, 2009, Totosy de Zepetnek et al., 2009b, Wilcock et al., 2009, Jordan et al., 2005, Cochrane, 2011, Dolny and Reyes, 2008).

These negative effects have an impact on musculoskeletal, peripheral, and central neurological, digestive, reproductive, visual, and vestibular system function, and cause vascular disorders (white finger disease) (Bovenzi, 2005, Merriman and Jackson, 2009, Brooke-Wavell and Mansfield, 2009, Totosy de Zepetnek et al., 2009b, Wilcock et al., 2009, Jordan et al., 2005, Pelmear, 1974, Brubaker et al., 1983, Dowd et al., 1998, Goldsmith et al., 1994, Griffin et al., 2003). Other diseases and disorders associated with exposure to vibration include osteoarthritis, spinal vertebrae degeneration, intervertebral disc displacement, visual impairment, vestibular damage, and hearing loss (Bovenzi, 2005, Merriman and Jackson, 2009, Brooke-Wavell and Mansfield, 2009, Totosy de Zepetnek et al., 2009b, Wilcock et al., 2009, Jordan et al., 2005). The negative effects on workers exposed to occupational vibration are due to high

transmission of vibrations to the soft tissue organs within the chest, the neck and the head.

Frequencies exceeding 70 Hz can cause muscle damage (Totosy de Zepetnek et al., 2009). Necking et al. (1996) confirmed in an experimental study that high vibration held at a constant frequency of 80 Hz and a constant acceleration of 32 $m \cdot s^{-2}$ for five hours daily during two days led to different degrees of degeneration of muscle fibres in some muscles. It was postulated that changes in the size of muscle fibres were the first indication of vibration-induced muscle injury, which may develop into chronic impairment of muscle function if the exposure continues for an extended period of time. However, the exposure to vibration in rehabilitative medicine and exercise is typically much lower in frequency (< 60 Hz), amplitude (< 12 mm) and duration (< 30 minutes) than in many occupational jobs and it has been shown to have positive effects on human health (e.g. improving skeletal muscle, bone density, blood circulation and flexibility).

## 1.4. Whole Body Vibration

WBV is a mechanical stimulus characterised by periodic oscillations transferred from the vibratory platform to the human body. Over the past decade, WBV exercise has been focus for researchers as a novel form of exercise that has beneficial effects on some physical performance. WBV can be used at single bout as an acute application or as multiple bouts, which are undertaken as training over a number of sessions over a number of weeks. It has been observed that exposure to WBV, in either acute form (Abercromby et al., 2007a, Cochrane and Stannard, 2005, Cormie et al., 2006, Erskine et al., 2007, Issurin and Tenenbaum, 1999, Rittweger et al., 2000, Abercromby et al., 2007b, Torvinen et al., 2002c, Torvinen et al., 2002b), or as training (Abercromby et al., 2007b, Cochrane et al., 2004, de Ruiter et al., 2003a, de Ruiter et al., 2003b, Delecluse et al., 2005, Issurin et al., 1994, Kvorning et al., 2006, Mahieu et al., 2006, Roelants et al., 2004a, Roelants et al., 2004b, Torvinen et al., 2002b, Verschueren et al., 2004) has an effect on the human body.

### *1.4.1. Types of WBV Equipment*

Vibration devices, known as WBV, are mostly used to transmit vibration to the whole body while the subject is standing on an oscillating platform. Currently, there are two different commercial systems of vibration platform devices available on the market for

exercise and physical therapy. One of the platforms operates in a side alternating way (i.e. left and right side), so that the right foot is highest when the left foot is lowest (e.g. Galileo ®). The other platform moves up and down in a vertical displacement, so that both feet are moved simultaneously and synchronously (e.g. Nemes ®, Power Plate ®, Fitvibe ®, Vibra Pro ®, VibroGym ®, Soloflex ®, PneuVibe ®, Juvent 1000N ®).

Rittweger et al. (2001) suggest that alternation of the feet during side alternating vibration causes rotational movement of the pelvis and flexion of the vertebral column, and therefore reduces the transmission of vibration mechanical energy to the head. A study done by Abercromby et al. (2007a) compared two different types of vibration platform regarding the neuromuscular activation response during acute exposure to WBV (frequency of 30 Hz and 4 mm peak-to-peak amplitude). They found that the activation of lower limb extensors (vastus lateralis and gastrocnemius) were significantly greater during side alternating than during vertical displacement; however, the tibialis anterior was activated to a significantly greater degree during vertical displacement than during side alternating vibration. Furthermore, side alternating vibration resulted in a greater activation in lower limb muscles during static (knee flexion at 18.5 °) and dynamic squatting (knee flexion from 10 ° to 35 °, at a tempo of 4 s up and 4 s down), when compared to vertical displacement. Another study performed by the same authors (Abercromby et al., 2007b) reported that acute exposure to WBV (30 Hz frequency and peak-to-peak amplitude of 4 mm) with different knee flexion angles (10 ° to 35 °) transmitted a greater vibration to the upper body and head, by 71 % to 189 %, during vertical displacement than during side alternating vibration. They concluded that the pelvis dampens the vibration energy more during side alternating vibration than the during the vertical displacement, as hypothesised by Rittweger et al. (2001). Overall, it seems that the discussion is currently equivocal on which type of vibration platform is superior and therefore it is still unknown which platform is the best to be used, which warrants further investigation.

### *1.4.2. Safety Issues of WBV*

It has already been expounded that occupational vibration can be harmful to the health of workers who are continually exposed to vibration from different types of machines. However, most vibration exercise studies, which are conducted both acutely and intermittently, did not show any incidences of severe side effects, although a few studies have reported minor side effects (Crewther et al., 2004, Cronin et al., 2004).

Crewther et al. (2004) reported that 17 untrained adult subjects suffered from some type of side effect, such as hot feet, itching of the lower limbs, severe head motion (i.e. excessive shaking), nausea, cramp, calf pain, lower back discomfort and severe discomfort in the hip region. The subjects were exposed to acute WBV at varying frequencies (10, 20, 30 Hz) and amplitudes (1.25, 3, 5.25 mm) with vertical displacement (range acceleration equal to 0.3-9.5 g) with static squatting exercises (standing double leg, standing single leg, a semi-squat). These side effects generally occurred at the highest frequency (30 Hz). They proposed that these side effects may be compounded by the fact that the heels were required to be in contact with the vibration surface. Moreover, Cronin et al. (2004) observed that a number of untrained adult subjects experienced pain of the jaw, neck and lower limbs (tibialis posterior) following a 5 minutes of acute exposure to WBV (frequency of 26 Hz and amplitude of 6 mm with vertical displacement; acceleration of 15 g), with standing only one foot and a slightly flexed knee on the platform. The pain subsided after 7 to 10 days of physiotherapy treatment. Both Crewther et al. (2004) and Cronin et al. (2004) concluded that the high frequency, high amplitude and hence high acceleration forces associated with the vibration treatment produced a training stimulus that was too intense for the relatively untrained subjects.

A possible explanation consistent with these findings of the side effects is that the participants in both studies may not have been familiarised with vibration sensation, because these researchers did not mention it in their studies. Another possible explanation is that both studies exposed their subjects to high acceleration loads and the subjects stood on one leg at a slight flexed knee and therefore this small knee angle may have reduced the ability to dampen the vibration, leading to an increase in the transmission of vibration to the upper body (e.g. hip, head). Furthermore, recent studies have demonstrated that a smaller angle of the knee produces greater transmission of vibration to the head (Abercromby et al., 2007a, Pel et al., 2009, Abercromby et al., 2007b, Mester et al., 2006, Dolny and Reyes, 2008).

On the other hand, the most common side effects of WBV exercise appear to be transient itching, erythema of the lower limbs, a hot sensation of the legs, oedema of the legs, and muscle soreness (Rittweger et al., 2000, Kemertzis et al., 2008, Russo et al., 2003, Roelants et al., 2004b, Hazell et al., 2008, Broadbent et al., 2010, Cheung et al., 2007, Kerschan-Schindl et al., 2001, Cronin et al., 2004). These symptoms were

observed on more than one individual, and appeared after receiving the first few sessions of WBV training, and normally dissipated within the first 3 to 10 WBV training sessions and subsided within minutes of the end of vibration exercise with no deleterious effect on the body (Russo et al., 2003, Roelants et al., 2004b).

Overall, Crewther et al. (2004) and Cronin et al. (2004) findings are not common with WBV exercise, however these findings should be considered by the scientific community when familiarising participants with the sensations of vibration prior to exercising or rehabilitation, especially with high acceleration forces. Therefore, the application of WBV should be used with caution at high frequency, high amplitude and hence high acceleration forces, particularly among populations more susceptible to injury, such as the elderly or untrained. It would also seem prudent to monitor the duration of vibration exposure at higher acceleration forces.

### *1.4.3. Safety Limits of Vibration*

Safety limits of vibration, that people can be expected to tolerate in industrial exposure, are defined by ISO 2631-1 and BS 6841 (Merriman and Jackson, 2009, Wilcock et al., 2009, Rittweger, 2010, Abercromby et al., 2007b). A combination of frequency, direction, exposure time and RMS acceleration of the actuator is used to determine the safety limits from the ISO 2361-1 standard. The safety limits for the ISO 2361-1 standard are set at 18 Hz and at 25 Hz for the frequencies and below 3 g for the acceleration. The time of exposure is limited by performance proficiency.

Several researchers have used vibration exposures that exceeded the safety limits for a short period of time (< 10 minutes) without any negative side effects being reported. A study carried out by Abercromby et al. (2007b) exceeded than the safety limits by using vibration held at a constant frequency of 30 Hz and a constant amplitude of 4 mm (acceleration equal to 7.2 g) for 10 minutes per a day, which were similar to those used for therapeutic purposes. Likewise, Rittweger et al. (2002) investigated the effects on patients with chronic lower back pain by using WBV set at a constant frequency of 18 Hz and a constant amplitude of 6 mm with a side alternating device (acceleration equal to 3.9 g) for 7 minutes per day. Despite the vibration protocol exceeding the safety limits by about threefold of acceleration, the researchers reported significant pain alleviation as a result of the intervention. Moreover, intensities of vibration in some

sports, such as skiing, are commonly much higher than the safety limits (Rittweger, 2010).

Based on the above, it seems that guidelines for the safety limits could be modified to consider exposure to vibration in rehabilitative medicine and exercise. The following paragraphs may give some guidelines in order to adopt reasonable safety margins until such new safety limits are available.

### *1.4.4. Safety Aspects of WBV Exercise*

The safety aspect in vibration training is more important than in traditional training. As mentioned above, this is due to the fact that high intensity and duration of vibration could lead to various damaging effects to the body. A high transmission of vibrations to the upper extremity of the body, in particular to the head, via the WBV platform should be avoided (Rittweger, 2010, Mester et al., 2006, Dolny and Reyes, 2008). Hence, the transmissibility factor to the head, which defined by the amplitude ratio experienced between the head and the vibrating source, depends on the frequency (Rittweger, 2010, Mester et al., 2006, Dolny and Reyes, 2008).

Resonance frequency can be defined as the frequency where the transmissibility reaches the maximum (Dolny and Reyes, 2008, Mester et al., 2006). The resonance frequency can occur within the trunk at vibration frequencies around 5 Hz, and in the lower extremities at frequencies below 20 Hz (Rittweger, 2010, Mester et al., 2006). Those resonance frequencies are considered to be a causative factor in low back pain and circulatory disorders (Liu et al., 2011). The resonance frequency increases with muscle stiffness and decreases with body mass (Dolny and Reyes, 2008, Mester et al., 2006). Because of these symptoms, frequencies below 20 Hz should be avoided. Therefore, avoiding the use of frequencies at and below 20 Hz, and at and above 70 Hz for WBV training is recommended as a safety measure (Totosy de Zepetnek et al., 2009). Moreover, Mester et al. (2006) recommend that the amplitude in vibration training should be low, between 1 to 2 mm, for leisure sports and as the starting point for elite sport, and also that the exposure duration should be very short, between 20 to 60 s for each vibration training, especially when working with high acceleration forces.

In addition, differences of body posture on the vibrating platform will produce a different transmissibility factor to the head for the same frequency. Several studies

claim that vibration transmissibility to the head can be reduced with some degree of flexion of the ankle, knee, and hip joints (Abercromby et al., 2007a, Pel et al., 2009, Abercromby et al., 2007b, Mester et al., 2006, Dolny and Reyes, 2008). Abercromby et al. (2007b) found in their study that vibration transmissibility to the head and trunk was halved by increasing the knee flexion angle from 10 ° to 30 °. Another technique that can dampen the transmission of vibration to the head is to stand upright with only the forefoot in contact with the platform, which means the heels are off the platform (Dolny and Reyes, 2008).

In summary, WBV exercise is safe overall for all genders and ages if certain safety considerations are adhered to. Only minor side effects have been observed, which dissipate within the first 3 to10 WBV training sessions and normally subside within minutes of vibration exercise, with no deleterious effect on the body. The high risks to health occur only with being constantly and continually exposed to vibrations. The vibration frequencies around and below 5 Hz in the trunk, frequencies below 20 Hz in the lower extremity, and frequencies exceeding 70 Hz should be avoided. In the application of WBV, especially among populations more susceptible to injury, such as the elderly or untrained, there should be caution with respect to frequency, amplitude, and hence gravitational force and also with duration. High vibration transmission to the head should always be avoided via some degree of flexion of the ankle, knee, and hip joints. Based on scientific evidence, these are general recommendations that allow a reasonable amount of vibration exposure and transmission on a practical basis.

### *1.4.5. Early Research on Physiological Effects of Vibration*

Vibration as a stimulus has been known for a long time but it was only used on a small scale in the past for therapeutic effects. In the 1880's, an examination of improvements in the pilgrims visiting Lourdes suffering the condition of Parkinson's disease was done by Jean-Martin Charcot, a French neurologist, and found that such improvements were due to the vibration from the horse drawn and railway carriages. Based on this finding he produced a chair with an electrically vibrating helmet. From 1890 to 1910, several therapists such as Kellogg (USA), Taylor (USA), and Zander (Sweden) produced and developed different kinds of vibration therapy for their patients' arms and back that were based on Charcot's idea. Sanders (1936) and Whedon et al. (1949) were the first researchers who performed some research on the use of an oscillating bed. In the 1960's, Bierman, conducted research on the influence of cycloid vibration massage on

trunk flexion (Bierman, 1960). Later on, an investigation into the use of vibration, as a standard tool, to identify any potential beneficial effects on neurological therapy was conducted by Hagbarth and Eklund (1969).

Based on Bierman's study, the Russian scientist, Nazarov, used Bierman's application, in the 1970's and developed and tested vibration training to be used with an athletes' programme. He found an improvement in strength, power and flexibility, and a greatly reduced susceptibility to injuries, when vibration was used in practical exercises. He concluded that vibration was an effective method for his athletes' programme. In the 1970's, the Russians were the first to utilise vibration training in the space programme, to prevent loss of bone density and muscles changes in astronauts. They observed that this new method of exercise had the potential to prevent muscle and bone loss, and also help to increase bone density and lean muscle mass in astronauts under microgravity conditions, which was suitable for countermeasures in space. Based on Nazarov and the Russian astronauts' findings and to advance the process Nazarov and Spivak (1985) were the first to employ WBV in exercise training to improve the Soviet athletes' performance. They suggested that applied vibration as a training modality would effectively enhance strength.

On 12$^{th}$ of November 1990, Dr. Nazarov suggested vibration therapy for the first time to the scientific community in a presentation at the Institute of Sports Science at the University of Vienna under the title of "Muscle Stimulation". This led the scientific community to be interested in vibration as a new method of exercise. Issurin et al. (1994) conducted the first study to combine weight training and vibration training. They found increased gains in both maximal strength and flexibility, of 49.8 % and 43.6 % respectively, following weight training with vibration (3 times a week, for 3 weeks, at a frequency of 44 Hz with 3 mm amplitude, equal to 11.7 g), compared with 16.1 % and 19.2 %, respectively, after weight training without vibration. The second study, which compared amateur and elite athletes with and without vibration performing bilateral biceps curl exercises of explosive exertion, was carried out by Issurin and Tenenbaum (1999). They found an improvement in explosive strength exertion with vibration (44 Hz frequency with amplitude of 3 mm, equal to 11.7 g) with maximal and mean power of 10.4 % and 10.2 % respectively in the elite athletes, and 7.9 % and 10.7 % respectively in the amateur athletes.

The previous findings showing the beneficial effects of vibration exposure on the human body encouraged companies to produce and market commercial vibration devices and also led the scientific community to investigate the use of WBV exercise alone or incorporated with traditional exercise in many aspects, including for sports, for example for muscle strength (Fagnani et al., 2006, Mahieu et al., 2006, Bosco et al., 1999a, Stewart et al., 2009, Torvinen et al., 2002a, Bosco et al., 1999b, de Ruiter et al., 2003a, Torvinen et al., 2002c, Torvinen et al., 2002b, Erskine et al., 2007, Delecluse et al., 2005, Rønnestad, 2004), muscle power (Torvinen et al., 2002a, Cochrane and Stannard, 2005, Bosco et al., 1999a, Bosco et al., 1999b, Bazett-Jones et al., 2008, Cochrane et al., 2004, Cormie et al., 2006, Torvinen et al., 2002c, Torvinen et al., 2002b, Delecluse et al., 2005, Di Giminiani et al., 2009, Fagnani et al., 2006, Rønnestad, 2004), speed (Bosco et al., 1999b, Torvinen et al., 2002c, Torvinen et al., 2002a, Torvinen et al., 2002b, Delecluse et al., 2005), blood circulation (Hazell et al., 2008, Kerschan-Schindl et al., 2001, Lohman et al., 2007, Lythgo et al., 2009, Maloney-Hinds et al., 2008, Stewart et al., 2005), and flexibility (Cochrane and Stannard, 2005, Fagnani et al., 2006, Issurin et al., 1994)). Its therapeutic uses were also investigated, for example for lower back pain (Rittweger et al., 2002, del Pozo-Cruz et al., 2011, Rittweger, 2010), osteoporosis (Totosy de Zepetnek et al., 2009a, Verschueren et al., 2004, Wei et al., 2014, Wysocki et al., 2011), and bone density (Fung et al., 2012, Lam et al., 2013, Lau et al., 2011, Slatkovska et al., 2011, Totosy de Zepetnek et al., 2009a, Verschueren et al., 2004, Blottner et al., 2006).

## 1.5. The Widespread Availability of WBV in the Fitness Industry

WBV has been used as a novel form of exercise that is becoming more frequently utilised as a safe and effective way to improve muscle strength, power, flexibility and coordination. Increasingly, vibration devices are becoming available in gyms and medical centres, either for exercising or physical therapy. Various professional sport clubs and individual professional athletes have incorporate vibration exercise session into their training schedule, for warming up and strengthening regimens or for recovery (Albasini et al., 2010). WBV has been utilised with the intention of potentially enhancing several physiological systems such as skeletal muscle, bone, blood circulation and the nervous system (Prisby et al., 2008).

### *1.5.1. Neuromuscular Theory of WBV*

It has been shown that the transmission of vibration mechanical energy applied to the skeletal muscle itself or tendon is able stimulate sensory receptors on muscle spindle primary endings, primarily Ia afferent nerve endings (Hagbarth and Eklund, 1966, Shinohara, 2005). Direct stimulation of the Ia afferent nerve endings of the muscle spindle through the vibration of the muscle excites the alpha-motor neurons, causing reflex contractions of the same muscle (Granit et al., 1956). The result is a tonic contraction of the muscle, also known as a tonic vibration reflex (Hagbarth and Eklund, 1966, Bongiovanni and Hagbarth, 1990, Burke et al., 1976a, Burke et al., 1976b, Claus et al., 1988, Johnston et al., 1970, Martin and Park, 1997, Mester et al., 1999).

The initial recruitment of these motor neurons is via signals from the brain to the muscles and these neurons generate muscle contractions, as described above for the tonic vibration reflex (Cunnington et al., 2002, Naito et al., 2000). Neuromuscular spindles are usually stimulated when a muscle is either under a static stretch, rapidly stretched or overstretched, leading to a quicker and more forceful tonic vibration reflex (Wilcock et al., 2009). It has been reported that when a muscle is exposed to vibration, the tonic vibration reflex is continuously stimulated by contracting and relaxing the muscle, until the vibration stimulus stops (Totosy de Zepetnek et al., 2009a, De Gail et al., 1966). A number of studies have demonstrated an increase in EMG activity in response to acute WBV exposure, indicating that an increase in neuromuscular activity has occurred under exposure to WBV (Cardinale and Lim, 2003, Abercromby et al., 2007a, Hazell et al., 2007). Therefore, repeating this tonic vibration reflex cycle might enhance voluntary skeletal muscle activation with the muscle "stiffening" in an attempt to dampen out the effect of vibration. Such an effect has been reported to result in an increase in muscle performance after exposure to vibration (Bautmans et al., 2005, Cochrane et al., 2004, Cochrane and Stannard, 2005, Cormie et al., 2006, de Ruiter et al., 2003b, Delecluse et al., 2005, Di Giminiani et al., 2009, Fagnani et al., 2006, Lau et al., 2011, Mahieu et al., 2006, Roelants et al., 2004b, Shinohara, 2005, Torvinen et al., 2002c, Torvinen et al., 2002a, Torvinen et al., 2002b, Torvinen et al., 2003).

Recently, an alternative form of exercise known as WBV has been utilised to deliver mechanical vibrations and oscillations to the muscle itself or tendons, to elicit responses in several physiological systems. These effects of WBV exercise on physiological systems might have the potential to modify the skeletal, muscular, endocrine, nervous,

and vascular systems (Prisby et al., 2008). Several studies have proposed that exposure to WBV either as an acute exposure or as a training regimen improves some aspects of the neuromuscular system, namely: muscle strength (Mahieu et al., 2006, Stewart et al., 2009, Torvinen et al., 2002a, Delecluse et al., 2003, Roelants et al., 2004a, de Ruiter et al., 2003a, Erskine et al., 2007, Bosco et al., 1999b, Fagnani et al., 2006), muscle power (Fagnani et al., 2006, Cochrane and Stannard, 2005, Bazett-Jones et al., 2008, Torvinen et al., 2002a, Delecluse et al., 2003, Bosco et al., 2000, Cochrane et al., 2008, Cormie et al., 2006, Bosco et al., 1999b, Di Giminiani et al., 2009), speed (Bosco et al., 1999b, Torvinen et al., 2002c), body stability (Torvinen et al., 2002a), body composition (Roelants et al., 2004a) and flexibility (Cochrane and Stannard, 2005), and therefore could lead to improvements in muscle performance and function for all gender and ages in both trained and untrained populations. Overall, these findings suggest that WBV exercise might be an appropriate solution for older or obese people who have difficulty in performing traditional exercise.

### *1.5.2. Effects of WBV on Cardiovascular System*

It has been demonstrated that vibration stimulus excites the tonic vibration reflex, leading to activating and improving the neuromuscular system (Hazell et al., 2007, Bosco et al., 2000, Cardinale and Lim, 2003, Abercromby et al., 2007a). This activation of the neuromuscular system requires the turnover of energy in the muscle, and thus there is an increase in the demand for energy. Producing the extra energy demanded by the muscle, requires supplying more blood flow to the skeletal muscle.

Recently, a number of studies have reported that itchiness, redness, erythema, and oedema have occurred transiently during the first few sessions of WBV exposure (Kerschan-Schindl et al., 2001, Roelants et al., 2004b, Rittweger et al., 2000, Hazell et al., 2008, Russo et al., 2003, Broadbent et al., 2010, Cronin et al., 2004). It has been proposed by Rittweger et al. (2000), Broadbent et al. (2010) and Rittweger et al. (2010) that the main contributor of these phenomena is due to the increase in blood flow.

On the other hand, there are several studies that have examined the effects of vibration exposure on cardiovascular function (Maloney-Hinds et al., 2008, Herrero et al., 2011b, Herrero et al., 2011a, Lohman et al., 2012, Hazell et al., 2008, Otsuki et al., 2008, Stewart et al., 2005, Kerschan-Schindl et al., 2001, Lohman et al., 2007, Lythgo et al., 2009, Johnson et al., 2014, Lohman et al., 2011). Kerschan-Schindl et al. (2001) were

the first to reported a significant increase in mean blood flow velocity of the popliteal artery, by 100 %, as well as muscular blood circulation of the thigh (quadriceps) and calf (gastrocnemius) muscles after 9 minutes of WBV (frequency of 26 Hz and 3 mm amplitude with side alternating displacement; acceleration equal to 4.1 g) performed in three positions (erect with forefeet parallel, static squat at 60-70 °, static squat at 60-70 ° with open legs by about 30 °) in young healthy adults. Despite these localised effects there was no apparent pressor response since no changes in heart rate (HR) or blood pressure (BP) were reported. Another study performed by Stewart et al. (2005) demonstrated a significant increase in calf blood flow, by 46 %, following 5-7 minutes of plantar vibration (50 Hz frequency with vertical displacement and acceleration of 0.2 g) during supine position at a 35 ° upright tilt in perimenopausal women. They proposed that plantar vibration significantly enhanced peripheral and systemic blood flow as well as peripheral lymphatic flow and venous drainage.

Moreover, Lohman et al. (2007) observed a 250 % ($P<0.01$) increase in skin blood flow of the calf (gastrocnemius) immediately after applying 3 minutes of passive acute vibration (30 Hz frequency and amplitude of 5-6 mm with vertical displacement; acceleration equal to 9.1-10.9 g) to a lower limb. The skin blood flow and remained significantly elevated (by 200 %) following 10 minutes of exposure during a recovery period, whereas static squatting exercise (knee flexion at 80 °, stand on toes with knees bent at 100 ° and at 25 °) with and without WBV had no effect on the calf skin blood flow. In contrast, Hazell et al. (2008) noted a significant increase in mean finger arterial blood pressure (MAP) and femoral artery blood flow but with no effect on HR during 15 minutes of acute exposure to intermittent WBV (frequency of 45 Hz and 2 mm amplitude with vertical displacement; acceleration equal to 8.2 g) with static squatting exercise (knee flexion at 120 °) in young healthy male adults, while vibration applied passively to the feet (seated in a chair with knee flexion at 90 °) did not show any significant changes in MAP, femoral artery blood flow or HR. Furthermore, only the MAP was significantly increased during and after static squatting exercise with and without WBV and this occurred without any significant changes in HR. Despite a reported increase in femoral artery blood flow with WBV, in combination with squatting, these increases were not different from squatting alone. In both cases the variability in femoral artery blood flow was large and may have obscured any increase in flow rate from baseline.

In another study, Maloney-Hinds et al. (2008) reported a significant increase in forearm skin blood flow within the first 5 minutes of vibration in frequencies at 30 and 50 Hz with amplitude of 5-6 mm in vertical displacement (acceleration equal to 9.1-10.9 g and 25.5-30.2 g, respectively) applied passively to dominant arm (elbow bent at 110 °) for a total of 10 minutes in young healthy adults. Skin blood flow remained high for the remaining 5minutes with no further significant change reported. In addition, the frequency of 50 Hz showed a greater increase in skin blood flow and remained higher than 30 Hz during and post-vibration, however the authors concluded that there was no vibration frequency superior to the other. Furthermore, Otsuki et al. (2008) demonstrated that brachial ankle pulse wave velocity acutely decreased after 20 and 40 minutes of recovery following 10 minutes of acute exposure to WBV (frequency of 26 Hz and 2-4 mm amplitude with vertical displacement; acceleration equal to 2.8-5.4 g) in static squatting exercise (knee flexion at 120 °) in young healthy male adults, but that this occurred without any effect on HR or BP. They proposed that WBV acutely decreased arterial stiffness.

Another study performed by Lythgo et al. (2009) compared a 12 minutes of static squatting exercise (knee flexion at 50 °) with and without WBV and measured blood cell velocity in the femoral artery by Ultrasound Doppler in young healthy male adults. The WBV set at varying frequencies (5, 10, 15, 20, 25, 30 Hz) combined with two amplitudes (2.5, 4.5 mm) on side alternating displacement. They reported that exposure to WBV at frequencies of 10 to 30 Hz increased mean blood cell velocity, by 33 %, whereas 20 to 30 Hz increased peak blood cell velocity, by 27 %, compared to the non WBV. In addition, the 4.5 mm amplitude showed a significant increase in leg blood flow when combined with the frequency of 30 Hz only (acceleration equal to 8.2 g). Herrero et al. (2011a) also investigated the effects of a 3 minutes of acute exposure to WBV (10, 20 and 30 Hz frequencies with amplitude of 5 mm; acceleration equal to 1, 4 and 9.2 g, respectively) with static squatting exercise (knee flexion at 60 °) in femoral artery blood flow velocity in Friedreich's ataxia patients. They reported that peak blood flow velocity was increased following 1, 2 and 3 minutes of WBV (14.8 %, 18.8 % and 19.7 %, respectively), and mean blood flow velocity was increased following 1, 2 and 3 minutes of WBV (17.3 %, 19.4 % and 16.6 %, respectively). This study demonstrated that a higher frequency of vibration (30 Hz) produced a greater increase in leg blood flow velocity.

In a follow-up, Herrero et al. (2011b) performed a study and repeated the previous protocol, but with a spinal cord injury patients. They found that peak blood flow velocity was increased following 1, 2 and 3 minutes of WBV (11.3 %, 19 % and 23 %, respectively) as well as mean blood flow velocity was increased following 1, 2 and 3 minutes of WBV (22%, 31.1 % and 36 %, respectively). Moreover, in both frequencies of 20 and 30 Hz showed a significant increase in leg blood flow velocity, which remained higher during the first minute post-vibration at frequency of 30 Hz only, whereas a 10 Hz frequency did not show any significant effects in blood flow. Another study performed by Lohman et al. (2011) noted a significant increase in skin blood flow over a calf muscle, observed in response to 10 minutes of acute passive lower leg vibration (50 Hz frequency and amplitude of 5-6 mm with vertical displacement; acceleration equal to 25.2-30.2 g), and which continued into 9 minutes recovery.

Moreover, Lohman et al. (2012) performed a study , in an identical manner to their previous protocol, but with healthy older subjects. They reported that a significant increase in the calf skin blood flow, by 67 %, observed immediately after acute passive lower leg vibration, and remained significantly elevated, by 37 %, following 10 minutes recovery, whereas standing with one foot on the WBV platform did not show any significant differences in skin blood flow of the calf. A recent study performed on diabetic peripheral neuropathy patients by Johnson et al. (2014) demonstrated that immediately following acute exposure to WBV (frequency of 26 Hz and 2 mm amplitude with side alternating displacement; acceleration equal to 2.7 g) for 5 minutes with static squatting exercise (knee flexion at 30 °-40 °) significantly increased skin blood flow, by 15 %, compared to a sham condition.

To date, some studies have suggested that cardiovascular function responds during exposure to WBV. It has been suggested that WBV is not only affecting the neuromuscular system but also the cardiovascular function. However, the combination of vibration exposure with activation of skeletal muscle via standing on the vibrating platform during WBV exercise might influence the regulation of the blood flow and therefore this issue could be a possible explanation of the increase in local muscular blood flow. Another possible explanation of this increase is that vibration induces shear stress, which results in arterial vasodilatation, since it has been hypothesised that the effects of increased shear stress at the vessel wall could be a mechanism to increase

flow as a result of mechanical vibrations (Suhr et al., 2007, Item et al., 2013). Thus, it is unclear whether this response of the cardiovascular function is a direct effect of vibration-induced shear stress on the peripheral blood flow, as a primary effect, or is a secondary effect in response to skeletal muscle activation due to functional hyperaemia. Overall, it seems that the mechanism of the effect of WBV on the peripheral cardiovascular function is not all that well understood in the scientific community, and therefore warrant further investigation. It is important to understand whether any increase in blood flow from WBV is due to an increase in metabolic activity or a direct effect on the vascular circulation. An understanding of how cardiovascular homeostasis is maintained is discussed in the next section.

## 1.6. Control of Blood Flow

The blood flow via the vessels of the circulatory system is the process depends on a function of the pressure in the system and the resistance to flow caused by the blood vessels. The flow of blood is directly proportional to pressure and inversely proportional to resistance (blood flow = pressure / resistance). This means that if the pressure is increased in a vessel, the blood flow in this vessel will increase. In contrast, if the resistance in a vessel is increased, the blood flow will decrease in this vessel. Moreover, resistance in the blood vessels is affected via length of the vessel, viscosity of the blood, and radius of the vessel. The longer vessel produces a greater resistance. The greater viscosity results in a greater resistance. The smaller radius produces a greater resistance.

The most effective factor, that affects blood flow, is the radius of the blood vessel. This means that if the radius of a blood vessel is increased by vasodilatation, the blood flow in this vessel will substantially increase. In contrast, if there is decrease in the radius of a blood vessel via vasoconstriction, the blood flow will significantly reduce in this vessel. Consequently, a small changes in the blood vessel radius causes a very large changes in blood flow, thus body controls blood flow to specific areas of the body by controlling the radius of arterioles servicing those areas. Furthermore, a change in blood flow could be controlled by intrinsic and extrinsic mechanisms. Moreover, blood flow varies from one organ to another and is regulated by altering the arterial resistance and can also be based upon the organ’s metabolic demands.

### *1.6.1. Local (Intrinsic) Control of Blood Flow:*

Examples of local (intrinsic) control of blood flow are autoregulation, functional hyperaemia, and reactive hyperaemia. Local control blood flow is known as blood flow autoregulation where the blood flow to an organ remains about constant over a wide range of perfusion pressures. Organs which exhibit autoregulation are the heart, brain, and kidney. For instance, if perfusion pressure to the heart is suddenly decreased, compensatory vasodilatation of the arterials will occur that will maintain a constant flow. Further, blood flow to an organ is proportional to its metabolic activity (i.e. functional hyperaemia). For example, if the metabolic activity in skeletal muscle increases in response to exercise, the blood flow to the muscle will increase proportionally, to meet metabolic demand. Another example of local control of blood flow is reactive hyperaemia. Reactive hyperaemia is the increase in blood flow to an organ that occurs following a period of arrested blood flow. Furthermore, a longer period of occluded blood flow results in a greater increase in blood flow, which is above pre-occlusion blood flow levels. Anderson and Mark (1989) reported that deflating the forearm occluding cuff after 10 minutes (reactive hyperaemia) significantly increased brachial artery blood flow by about 50 % compared to the baseline prior to occluding the blood flow.

There are two mechanisms that explain local control of blood flow. One mechanism is the myogenic hypothesis while the other mechanism is the metabolic hypothesis. The myogenic hypothesis explains autoregulation but not functional or reactive hyperaemia. The myogenic hypothesis is that vascular smooth muscle contracts when it stretched. For instance, if perfusion pressure to an organ is suddenly increased, the arterial smooth muscle will be stretched and will contract as an automatic response, resulting in vasoconstriction, which will maintain a constant flow. Without this vasoconstriction, blood flow would increase in response to increased pressure. The metabolic hypothesis is that supply of oxygen to the tissue is matched to tissue demand for oxygen. Moreover, vasodilator metabolites are produced in response to metabolic activity in tissue, such as carbon dioxide, protons, potassium, lactate, and adenosine. The metabolic activity of the tissue increases during exercise leading to an increase in both the demand for oxygen and the production of vasodilatation metabolites. Therefore, the increase in metabolites causes arterial vasodilatation that increases blood flow and thus increases oxygen delivery to the tissue to meet demand. Another example is that if the

blood flow to an organ suddenly increases, as a result of a spontaneous increase in arterial pressure, more oxygen is provided for the metabolic activity but at the same time the increased flow washes out the vasodilatation metabolites. As a result of this washout, arterial vasoconstriction occurs, and thereby resistance increases and blood flow is returned to normal.

Furthermore, some vasodilators have an effect on vascular smooth muscle through stimulating the release of nitric oxide. An endothelium-dependent vasodilatation in arteries will be elicited through an increase in velocity of blood flow or in shear stress. Prostaglandins seem to be important mediators of this vasodilatation in skeletal muscle, rather than nitric oxide (Koller and Kaley, 1990). An understanding of the effects of prostaglandins hormones on the control of blood flow is described in the next section.

### *1.6.2. Hormonal (Extrinsic) Control of Blood Flow:*

There are two extrinsic components responsible for control of blood flow. One component is sympathetic innervations of vascular smooth muscle and the other component is other vasoactive hormones. In sympathetic innervations of vascular smooth muscle, an increase in the sympathetic tone causes vasoconstriction. In contrast, vasodilatation occurs in response to a decrease in sympathetic tone. The density of sympathetic innervation varies widely among tissues. The skin has the greatest innervation, whereas the least innervation is observed in the coronary, pulmonary, and cerebral vessels.

On the other hand, there are four other vasoactive hormones that are important in this extrinsic pathway. The four hormones are histamine, bradykinin, serotonin, and prostaglandins. Both the histamine and bradykinin hormones cause arteriolar dilation and venous constriction. This combination of the effect arteriolar dilation and venous constriction will increase capillary hydrostatic pressure, causing increased filtration of intravascular fluid, leading to local oedema. The other vasoactive hormone is serotonin, which is known as 5-hydroxytryptamine, which causes arteriolar constriction and is released in response to blood vessel damage, to help prevent blood loss. Serotonin has been implicated in the vascular spasm of migraine headaches. Another group of vasoactive hormones are the prostaglandins, which include prostacyclin, E-series prostaglandin, F-series prostaglandin and thromboxane A2. Prostacyclin is a vasodilator

in several vascular beds. E-series prostaglandin is also a vasodilator, whereas F-series prostaglandins and thromboxane A2 are vasoconstrictors.

### *1.6.3. The Role of Vascular Endothelium and Shear Stress*

The importance of the vascular endothelium and its major role in the initiation and/or modulation of vasomotor responses was discovered by Furchgott and Zawadzki in 1980, and thus instigating a new field of research (Rowell, 2004). The physical forces exerted on the blood vessels wall through the intravascular passage of blood are pressure and shear stress. These pressure and shear stress forces are derived from the movement generated in the blood through cardiac output. Pressure is exerted radially at right angles to the flow and results in tangential stress on the elements of the wall, mainly dilating the smooth muscle cells. Meanwhile, shear stress is exerted on the vessel wall and usually in the same direction as flow. On the blood vessel's internal surface, the drag is communicated via the vessel wall and is inclined to deform the transverse profiles of the smooth muscle cells (Bevan and Laher, 1991).

Several studies have been reported that after blocking production of nitric oxide synthase, the flow effects are still observed, although decreased (Song and Munn, 2011, Bevan, 1993). This flow implies that the effect of shear stress is extended mechanically to the subendothelial tissues (Bevan, 1993, Song and Munn, 2011). This confirmed that shear stress causes changes of conformation in the glycosaminoglycans by extending them from a randomly coiled assembled state to a more expanded condition along the flow line (Bevan, 1993).

Likewise, via using a microfluidic model of angiogenic sprouting, Song and Munn (2011) found that through the nitric oxide pathway, the fluid shear stress prevents morphogenesis of the vessel, that is, rearrangement of the vessel wall microanatomy, which led to either sprouting or invasion into the matrix, and that the interstitial flow increases the morphogenesis rate.

Endothelial cells in blood vessels are subjected to mechanical forces in contact with the endothelial surface because of blood flow and through the vessel wall and because of interstitial plasma flow (Song and Munn, 2011). Fluid shear stress can induce many changes via signals which mediate endothelial cell transcription, vascular endothelial growth factor receptor changes, function as a barrier, the morphology of intralumina,

the formation of tubules, membrane fluidity, and maintenance of the homeostasis of vessel. These culminate in, maintaining the vessel lumen and controlling proliferation and turnover of endothelial cells (Song and Munn, 2011). Furthermore, shear stress can cause significant changes in morphology of the endothelial cell and rearrangement of the actin cytoskeleton, while flow transverse to the endothelium and via the interstitial space can also induce morphogenesis of the endothelia (Song and Munn, 2011).

On the other hand, there was evidence that vasoconstriction occurs in the blood vessels in response to abnormal flow pattern in order to re-regulate endothelial dysfunction, and this includes recirculation eddies, flow separation and reattachment, and reciprocating flow (Chiu and Chien, 2011). This autoregulation function is called the myogenic hypothesis, as described above in the Local (Intrinsic) Control of Blood Flow, section 1.6.1. Consequently, it is postulated that if blood flow is altered from laminar to turbulent, in response to vibration exposure, this would result in vasoconstriction to reduce the abnormal blood flow (i.e. eddies). Furthermore, when the vibration is terminated, blood flow should return to luminal flow from the turbulent pattern that would cause vasodilatation through a decrease in shear stress at the blood vessels wall interface and thereby increasing blood flow as an autoregulation function of blood flow (Anderson and Mark, 1989).

Therefore, an angiogenesis-inducing potential could occur because of a potential increase in shear stress mechanism at the wall of blood vessels (Galie et al., 2014), as a reaction to blood flow autoregulation, that results in an increase in vasodilatation and leads to an increase in circulating blood flow in response to vibration exposure. Detecting the potential vasodilatory effects of exposure to low frequency WBV through induced shear stress, which increases skeletal muscle blood flow and therefore might be helpful in assisting recovery routines from exertion. This low-frequency stimulus might also have the potential as a novel training stimulus, since there was evidence that high frequency vibration exposure is reported to be detrimental on the body and is limited by the Health and Safety Executive (Bovenzi, 2005, Merriman and Jackson, 2009, Brooke-Wavell and Mansfield, 2009, Totosy de Zepetnek et al., 2009b, Wilcock et al., 2009, Jordan et al., 2005, Cochrane, 2011, Dolny and Reyes, 2008). Hence, the potential for WBV stimulus to produce shear stress within the vascular tree is of interest because of its angiogenesis-inducing potential.

## 1.7. Aims and Objectives

This review has discussed the effect of WBV on peripheral cardiovascular function. A new and novel form of exercise known as WBV has not only been identified as helping to improve some aspects of the human musculoskeletal system, namely improving muscle strength, force, power production, speed, flexibility and coordination, but also found to enhance the cardiovascular function. It has been proven that exposure of the human body to vibration, either by standing on a vibrating platform or having it applied passively to a limb, could help to increase local skeletal muscle blood flow (Maloney-Hinds et al., 2008, Lohman et al., 2011, Hazell et al., 2008, Lythgo et al., 2009, Kerschan-Schindl et al., 2001, Stewart et al., 2005, Herrero et al., 2011b, Herrero et al., 2011a, Lohman et al., 2007, Lohman et al., 2012). In addition, several transient symptoms such as itchiness, redness, erythema and oedema have been observed during the first few sessions of WBV exposure, and it appears that these symptoms stem from the increased local skin and muscular blood flow in response to vibration exposure, which might suggest that shear stress occurs during exposure to WBV, resulting in arterial vasodilatation (Rittweger et al., 2000, Rittweger, 2010, Broadbent et al., 2010). However, until now it has not been reported that vibration directly affects the peripheral cardiovascular function via inducing an increase in shear stress at the wall of the blood vessels, as a primary effect or whether it might be that this increase occurs only in skin and muscle blood flow following WBV due to functional hyperaemia in response to skeletal muscle activation. Thus, understanding the mechanism that would explain the effect of vibration on the peripheral cardiovascular function requires further investigation. On the other hand, it has been demonstrated that an increase of blood flow following exposure to WBV was observed only in local skin and muscle, whereas there are no studies reporting any systemic effects of WBV on blood flow.

The main aim of this thesis was to investigate the mechanism of the effect of WBV on the peripheral vascular blood flow. It was hoped to detect the potential vasodilatory effects of vibration that enhance peripheral blood flow and could thus be helpful in assisting recovery from exertion and also have potential as a novel training stimulus.

The specific objectives to achieve the research aim and hypotheses are set out as 3:

The first study in this thesis (Chapter 2) investigated the potential systemic effects of WBV on blood flow. It was hypothesised that forearm limb blood flow would be

increased by a greater extent following a single bout of unloaded squatting exercise with exposure to WBV when compared to a single bout of unloaded squatting exercise without WBV. Furthermore, forearm limb blood flow was hypothesised to increase by a greater extent following a single bout of squatting exercise, with an addition of 15 % body mass (BM) loading, with exposure to WBV when compared to a single bout of squatting exercise with the addition of 15 % BM loading without WBV.

The second study in this thesis (Chapter 3) investigated the potential effects on the peripheral circulation of passively applied vibration to the lower legs. It was hypothesised that peripheral cardiovascular function would be increased by a greater extent following acute exposure to passive lower limb vibration when compared to control condition, which was sham.

The third study in this thesis (Chapter 4) detected the effects on the peripheral blood flow of varying durations of passively applied vibration to the lower limb. It was hypothesised that peripheral blood flow would be increased by a greater extent following exposure to a longer duration of passive lower limb vibration when compared to the previous duration of exposure to passive lower limb vibration.

The fourth study in this thesis (Chapter 5) detected the effects of passively applied vibration to the lower limb on skeletal muscle activation and/or local muscle blood flow. It was hypothesised that peripheral blood flow would be increased by a greater extent during exposure to passive lower limb vibration when compared to either control (sham), occlusion of the lower limb or occlusion of the lower limb plus vibration stimulus conditions. The peripheral blood flow was hypothesised to increase by a greater extent during recovery following exposure to passive lower limb vibration and occlusion of the lower limb plus vibration when compared to either control (sham) or occlusion of the lower limb conditions.

# Chapter 2 - Potential Systemic Cardiovascular Response Following Exposure to Whole Body Vibration

## 2.1. Introduction

In recent years, using whole body vibration (WBV) is of increasing interest for its physical training (Delecluse et al., 2005, Cochrane and Stannard, 2005) and rehabilitation applications (Ebersbach et al., 2008, Bautmans et al., 2005). It has been previously demonstrated that exposure to vibration will increase muscle spindle and Golgi tendon organ activity that could be indicative of an increase in skeletal muscle activity (Burke et al., 1976b). Indeed, electromyogram data have illustrated that WBV increases the activation of skeletal muscle (Cardinale and Lim, 2003, Abercromby et al., 2007a, Hazell et al., 2007). Most studies demonstrate that acute exposure to WBV results in an improvement in the musculoskeletal system, as reflected by muscle strength, muscle power, body stability and flexibility (Torvinen et al., 2002a, Cochrane and Stannard, 2005). Consequently, it has been postulated that if an increase in skeletal muscle activation occurs during exposure to vibration, this increase in skeletal muscle activity should lead to increased blood flow to the activated muscle bed.

In a previous study by Green et al. (2002) it was shown that exercise at a sufficiently high intensity involving a substantially large muscle group can have effects on the whole cardiovascular system via an increase in skeletal muscle blood flow distal to the main muscle activation site (i.e. a systemic effect on the circulation). They found that forearm blood flow (FBF) was significantly increased only during high intensities of lower limb exercise (cycle ergometer exercise) at 100 and 160 Watts, whereas a significant decrease in FBF was observed in response to lower cycle exercise intensity, at 40 Watts, which remained unchanged at intensities of 60 and 80 Watts. A follow-up study performed by Green et al. (2005) reported that FBF during cycle ergometer exercise was significantly reduced at an intensity of 60 Watts and remained unchanged at 80 Watts, whereas FBF was significantly increased with an increase the intensity to120 Watts. These findings from the studies of Green et al. (2002) and Green et al. (2005) indicate that whole body exercise, predominantly involving lower limb exercise (e.g. running, cycling, squatting), at a moderately-high intensity (oxygen consumption ~1.8 l/min) results in an increase in distal blood flow (i.e. FBF), while FBF reduces or does not change during whole body exercise at low intensity (low metabolic rate).

WBV has been reported to increase local muscular blood flow (Hazell et al., 2008, Lythgo et al., 2009, Kerschan-Schindl et al., 2001, Stewart et al., 2005, Herrero et al., 2011b, Herrero et al., 2011a); however, there are no studies reporting any systemic

effects of WBV on blood flow. Therefore, it is unknown whether this increased response within the cardiovascular function which is an effect of WBV results in a general systemic vasodilatory effect that is consistent with the increase in local muscular vasodilatation or an increase vasodilatation occurs only on the local peripheral cardiovascular function.

Thus, there is interest in investigating the systemic blood flow effects of vibration to provide information that was not previously available. The aim of this study was to investigate any potential systemic blood flow effect of WBV, its effect on skeletal muscle blood flow distal (i.e. in the forearm) to the main site (the lower limbs) of muscle activation was investigated. This study was designed to compare the effects of exposure to WBV during the completion of dynamic squatting exercise with those of dynamic squatting exercise alone at varying intensities (unloaded and loaded) on FBF, in order to discover any potential systemic effect on the circulation, in a similar manner to the studies by Green et al. (2002) and Green et al. (2005). Regarding Green's findings, it was hypothesised that a single bout of unloaded and loaded dynamic squatting exercise with additional exposure to WBV would result in a general systemic vasodilatory effect that causes a greater increase in upper limb blood flow when compared to that caused by either unloaded or loaded squatting exercise without WBV conditions.

## 2.2. Methods

### *2.2.1. Participants*

Eleven healthy young adults (9 males, 2 females) with an age range from 18 to 21 years were recruited to take part in the study. The subjects were recruited from the general population of the Heriot-Watt University and from personal contacts. The study was approved by the Ethics Committee of the School of Life Sciences at the Heriot-Watt University and was conducted in accordance with the Declaration of Helsinki. The participants were fully informed, verbally and in writing, of the purposes and protocol of the study and the risks and discomfort associated with the experiment before giving their written informed consent to participate. A participants' health screening was assessed by asking verbal questions prior to commencing the study. Subjects completed all bouts of unloaded and loaded squatting exercise with and without whole body vibration (WBV) sessions and were randomly ordered to these bouts (described below in Experimental Sessions, 2.2.4). The subjects were acquainted with the procedures of the study during a familiarisation session prior to commencing the experimental sessions (described below in the Familiarisation Session, 2.2.3).

As ascertained from the health screening questions, with respect to regular physical activity, all volunteers were required to be active but not highly trained and subjects who had previous health issues, in particular any related to the cardiovascular system, were excluded from this experiment. Subjects were asked to maintain their regular diet and normal life-style patterns during the study period.

Subjects were asked to refrain from smoking and drinking alcohol at least 24 hours prior to participating in each experimental session, and to avoid the consumption of caffeine-containing beverages (e.g. tea, coffee, coca cola) and foods (e.g. chocolate) at least 2 hours prior participating in each test session. Subjects were also asked to refrain from participating in any heavy strenuous physical activity at least 24 hours prior to participating in each test session. The subjects were barefoot during the test sessions, to avoid footwear dependent attenuation of the vibration.

All procedures associated with the investigation were undertaken in the Laboratory of Sport and Exercise Sciences Department located in the Sports Academy at Heriot-Watt University. Temperature in the laboratory was regulated between 21 to 23 °C. Upon

arriving at the laboratory, subjects were asked to exercise and then lie at rest on an examination couch during each session.

### *2.2.2. Overview of Experimental Method*

Subjects completed three sessions on three separate occasions. Before the experimental protocol, subjects initially performed a familiarisation routine in order to become accustomed to squatting exercise, all the cardiovascular measurements, treatment procedures and vibration exposure (described below in the Familiarisation Session, 2.2.3). The experimental protocol involved completing two separate sessions under two different bouts of unloaded or loaded exercise with or without WBV on each session. There was at least two days between the sessions. The four different exercise conditions are presented in Table 2.1. The experimental procedure consisted of (i) baseline measurement of heart rate (HR), brachial blood pressure (BP) and forearm blood flow (FBF); (ii) a squatting exercise with or without WBV exposure and with or without load; and (iii) post-treatment measurements that were conducted in an identical manner to the baseline measurements. The key variables of interest in this study were HR, FBF, mean brachial arterial blood pressure (MAP) and arm vascular conductance (AVC). During all sessions, subjects were required to complete squatting exercise with or without exposure to vibration and then lie at rest on examination couch with their arm resting and elevated on supporting foam mats as shown in Figure 2.1.

**Table 2.1 The four different exercise conditions.**

| Abbreviation | Condition |
|---|---|
| Unloaded squats (□) | 60 squats exercise |
| Unloaded squats with WBV (△) | 60 squats exercise with WBV |
| Loaded squats (■) | 60 squats exercise with 15% of BM |
| Loaded squats with WBV (▲) | 60 squats exercise with WBV with 15% of BM |

WBV: whole body vibration, %: percent, BM: body mass.

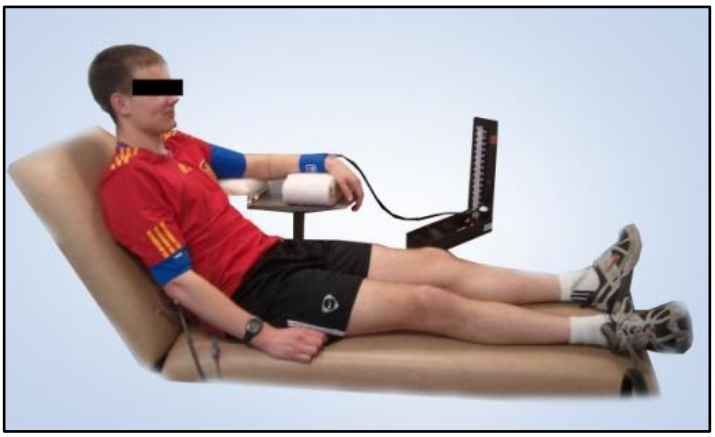

**Figure 2.1 Application of all measurements during lying at rest on an examination couch.**

### *2.2.3. Familiarisation Session*

After the participants had given their written and informed consent, which included receiving a full explanation of the study, their age, height, body mass, resting BP and HR were recorded. The subjects then lay down on the examination couch with their arm resting on supporting foam mats. Measurement of circumference of the widest part of the forearm was taken for the application of the strain gauge in the experimental sessions. A venous occlusion plethysmograph (Hokanson, Bellvue, WA, USA) and an automated BP monitor (Tango+, SunTech Medical Instruments, NC, USA) were demonstrated at a separate time in order to familiarise the participants with the cuffs and the measurements before testing, to avoid stress and excitement in the experimental sessions on the day of testing.

After that, subjects were moved slowly from the examination couch to stand on the vibration platform to perform a dynamic squatting exercise at a tempo of 1 s up and 1 s down, in time to a metronome (Seiko SQ-50 Quartz Metronome Seiko S-Yard Co., China) set to 60 beats per minute (bpm) (i.e. a frequency of 1 Hz) at approximately 75 ° of knee flexion and holding their hands in front of the body. The degree of knee flexion was determined using goniometry. Finally, subjects were vibrated at a frequency of 30 Hz for a period of 30 seconds in order to familiarise the participants with the sensation of vibration.

### *2.2.4. Experimental Sessions*

The two experimental sessions were composed of unloaded and loaded squatting exercise with and without WBV. In the two experimental sessions, subjects were involved in completing two separate sessions under four bouts of exercise conditions i.e. unloaded, loaded and with and without exposure to WBV (Table 2.1). During each session, two bouts of exercise conditions were completed requiring the completion of 60 repetitions of squats with or without WBV exposure and with or without carrying a back pack for external load equivalent to 15 % of the subject's body mass (BM), as applied in the familiarisation session. All the exercise conditions were performed on the vibration platform, as shown in Figure 2.2. A Latin square design was used to randomly assign the participants to undergo two bouts of the exercise conditions in each session. The WBV exposure was applied at a constant frequency of 30 Hz and an amplitude of 3 mm with a vertical displacement, which produced a peak acceleration of approximately 5 g (i.e. 5 x 9.81 $m/s^2$). The two bouts of exercise conditions in each session were separated by 30 minutes of rest. The duration for each bout of exercise condition was constant at 2 minutes.

On the testing day, all equipment was set up and the room temperature was pre-warmed to 21-23 °C for at least 30 minutes prior to the arrival of the subjects so that the temperature of all of the supporting foam mats, equipment and walls was similar. On arrival at the laboratory, subjects lay down on the examination couch for 10 minutes to achieve a baseline blood flow prior to vascular function testing and also to acclimatise to the temperature in the room. Baseline FBF, brachial BP and HR measurements were taken after the 10 minutes of rest. Following the baseline measurements, subjects were then moved slowly from the examination couch to stand on the vibration platform to undergo one of the conditions, either performing the squatting exercise unloaded or loaded and with or without WBV exposure. Only the HR was recorded during the intervention. Immediately after completing the intervention, subjects were moved back slowly and comfortably from the vibration platform to lie down on the examination couch for 23 minutes of recovery. The post-treatment measurements were then performed 1.5 minute following the intervention and repeated at 3 minutes intervals thereafter during the total of 23 minutes of recovery.

After that, subjects lay continuously in a supine position for 10 minutes before the baseline measurements were made in order to separate the two interventions by

30 minutes. Once the procedures of baseline measurements, a further treatment condition, and post-treatment measurements has been conducted, in an identical manner to the procedure of the first condition, the session ended. The second experimental session was conducted in an identical manner to the procedure of first experimental session.

**Figure 2.2 Application of whole body vibration (WBV).**

### *Vibration Device*

Vibration stimulus was applied to subject's body via the lower legs with a vertical sinusoidal vibration using the Nemes device (Nemes, Bosco System, Italy) while subjects were standing on the vibration platform (Figure 2.2). The Nemes is a vibration platform with frequency settings ranging from 20 to 50 Hz (deflection per second) with a constant amplitude plate oscillation at 3 mm (size of each deflection).

### *Accelerometer Calibration*

The frequency, amplitude and acceleration of vibration were measured using a digital accelerometer (4000A Accelerometer, Measurement Specialties, CA, USA). The accelerometer was fixed in the centre of the vibration platform to measure the platform movement that was at the closest point to foot exposure. Attachment of the

accelerometer to the vibration platform site was accomplished using industrial double-sided adhesive strength tape to ensure the accelerometer was secure. The accelerometer was connected into the Powerlab (PowerLab /16SP, ADInstruments, Castle Hill, Australia) in order to sample the signals for offline analysis via using Chart 5 software (version 5.5.6, ADInstruments) and recorded into a standard laptop. The accelerometer was calibrated on the basis of a two point calibration by applying zero gravity and the earth's gravity of 1 g (9.81 $m \cdot s^{-2}$).

### *2.2.5. Measurements*

All subjects had their vascular function assessments pre- and post-dynamic squatting exercise. All measurements were performed following 10 minutes of rest to establish baseline values, 1.5 minute after intervention and then repeated every 3 minutes for a total of 23 minutes of recovery. Only the HR was recorded during squatting exercise at 30 squats (1 minute) and 60 squats (2 minutes). An automated venous occlusion strain gauge plethysmograph (Hokanson, Bellvue, WA, USA) was used to measure FBF after applying a venous occlusion to the upper arm. The venous occlusion cuff ($SC10D^{TM}$, Hokanson, Bellvue, WA, USA) was attached around the left upper arm and connected to an adjustable venous occlusion air pressure source (E20 Rapid Cuff Inflator and AG101 Cuff Inflator Air Source, Hokanson, Bellvue, WA, USA) whilst an arterial occlusion cuff ($TMC7^{TM}$, Hokanson, Bellvue, WA, USA) was attached around the left wrist and connected to an adjustable arterial occlusion handheld sphygmomanometer (Accoson, England) as shown in Figure 2.1. The venous occlusion cuff was rapidly inflated for 15 seconds to a pressure of 50 mmHg, which is less than diastolic blood pressure, in order to allow arterial inflow but prevent venous outflow. This process was repeated three times with 10 seconds between each measurement to allow the blood flow to return. Ten seconds prior to rapid inflation of the venous occlusion cuff, the arterial occlusion cuff was inflated to 225 mmHg, which is higher than systolic blood pressure, in order to occlude the blood flow to the hand. Immediately after obtaining the third blood flow measurement, the wrist cuff was quickly deflated.

The FBF measurements were carried out while the subjects were lying on the examination couch with their left arm at the elbow and wrist resting in line with the heart level and relaxing on supporting foam mats for comfort and to elevate the centre part of the forearm. This was in order to make space for the strain gauge, and to ensure the subject did not touch anything and was not moving during the measurement (Figure

2.1). The strain gauge was placed around the widest part of the forearm to be same as the limb circumference being measured to measure the change in volume of the forearm. The strain gauges are made from mercury in rubber and designed to be flexible and stretch (Hokanson Strain Gauges, Hokanson, Bellvue, WA, USA). The size of the strain gauge selected was 1 to 3 cm less than the circumference of the forearm, as instructed by the manufacturer, so that it would expand and stretch slightly. The strain gauge was connected into a dual channel plethysmograph (EC6 Plethysmograph, Hokanson, Bellvue, WA, USA), which was connected into the Powerlab (PowerLab /16SP, ADInstruments, Castle Hill, Australia) in order to sample the blood flow trace from the plethsymographic signal for offline analysis via using Chart 5 software (version 5.5.6, ADInstruments) and recorded into a standard laptop.

The slope of the line used to determine blood flow is shown in Figure 2.3. The arrow indicates the start of cuff inflation. The first half-second of the trace was disregarded to avoid artifacts due to inflation and the line shows the initial gradient for the first 3 heart beats, used to calculate blood flow. The blood flow slope was calculated using the formula:

$$BF = (\Delta v \times Scale) / (\frac{\Delta t}{60})$$

where *BF* is blood flow (ml/100ml/min), $\Delta v$ is longitudinal distance from the peak of the first heart beat to the peak of the third heart beat (mm), *Scale* is the scale set for the slope (%), $\Delta t$ is time from the peak of the first heart beat to the peak of third heart beat (s), and *60* is 60 seconds.

The mean slope of the blood flow was taken from the three measurements of the slope. The blood flow slope is presented in ml/100ml/min.

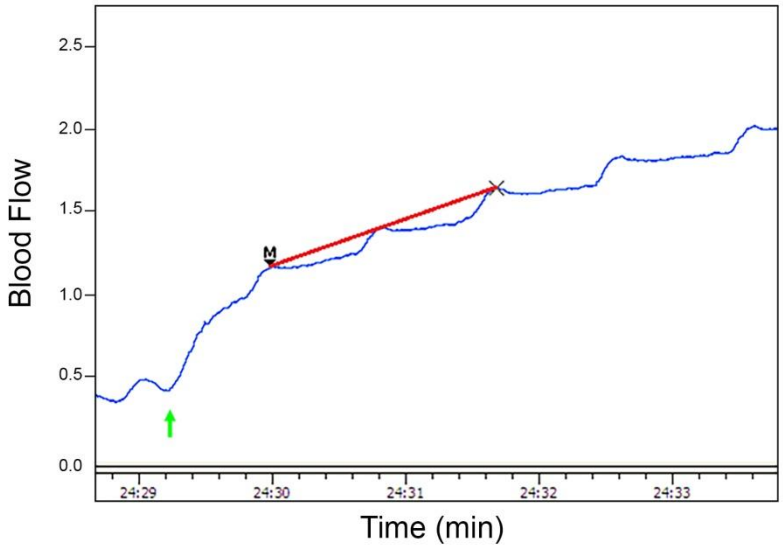


**Figure 2.3 Example trace from one subject, showing the slope of the line used to determine blood flow.**

Brachial BP was measured using the automated monitor (Tango+, SunTech Medical Instruments, NC, USA). Three electrocardiography (ECG) electrodes (R-00-S/25, Ambu Blue Sensor R, Malaysia) were applied on the subject's upper body and placed over a bony area; the V2 electrode (negative) was placed on the right shoulder, the V6 electrode (positive) was attached on the left hip, and the RL electrode (earth) was positioned on right hip. The BP cuff was placed on the subject's right arm, with a sensor located over the brachial artery. The MAP was calculated using the equation

$$MAP = \frac{(2 \times DBP) + SBP}{3}$$

where *MAP* is mean arterial blood pressure (mmHg), *DBP* is diastolic blood pressure (mmHg), and *SBP* is systolic blood pressure (mmHg). The HR was measured using a heart rate monitor (Polar CE0537, Polar Electro, Finland) and measured in bpm. The vascular conductance is the ratio of the blood flow to mean arterial blood pressure. The AVC was calculated using the formula:

$$AVC = \frac{FBF}{MAP}$$

where AVC is arm vascular conductance (ml/100ml/min/mmHg), FBF is forearm blood flow (ml/100ml/min), and MAP is mean arterial blood pressure (mmHg).

### *Strain Gauge Viability*

Each strain gauge was tested for viability using a specially built apparatus of rubber tubes with an inflatable cuff. The rubber tubes were arranged to fit the size of each strain gauge, where the inflatable cuff was located in the middle of the rubber tubes. The selected size of the strain gauge was placed around these rubber tubes and then the cuff was inflated to generate a variety of circumferences.

### *2.2.6. Statistical Analysis*

All the data were analysed using Minitab 17 statistics software (version 17.1.0, Minitab). Data presented in the results are mean ± SEM. Statistical analysis was performed using analysis of variance (ANOVA) with a mixed, that is fixed and random, effects model with statistical significance accepted at $P < 0.05$. Post-hoc tests for significant differences were performed using the Bonferonni correction, with an uncorrected 1-sided alpha value of 0.05 (Kutner et al., 2005), Chapter 27, 1127-1172.

## 2.3. Results

### *2.3.1. Subject Characteristics*

Ten (mean ± SD: age 20.2 ± 1.1 years, height 1.76 ± 0.08 m, body mass 76.1 ± 6.8 kg) out of the eleven participants successfully completed the sessions with 100 % compliance and were free of injury. Only one subject (male) withdrew from the study after completing the familiarisation session, for reasons unrelated to the experiment. There were no side effects or adverse reactions reported by the participants during any of the sessions.

### *2.3.2. Heart Rate Responses*

There was no interaction between condition and time for heart rate (HR) ($P = 0.803$). HRs in the four conditions were similar at baseline ($P > 0.05$) (Figure 2.4). The four various conditions significantly increased HR over the baseline during exercise at 30 squats (1 minute) and 60 squats (2 minutes) ($P < 0.05$). The addition of whole body vibration (WBV) to unloaded and loaded squat exercises resulted in a significant increase in HR during exercise at 2 minutes (60 squat) when compared to 1 minute of exercise (30 squat) ($P < 0.05$), whereas no significant difference in HR was found for either the unloaded and loaded squat exercise conditions during 2 minutes of exercise compared to exercise at 1 minute (30 squats versus 60 squats) ($P > 0.05$). HRs in the unloaded squat, loaded squat and loaded squat with WBV exercise conditions were significantly increased above baseline at 1.5 minute recovery post-exercise ($P < 0.05$), whereas the addition of WBV to the unloaded squat exercise did not result any significant difference over baseline at any time point during recovery ($P > 0.05$). There was also no significant difference in HR between the four various conditions at any time point during and after exercise ($P = 0.822$, $P = 0.894$, respectively).

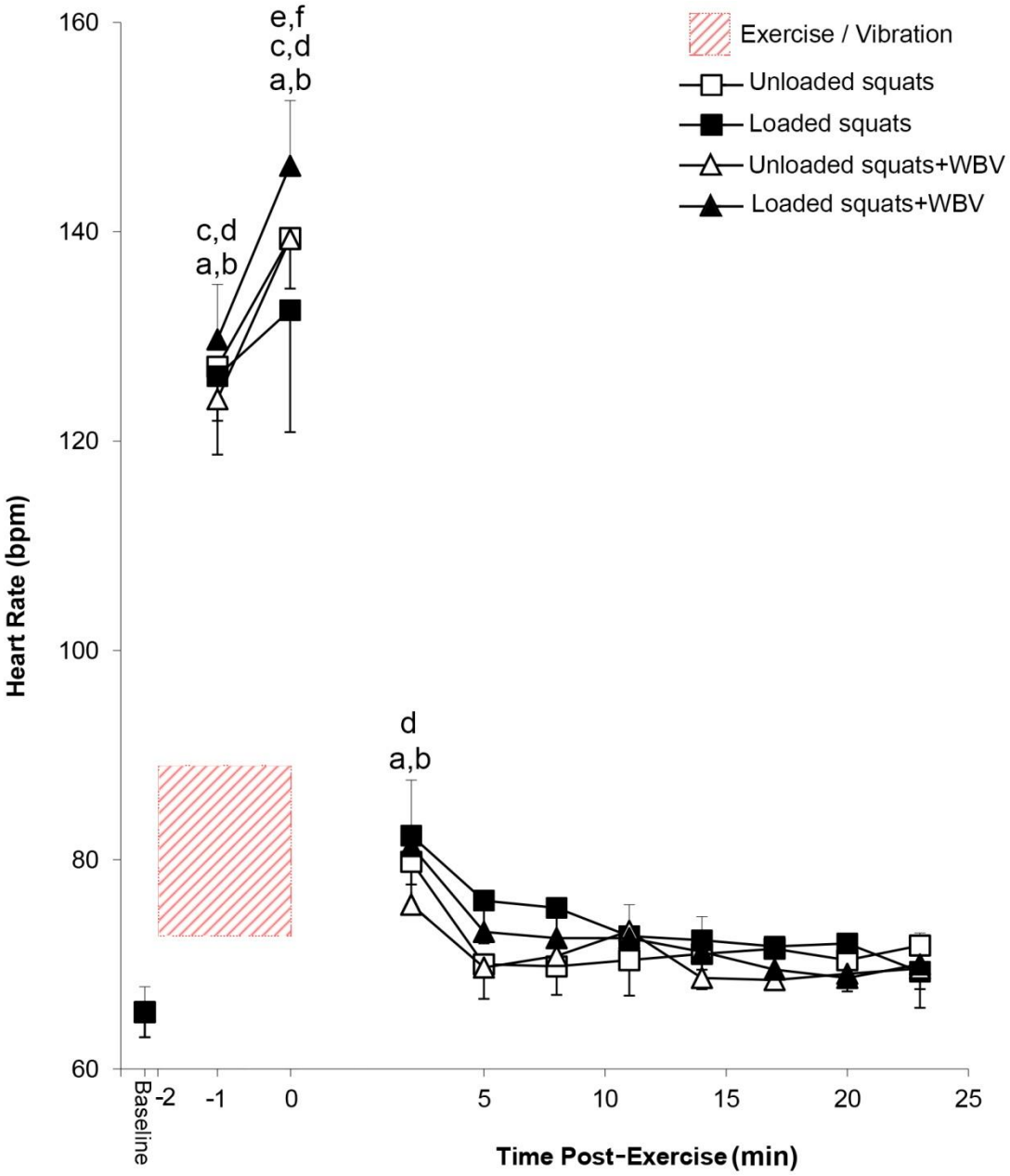


**Figure 2.4 Heart rate (HR) pre-, during and post-exercise at various time points.**

**"a" indicates significant increases over baseline for the unloaded squats condition ($P < 0.05$). "b" indicates significant increases over baseline for the loaded squats condition ($P < 0.05$). "c" indicates significant increases over baseline for the unloaded squats with WBV condition ($P < 0.05$). "d" indicates significant increases over baseline for the loaded squats with WBV condition ($P < 0.05$). "e" indicates significant increases over 1 min during exercise for the unloaded squats with WBV condition ($P < 0.05$). "f" indicates significant increases over 1 min during exercise for the loaded squats with WBV condition ($P < 0.05$). None of the differences between conditions reached statistical significance. Data are shown as mean (n = 10) and error bars indicate SEM.**

### *2.3.3. Forearm Blood Flow Responses*

There was no interaction between condition and time for forearm blood flow (FBF) ($P = 0.605$). At baseline prior to the exercise, FBF was similar for the four various conditions ($P > 0.05$) (Figure 2.5). The calculated coefficient of variation was found to be 11.4 % for the measurement of the baseline FBF. There was also no significant difference in FBF among the four various conditions at any time point ($P = 0.951$). Following exercise, at 1.5 minute of the recovery period, FBF tended to increase over baseline with the unloaded squats condition but did not reach significance. The addition of WBV to unloaded squats resulted in an attenuation in the increase of FBF when compared to the unloaded squats condition. In contrast, FBF was unchanged over baseline in the loaded squats condition, and although it increased from loaded squats to loaded squats with WBV, it did not reach significance.

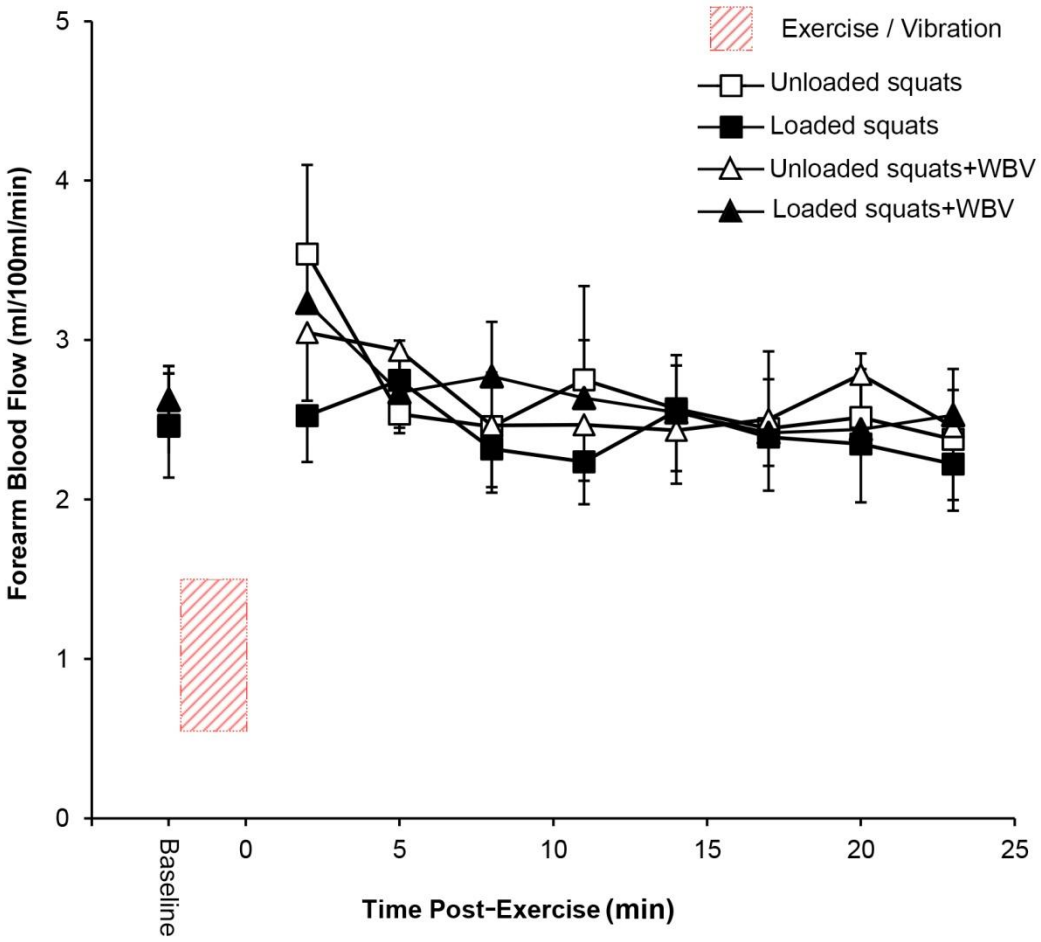


**Figure 2.5 Forearm blood flow (FBF) pre- and post-exercise at various time points.**

**None of the differences between conditions reached statistical significance. Data are shown as mean (n = 10) and error bars indicate SEM.**

### *2.3.4. Mean Brachial Arterial Blood Pressure Responses*

There was no interaction between condition and time for mean brachial arterial pressure (MAP) ($P = 0.758$). MAP in the four various conditions were not different at the baseline ($P > 0.05$) and there was no significant difference in MAP between the four various conditions at any time point ($P = 0.903$) (Figure 2.6). There were also no significant differences in MAP over baseline for either the unloaded or loaded squats with or without WBV conditions at any time point ($P > 0.05$).

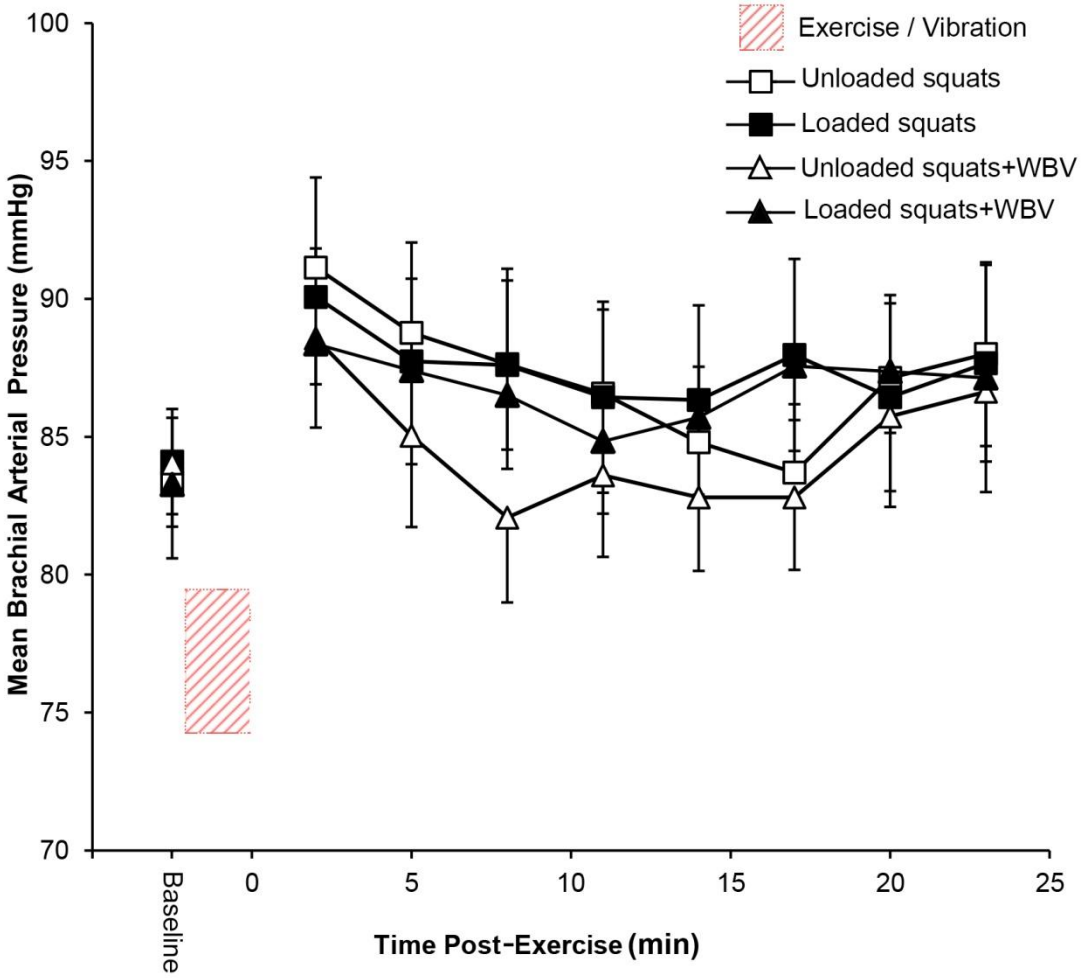


**Figure 2.6 Mean brachial arterial blood pressure (MAP) pre- and post-exercise at various time points.**

**None of the observed changes reached statistical significance. Data are shown as mean (n = 10) and error bars indicate SEM.**

### *2.3.5. Arm Vascular Conductance Responses*

There was no interaction between conditions and time for arm vascular conductance (AVC) ($P > 0.05$). AVC in the four various conditions were similar at the baseline ($P > 0.05$) and there was no significant difference in AVC among the four various conditions at any time point ($P > 0.05$) (Figure 2.7). There were also no significant differences in AVC over baseline for either the unloaded or loaded squats with or without WBV conditions at any time point ($P > 0.05$).

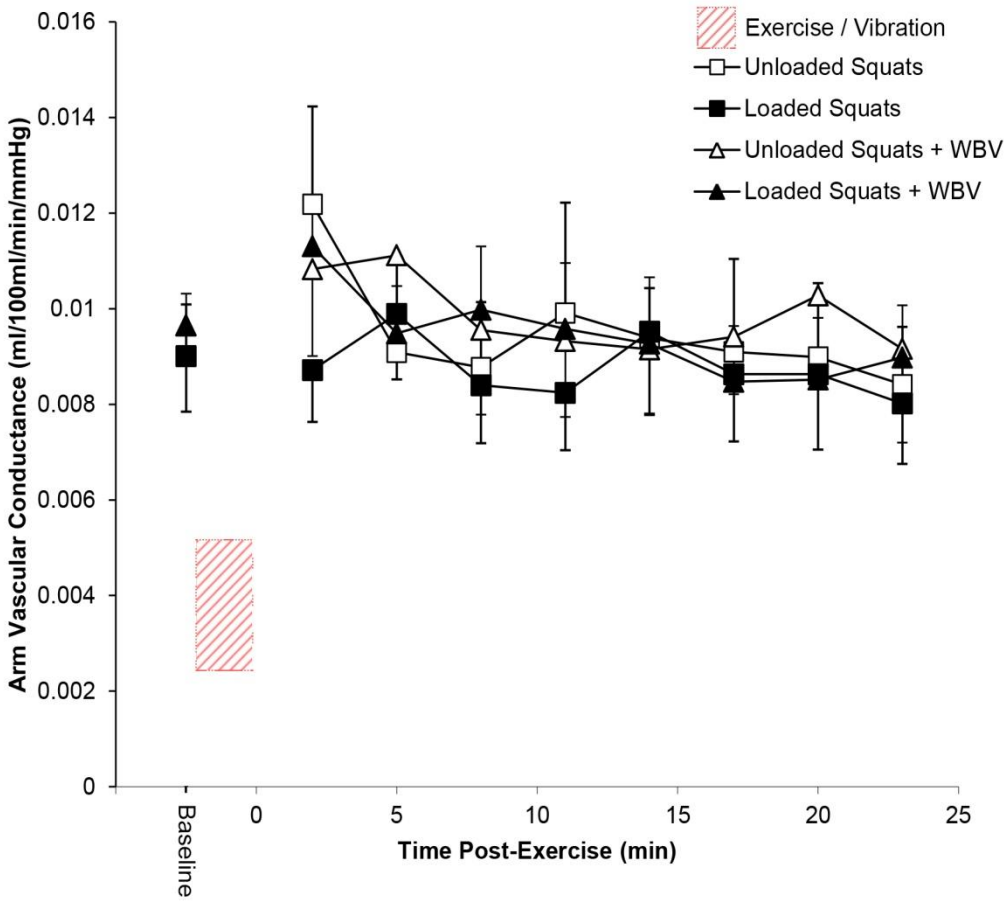


**Figure 2.7 Arm vascular conductance (AVC) pre- and post-exercise at various time points.**

**None of the observed changes reached statistical significance. Data are shown as mean (n = 10) and error bars indicate SEM.**

## 2.4. Discussion

The current study examined the markers of systemic circulating function following an acute bout of whole body vibration (WBV) combined with dynamic squatting exercise at two varying intensities (unloaded and loaded). The main finding from this study was that the addition of WBV during unloaded and loaded squatting exercise did not result in any statistically significant differences in forearm blood flow (FBF), mean arterial pressure (MAP), arm vascular conductance (AVC) or heart rate (HR) in the post-exercise period, when compared with the unloaded or loaded squat exercises alone in healthy young adults.

The present data show that HR was substantially increased over baseline during 1 minute (30 squats) and 2 minutes exercise (60 squats), but without significant differences between the four various conditions. These data suggest that metabolic demand increased during all the squatting exercise conditions; thus the effects of exercise on cardiovascular function occurred during all exercise conditions. However, the effect of WBV during squatting exercise with and without load resulted in a significant increase in HR after 60 squats relative to the increase after 30 squats, while this difference between the 30 and 60 squats was absent in the unloaded and loaded squat exercise conditions. It seems that with the addition of WBV exposure, the metabolic requirement progressively increased as exercise progressed, therefore exposure to WBV appears to make a greater demand on cardiovascular function. Thus, these findings suggest that the addition of WBV to unloaded and loaded squat exercises may lead to a relatively higher metabolic rate than the unloaded and loaded squats exercises alone.

On the other hand, there was an overall trend towards differences in FBF observed 1.5 minute into the recovery period after exercise. FBF appeared to increase in the unloaded squats alone condition but this did not reach significance, whereas this increase in FBF was attenuated in response to unloaded squats with WBV treatment. In contrast, FBF remained unchanged compared with the baseline in the loaded squats alone condition and although it appeared to increase from loaded squats alone to loaded squats with WBV exposure, this apparent change did not reach significance.

Green et al. (2002) demonstrated that a significant increase in FBF was found during 3 minutes of high workloads of cycle ergometer exercise at 100 and 160 Watts. In

contrast, FBF significantly decreased in response to a lower cycle workload at 40 Watts and remained unchanged between 60 and 80 Watt workloads and baseline. Furthermore, another study by Green et al. (2005) noted that at a high workload of 120 Watts, FBF increased within only 3 minutes of cycle ergometer exercise. Conversely, FBF during lower cycle workloads at 60 and 80 Watts was substantially lower than baseline. These observations indicate that a moderately-high workload exercise (oxygen consumption ~1.8 l/min) can increases distal blood flow (i.e. FBF), while distal blood flow decreases or does not change during low workload exercise, and thus different exercise workloads present different haemodynamic stimuli to the endothelium.

In the current study, it has been assumed that WBV exposure combined with unloaded squat exercise was intended to be at low intensity, whereas the combination of WBV with loaded squat exercise was intended to be at high intensity in order to be comparable with the intensities used on the studies by Green et al. (2002) and Green et al. (2005). However, the workloads in both unloaded and loaded squatting exercise (approximately equal to 190 and 215 Watts, respectively) were in all likelihood higher than the lower exercise intensities used in Green et al. (2002) and Green et al. (2005). It seems that the blood flow response may differ in the distal limb during higher intensity exercise. This, indeed, might be a possible explanation of the case with the results of FBF in the current study, which showed no significant differences in FBF observed after unloaded and loaded WBV compared to the unloaded and loaded squatting exercise conditions, respectively. Thus, it appears that it is not possible to detect an effect of WBV in upper limb blood flow due to high intensity of exercise.

Moreover, it has been found that brachial retrograde diastolic flow increased substantially during all cycling exercise workloads, while brachial antegrade systolic flow progressively increased with increasing workloads of cycle ergometer exercise (Green et al., 2005, Green et al., 2002). These observations indicate that the differences in the response of FBF with different workloads of exercise were related to the impact of retrograde diastolic flow, which was relatively larger at lower workloads of exercise, rather than antegrade systolic flow, which was modest during all exercise intensities. The responses in antegrade and retrograde flow during cycling exercise were in contrast to those observed during forearm exercise (handgrip), where antegrade flow in the brachial artery was higher than in leg exercise and retrograde flow was extremely low. Therefore, these findings suggest that retrograde diastolic flow, rather than antegrade

systolic flow, plays an essential role in the responses of blood flow in a distal limb during different intensities of systemic exercise, in particular at lower intensity of exercise. Consequently, it is hypothesised that retrograde diastolic blood flow in FBF was relatively high during all the conditions of unloaded and loaded squatting exercises, and with and without WBV, which resulted in no statistical significant difference between these conditions in terms of FBF.

Overall, there are several possible explanations consistent with these observations. One possible explanation is that the sensitivity of the equipment to detect a change in upper limb blood flow may have been too small or the effect only lasted for a very short duration. This might be due to either the intensity of vibration (i.e. frequency, amplitude, therefore acceleration), duration of the exposure, the body position, or the type of vibration platform. Another possible explanation is that the experimental design required the subject to undergo the WBV combined with the varying intensities of squatting exercise, in an identical manner to the studies by Green et al. (2002) and Green et al. (2005); therefore vasodilatation in the activated skeletal muscle of the lower could 'steal' the blood flow from distal site (i.e. forearm) to the main site (i.e. lower limb), as described by Green et al. (2002) and Green et al. (2005). It could be possible that systemic blood flow might respond to exposure to vibration but the metabolic requirement from skeletal muscle activation could result in redirecting blood flow from forearm to the lower limb as a likely response. Hence, the present results were not clear enough to indicate any potential vasodilatory effects of WBV on upper limb blood flow. In order to avoid the complication of skeletal muscle activation at high intensity, a new model of the effects of vibration exposure is needed to be developed for future studies.

In conclusion, there were varying responses but without any statistically significant difference in HR between conditions during and after the intervention. Neither was there any effect on FBF, MAP and AVC following the intervention between the four various conditions. These results suggest that there was a pressor response to exercise but the effects of WBV on the vascular function were not clear enough to indicate any potential vasodilatory effects, which is most likely due to the high intensity of exercise undertaken. These results should be considered preliminary, but indicate that the potential systemic effect of cardiovascular system warrants further investigation via a new approach of vibration exposure or better methods of analysis.

# Chapter 3 - Effects of Passive Lower Limb Vibration on the Peripheral Cardiovascular System

## 3.1. Introduction

Whole body vibration (WBV) exercise, which involves standing on a vibrating platform and can be employed as a novel form of exercise, has been reported to have beneficial effects on the musculoskeletal system (Torvinen et al., 2002a, Cochrane and Stannard, 2005). Torvinen et al. (2002a) noted an increase in the isometric extension strength of lower extremities (muscle strength) and jump height (muscle power) as well as an improvement in body balance (body stability) after exposure to WBV. In addition, Cochrane and Stannard (2005) reported an increase in jump height (muscle power) and flexibility following exposure to WBV. In an earlier study Burke et al. (1976b) demonstrated that exposure to vibration can increase the activity of the muscle spindle and Golgi tendon organ, which could be indicative of an increase in skeletal muscle activity. Indeed, electromyography activity data have shown that exposure to WBV increases skeletal muscle activity (Cardinale and Lim, 2003, Abercromby et al., 2007a, Hazell et al., 2007). It is also well known that an increase in muscle fibre activity can result in an increase in blood flow. Several studies have observed an increase in local muscular blood flow in response to WBV exposure (Hazell et al., 2008, Lythgo et al., 2009, Kerschan-Schindl et al., 2001, Stewart et al., 2005, Herrero et al., 2011b, Herrero et al., 2011a). It is therefore suggested that this increase response within the local muscular blood flow may be due to functional hyperaemia in response to skeletal muscle activation by WBV, as a secondary effect or a direct effect of vibration induced shear stress on the peripheral cardiovascular function, as a primary effect.

It has been previously documented, by Burke et al. (1976b) that activation of skeletal muscle was found to be relatively low in response to passively applied vibration to a limb. Their data suggest that vibration applied to unloaded muscles appears to provide only a minimal stimulus for skeletal muscle activation. A study performed by Lohman et al. (2007) reported that immediately after applying 3 minutes of acute passive vibration (30 Hz frequency and amplitude of 5-6 mm with vertical displacement; acceleration equal to 9.1-10.9 g) to a lower limb, skin blood flow was significantly increased over the calf (gastrocnemius) by 250 % and remained significantly higher by 200 % above baseline during 10 minutes of recovery. A follow-up passive vibration study by Maloney-Hinds et al. (2008) reported an increase in forearm skin blood flow during 10 minutes of passively applied vibration (30 and 50 Hz frequencies and amplitude of 5-6 mm with vertical displacement; acceleration equal to 9.1-10.9 g and

25.5-30.2 g, respectively) to the dominant arm, which remained elevated during 15 minutes recovery post-passive vibration exposure. Lohman et al. (2011) noted a significant increase in skin blood flow over a calf muscle, observed in response to 10 minutes of acute passive lower leg vibration (50 Hz frequency and amplitude of 5-6 mm with vertical displacement; acceleration equal to 25.2-30.2 g), and which continued into 9 minutes recovery. Another study by Lohman et al. (2012) reported that immediately after applying 10 minutes of acute passive lower limb vibration, calf skin blood flow was significantly increased, by 67 %, and remained significantly higher, by 37 % over baseline for the following 10 minutes of recovery. Generally, these passive vibration studies might be indicative that vibration has a direct effect on the peripheral cardiovascular function; however, the mechanism underlying this effect is not all well understood.

Even though passive vibration provides a minimal stimulus for skeletal muscle activation (Burke et al., 1976b), it is unknown whether this increase response within the localised blood flow is a secondary effect in response to skeletal muscle activation or a separate effect on the peripheral cardiovascular function. The potential for WBV to produce shear stress within the vascular tree is of interest for its angiogenesis-inducing potential. The initial WBV study (Chapter 2) of this thesis examined the effect of WBV combined with varying intensities (unloaded and loaded) of squatting exercises on systemic blood flow [i.e. distal blood flow (forearm)], in order to be comparable with the Green's studies (2005, 2002). The unloaded and loaded squatting exercises, with and without exposure to WBV, resulted in no significant differences in forearm blood flow (FBF) and arm vascular conductance (AVC) between these conditions. It was concluded that the intensity during all exercise conditions was high, which may lead the blood flow to respond differently in the distal limb, due to skeletal muscle activation 'stealing' the blood flow from the forearm to the lower limb. There might be an effect of shear-stress on the blood vessel, occurring in response to WBV exposure, but the combination of exposure to WBV with exercise caused a high intensity of exercise that could have complicated the effects of WBV on the vascular function. Consequently, the results were not clear enough to indicate any potential vasodilatory effect of WBV on upper limb blood flow.

Therefore, it was difficult to investigate the potential mechanism of the effects of vibration on peripheral cardiovascular function, due to the combination of vibration

exposure to either static or dynamic squats which activate skeletal muscle, thereby complicating the effects of vibration on the vascular function. In order to focus solely on the potential mechanism inducing effects and avoid complications due to skeletal muscle activation (Pollock et al., 2010), a technique to apply vibration passively to the lower limb has been used in this study in a way comparable with the protocol used by Lohman et al (2007). The aim of this study was to investigate the potential effects of passive vibration on the peripheral circulation. It was hypothesised that acute exposure of the lower limbs to vibration stimulation, while lying in a supine position, would result in an increased vasodilatation that would enhance the peripheral blood flow beyond that in the control condition.

## 3.2. Methods

### *3.2.1. Participants*

Twenty two healthy young adults (12 males, 10 females) with an age range from 18 to 27 years were recruited to take part in the study. The subjects were recruited from the general population of the Heriot-Watt University and from personal contacts. The study was approved by the Ethics Committee of the School of Life Sciences at the Heriot-Watt University and was conducted in accordance with the Declaration of Helsinki. The participants were fully informed verbally and in writing of the purposes and protocol of the study, and any risks and discomfort associated with the experiment before giving their written informed consent to participate. Each volunteer completed a health screening questionnaire prior to commencing the study. Subjects completed both vibration and control (sham) treatment sessions and were randomly ordered to these treatments (described below in Experimental Sessions, 3.2.4). The subjects were acquainted with the procedures of the study during a familiarisation session (described below in the Familiarisation Session, 3.2.3).

As ascertained from the health screening questionnaire, with respect to regular physical activity, all volunteers were required to be active but not highly trained, and subjects who had previous health issues, in particular any related to the cardiovascular system, were excluded from this experiment. Because the subjects' calf was in direct contact with the vibration platform, there were further exclusionary criteria: subjects who had undertaken a long haul flight in the previous week as well as anyone who was positive for a Homan's sign (described below in the Familiarisation Session, 3.2.3) as part of the health screening were excluded due to the potential risk of having a deep vein thrombosis, which is a contraindication to WBV.

Subjects were asked to maintain their regular diet and normal life-style patterns during the study period. Subjects were asked to refrain from drinking alcohol and avoid the consumption of caffeine-containing beverages (e.g. tea, coffee, coca cola) from at least the night prior participating in each test session. Subjects were also asked to refrain from participating in any heavy strenuous physical activity at least two days prior to each test session. The subjects were barefoot during the test sessions, to avoid footwear dependent attenuation of the vibration.

All procedures associated with the investigation were undertaken in the Laboratory of Sport and Exercise Sciences Department located in the Sports Academy at the Heriot-Watt University. Temperature in the laboratory was regulated between 21 to 23 °C. Upon arriving at the laboratory, subjects assumed a supine position on supporting foam mats during each session.

### *3.2.2. Overview of Experimental Method*

Subjects completed three sessions on three separate occasions. Before the experimental protocol, subjects initially performed a familiarisation session in order to become accustomed to all the cardiovascular measurements, treatment procedures and to vibration exposure (as described below in the Familiarisation Session, 3.2.3). The experimental protocol involved completing two separate sessions under two different treatments, with or without vibration. There was at least one day between the sessions. The experimental procedure consisted of (i) baseline measurement of heart rate (HR), brachial blood pressure (BP), ankle systolic blood pressure (ASBP), forearm blood flow (FBF) and lower leg blood flow (LLBF); (ii) a treatment with or without exposure to vibration; and (iii) post-treatment measurements that were conducted in an identical manner to the baseline measurements. The key variables of interest in this study were FBF, LLBF, brachial systolic blood pressure (BSBP), ASBP, ankle brachial pressure index (ABPI), arm vascular conductance (AVC), lower leg vascular conductance (LLVC) and HR. During all sessions, subjects were required to lie down in the supine position, with their arm and leg resting and elevated on foam mats specially designed to be equivalent to the height of the vibration platform, as shown in Figure 3.1.

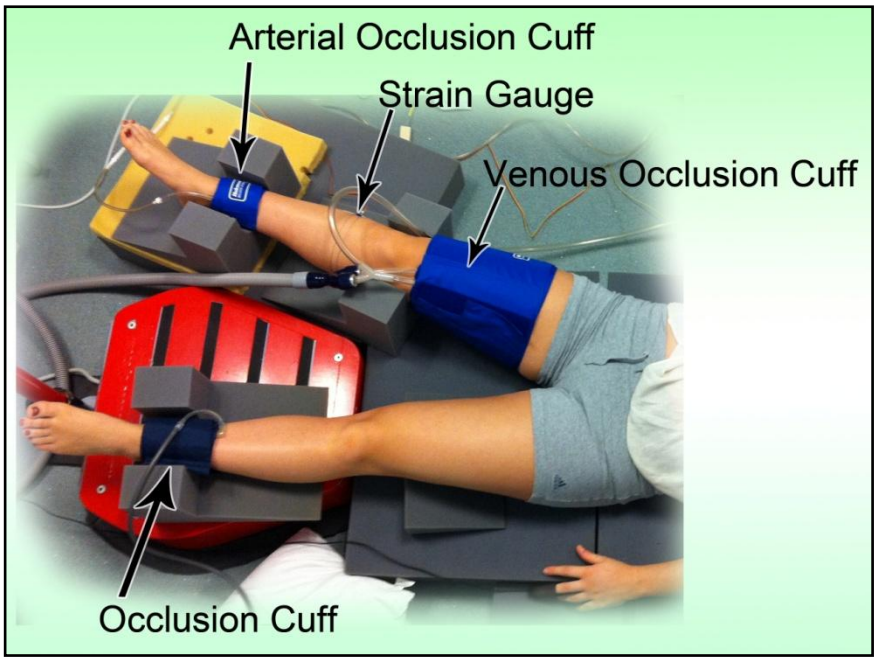


**Figure 3.1 Application of lower limb variable measurements with subject lying in the supine position with leg resting and elevated on foam mats specially designed to be equivalent in height to the vibrating platform.**

### *3.2.3. Familiarisation Session*

After the participants had given their written and informed consent, they completed the health screening questionnaire and their age, height, body mass, resting BP and HR were recorded. The Homan's sign test was performed to assess for pain or resistance in the posterior aspect of the calf through passive dorsiflexion in the subject's ankle, and if they did not pass this test they would be excluded from the study.

Subjects then lay down in a supine position with their arm resting on supporting foam mats and with their calves positioned with the toes pointing outward 30 to 45 ° to maximise the calves' contact with the vibration platform. Measurements of the circumference of the widest part of the forearm and calf were completed for application of the strain gauges in the experimental sessions. In order to familiarise the participants with the cuffs and the measurements before testing to avoid stress and excitement on the day of testing at the experimental sessions, venous occlusion plethysmograph (Hokanson, Bellvue, WA, USA), an automated BP monitor (Tango+, SunTech Medical Instruments, NC, USA), and a Doppler flow probe (HI ∘ dop BT-200 Vascular Doppler, Bistos Co., Seoul, Korea) were demonstrated at a separate time. Finally, subjects' legs

were moved slowly and comfortably by a researcher, and placed on a vibrating platform in order to familiarise them with the sensation of the vibration, which was set at a frequency of 40 Hz for a period of 30 seconds.

### *3.2.4. Experimental Sessions*

The two experimental sessions were composed of passive vibration of the lower legs and control (sham) treatments. During the treatments, the subjects lay down in the supine position while their lower legs rested on the vibration platform, as applied in the familiarisation session. The treatments, either control or passive lower leg vibration, consisted of three 60 seconds bouts with 10 seconds rest between bouts, giving a total duration of 3 minutes and 20 seconds, which was similar to the protocol used in a previous study (Lohman et al., 2007). A Latin square design was used to assign the participants to undergo one of the treatments that either started with control or vibration treatments. All experimental sessions were conducted in the morning, in order to avoid any potential of order effect from circadian rhythms that could affect the cardiovascular system.

On the testing day, all the equipment was set up and the room temperature pre-warmed to 21-23 °C for at least 30 minutes prior to the arrival of subjects, so that the temperature of all the supporting foam mats, equipment and walls was similar. On arrival at the laboratory, subjects lay down in the supine position on supporting foam mats for 15 minutes, to achieve a baseline blood flow prior to vascular function testing and also to acclimatise to the temperature in the room. Baseline FBF and LLBF, brachial BP and HR, and ASBP measurements were taken after 15 minutes of supine rest. Following the baseline measurements, subjects' legs were then passively moved slowly and comfortably from the supporting foam mats and placed on the vibration platform. Next, subjects underwent one of the treatments, either control or vibration. Immediately after completing the treatment, and while subjects were resting in the supine position, the subjects' legs were passively moved back slowly and comfortably from the vibration platform, and placed on the supporting foam mats for 10 minutes of recovery. Finally, the post-treatment measurements were performed 1 minute following treatment and then repeated at 3 minutes intervals thereafter for a total of 10 minutes of recovery, which ended the session. The second experimental session was conducted in an identical manner to the procedure of first experimental session.

### *Vibration Session*

Vibration stimulus was applied to the subjects' lower legs through a vertical sinusoidal vibration using the Nemes device (Nemes, Bosco System, Italy) while subjects were lying in the supine position (shown in the lower left corner of Figure 3.1). This study used the same vibration device as that employed in the initial WBV study (Chapter 2) of this thesis. Because the amplitude in the vibration device was constant at 3 mm, the parameters of the mechanical vibration stimulus were set at the frequency of 40 Hz with the vertical displacement, which produced a peak acceleration of approximately 10 g (i.e. 10 x 9.81 $m/s^2$) in order to reach the same acceleration as used in a previous study (Lohman et al., 2007).

### *Control Session*

The control session was conducted in an identical manner to the passive vibration session but without the Nemes device being switched on, i.e. at a frequency of 0 Hz, and the amplitude of 0 mm to constitute the sham treatment.

### *Accelerometer Calibration*

The frequency, amplitude and acceleration of vibration were measured using a digital accelerometer (4000A Accelerometer, Measurement Specialties, CA, USA), and the measurements were conducted in an identical manner to those in the initial WBV study (Chapter 2) of this thesis.

## *3.2.5. Measurements*

All subjects completed the vascular function assessments pre- and post- both vibration and control treatments. All measurements were performed following 15 minutes of supine rest to establish baseline values, then 1 minute after treatment and repeated every 3 minutes for a total of 10 minutes of recovery. FBF and LLBF were measured using an automated venous occlusion strain gauge plethysmograph (Hokanson, Bellvue, WA, USA), in an identical manner to the measurement of FBF in the initial WBV study (Chapter 2), however, with some development in the procedure. This was the addition of a leg venous occlusion cuff ($CC22^{TM}$, Hokanson, Bellvue, WA, USA) to the right thigh was attached, while a leg arterial occlusion cuff ($TMC7^{TM}$, Hokanson, Bellvue, WA, USA) was attached around the right ankle. The arterial occlusion cuffs in both wrist and ankle were inflated using an adjustable arterial occlusion air pressure source

(moorVMS-PRES, Moor Instruments, Devon, England). Another development was that a Powerlab (PowerLab /16SP, ADInstruments, Castle Hill, Australia) was used to automate the balancing of the strain gauge plethysmograph cuffs via rapid inflation of both the brachial and thigh venous occlusion cuffs (E20 Rapid Cuff Inflator and AG101 Cuff Inflator Air Source, Hokanson, Bellvue, WA, USA) for 6 seconds followed by deflation for 6 seconds, repeated five times, as shown in Figure 3.2. The mean slope of the blood flow was taken from the first three acceptable measurements of each of the five slopes.

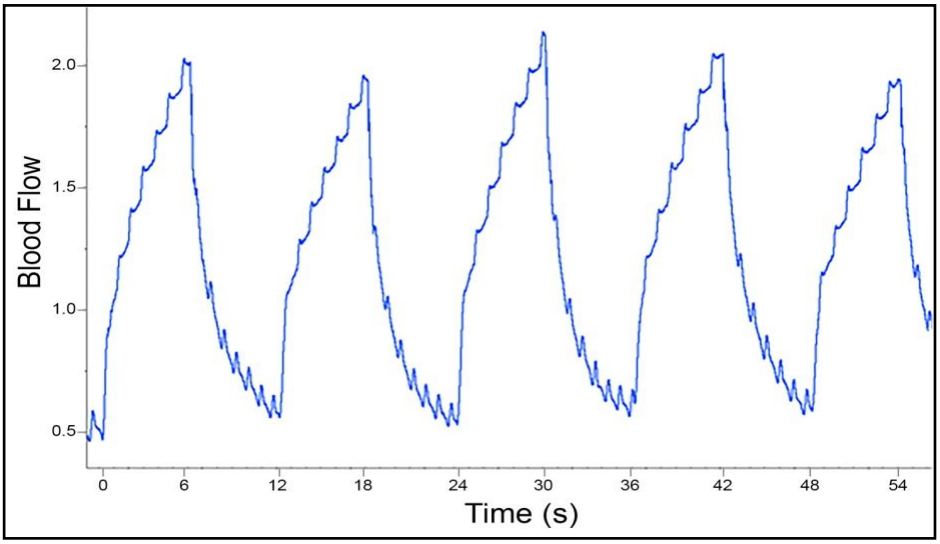


**Figure 3.2 Example trace from one subject, showing the 5 cycles of strain gauge measurement in response to rapid inflation for 6 seconds and then release for 6 seconds.**

Brachial BP was measured using an automated monitor (Tango+, SunTech Medical Instruments, NC, USA); the measurement was conducted in an identical manner to that described for the initial WBV study (Chapter 2). The HR was recorded and taken from the automated monitor. The ASBP was measured using a 4 megahertz Doppler ultrasound probe (HI ∘ dop BT-200 Vascular Doppler, Bistos Co., Seoul, Korea) and a sphygmomanometer cuff (TMC7$^{TM}$, Hokanson, Bellvue, WA, USA). The Doppler ultrasound probe was positioned on the dorsalis pedis in the subject's left foot at angle of 45 ° to skin surface in line with the tibial artery, using contact gel to obtain a clear heartbeat sound. The sphygmomanometer cuff was placed on the subject's left ankle

and inflated with a handheld sphygmomanometer (DS400 Aneroid Sphygmomanometer, Hokanson, Bellvue, WA, USA) until the heart beat disappeared, which is above the ASBP, then pressure was slowly deflated until the heart beat sound reappeared, which indicated the ASBP. This procedure was carried out in duplicate in order to obtain the ASBP twice. Immediately after obtaining the second ASBP measurement, the ankle cuff was quickly deflated. The ABPI is the ratio of the ASBP to BSBP. The ABPI was calculated using the equation:

$$ABPI = \frac{ASBP}{BSBP}$$

where ABPI is ankle brachial pressure index (mmHg), ASBP is ankle systolic blood pressure (mmHg), and BSBP is brachial systolic blood pressure (mmHg). The higher of the two values of ASBP was used to calculate the ABPI. The vascular conductance is the ratio of the blood flow to mean arterial blood pressure. The AVC was calculated using the formula:

$$AVC = \frac{FBF}{MAP}$$

where AVC is arm vascular conductance (ml/100ml/min/mmHg), FBF is forearm blood flow (ml/100ml/min), and MAP is mean arterial blood pressure (mmHg). The LLVC was calculated using the equation:

$$LLVC = \frac{LLBF}{MAP}$$

where *LLVC* is lower leg vascular conductance (ml/100ml/min/mmHg), LLBF is lower leg blood flow (ml/100ml/min), and MAP is mean arterial blood pressure (mmHg).

### *Strain Gauge Viability*

Each strain gauge was tested for viability using a specially built apparatus of rubber tubes with an inflatable cuff and the test was conducted in an identical manner to that in the initial WBV study (Chapter 2).

### *3.2.6. Statistical Analysis*

All the data were analysed using Minitab 17 statistics software (version 17.1.0, Minitab). Data presented in the results are mean ± SEM. Statistical analysis was performed using analysis of variance (ANOVA) with a mixed, that is fixed and random, effects model with statistical significance accepted at $P < 0.05$. Post-hoc tests for significant differences were performed using the Bonferonni correction, with an uncorrected 1-sided alpha value of 0.05 (Kutner et al., 2005), Chapter 27, 1127-1172.

## 3.3. Results

### *3.3.1. Subject Characteristics*

Eighteen (mean ± SD; age 22.0 ± 2.3 years, height 1.72 ± 0.09 m, body mass 70.1 ± 13.0 kg) out of the twenty two participants successfully completed the sessions with 100 % compliance and free of injury. Four subjects (3 male, 1 female) withdrew from the study after completing the familiarisation session, for reasons unrelated to the experiment. Despite the fact that subjects did not report any severe side effects or adverse reactions related to vibration, seven subjects (3 males, 4 females) reported some transient itching of the legs during and after about 1 to 2 min of vibration treatment. This symptom was always temporary, mild, not disturbing, and resolved rapidly.

### *3.3.2. Forearm Blood Flow Responses*

There was no interaction between condition and time for forearm blood flow (FBF) ($P = 0.349$). FBF was significantly different between the control and passive vibration conditions at baseline prior to the intervention as well as 1 minute and 4 minutes into recovery after intervention ($P < 0.05$) (Figure 3.3 A). The calculated coefficient of variation was found to be 33.3 % for the measurement of the baseline FBF. There was no significant difference in FBF for either the control or passive vibration conditions at any time point over baseline ($P = 0.150$). Following intervention with the passive vibration condition, FBF tended to reduce after 1 minute of the recovery period, but did not reach significance ($P > 0.05$). Finally, FBF remained unchanged during the control condition ($P > 0.05$).

### *3.3.3. Lower Leg Blood Flow Responses*

There was a significant interaction between condition and time for lower leg blood flow (LLBF) ($P < 0.05$). At baseline, prior to the intervention, LLBF was similar in both the control and passive vibration conditions ($P > 0.05$) (Figure 3.3 B). The calculated coefficient of variation was found to be 26.6 % for the measurement of the baseline LLBF. A significant increase in LLBF with passive vibration was observed over the control condition at 1 minute and 10 minutes into recovery following intervention ($P < 0.05$). In contrast, LLBF was significantly reduced below the baseline during the control condition within all recovery time points following intervention (after 1 minute, 4 minutes, 7 minutes and 10 minutes recovery) ($P < 0.05$).

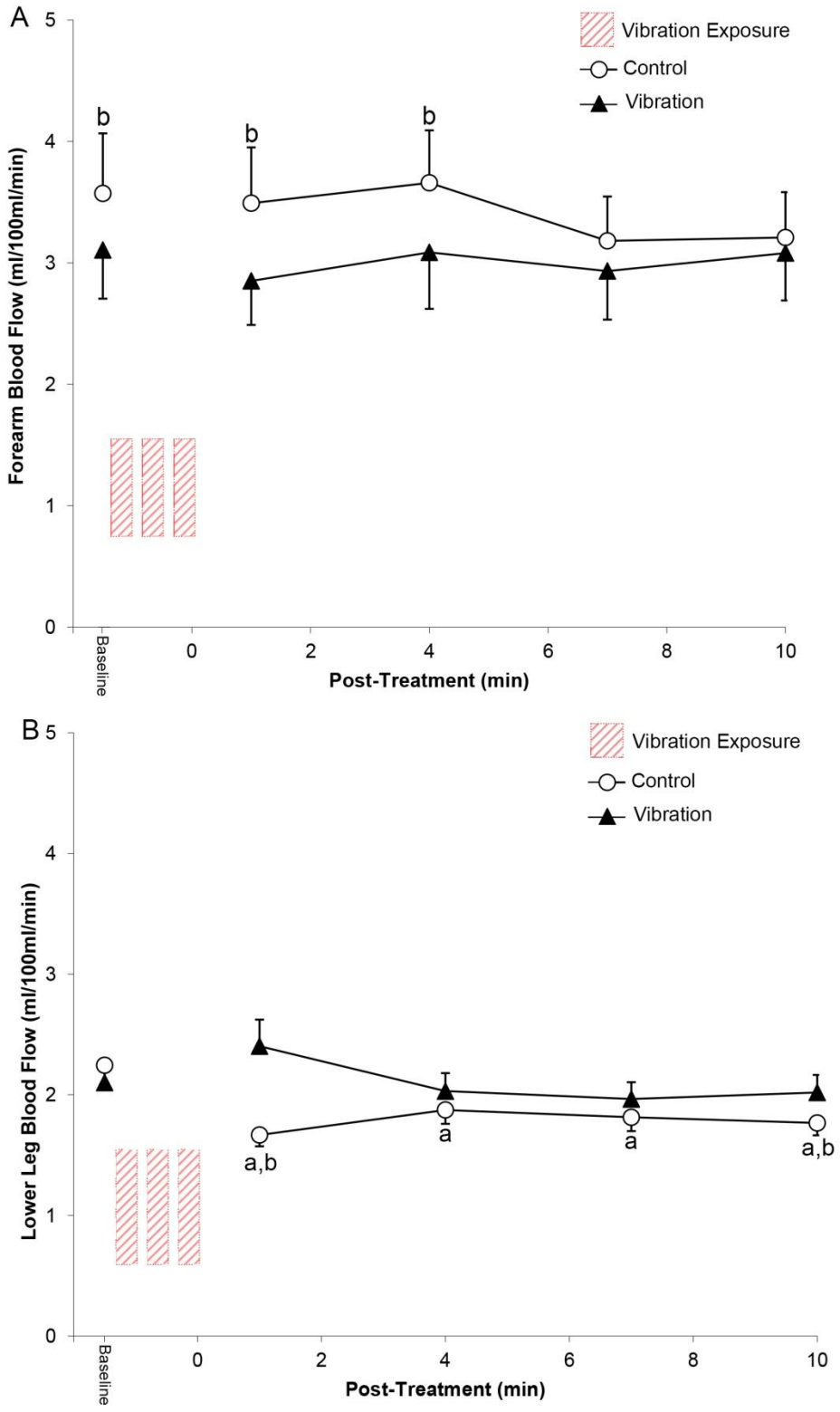


**Figure 3.3 Forearm blood flow (A) and lower leg blood flow (B) pre- and post-treatment at various time points.**

**"a" indicates significant differences below baseline for the control condition ($P < 0.05$). "b" indicates significant differences between the control and passive vibration conditions ($P < 0.05$). Data are shown as means ($n = 18$) and error bars indicate SEM.**

### *3.3.4. Brachial Systolic Blood Pressure Responses*

There was no interaction between condition and time for brachial systolic blood pressure (BSBP) ($P = 0.817$). BSBP was significantly different between the control and passive vibration conditions at baseline prior to the intervention as well as all recovery time points after intervention (after 1 minute, 4 minutes, 7 minutes and 10 minutes recovery) ($P < 0.05$) (Figure 3.4 A). There was no significant difference in BSBP for either the control or passive vibration conditions at any time point over baseline ($P = 0.814$).

### *3.3.5. Ankle Systolic Blood Pressure Responses*

There was a significant interaction between condition and time for ankle systolic blood pressure (ASBP) ($P < 0.05$). ASBP in the control and passive vibration conditions showed no difference at baseline prior to the intervention ($P > 0.05$) (Figure 3.4 B). There was a significant reduction in ASBP below the control condition with the passive vibration condition during all the recovery time points after intervention (after 1 minute, 4 minutes, 7 minutes and 10 minutes recovery) ($P < 0.05$). The control intervention did not affect ASBP at any time point ($P > 0.05$), while the passive vibration treatment significantly decreased ASBP below baseline at several recovery time points following intervention (after 1 minute, 4 minutes and 7 minutes recovery) ($P < 0.05$).

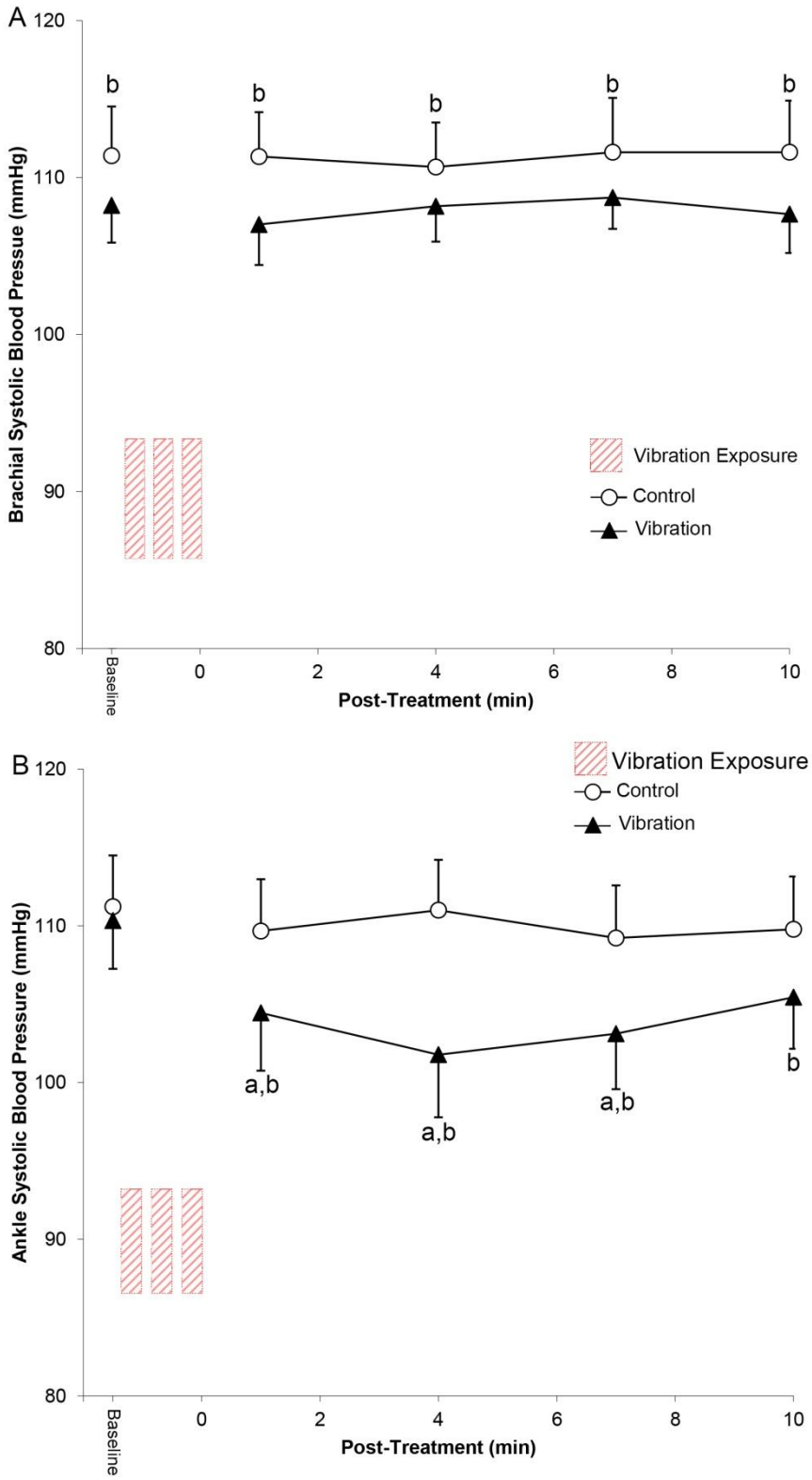


**Figure 3.4 Brachial systolic blood pressure (A) and ankle systolic blood pressure (B) pre- and post-treatment at various time points.**

**"a" indicates significant differences below baseline for the passive vibration condition ($P < 0.05$)."b" indicates significant differences between the control and passive vibration conditions ($P < 0.05$). Data are shown as means (n = 18) and error bars indicate SEM.**

### *3.3.6. Ankle Brachial Pressure Index Responses*

There was a significant interaction between condition and time for the ankle brachial pressure index (ABPI) ($P < 0.05$). Baseline ABPI in the control and passive vibration conditions was similar ($P > 0.05$) (Figure 3.5). ABPI decreased significantly below baseline at 4 minutes and 7 minutes into the post-passive vibration treatment recovery period ($P < 0.05$), whereas the control condition did not affect ABPI at any time point over baseline ($P > 0.05$). A significant reduction in ABPI compared to the control condition was also observed in response to passive vibration at 4 minutes and 7 minutes of recovery after intervention ($P < 0.05$).

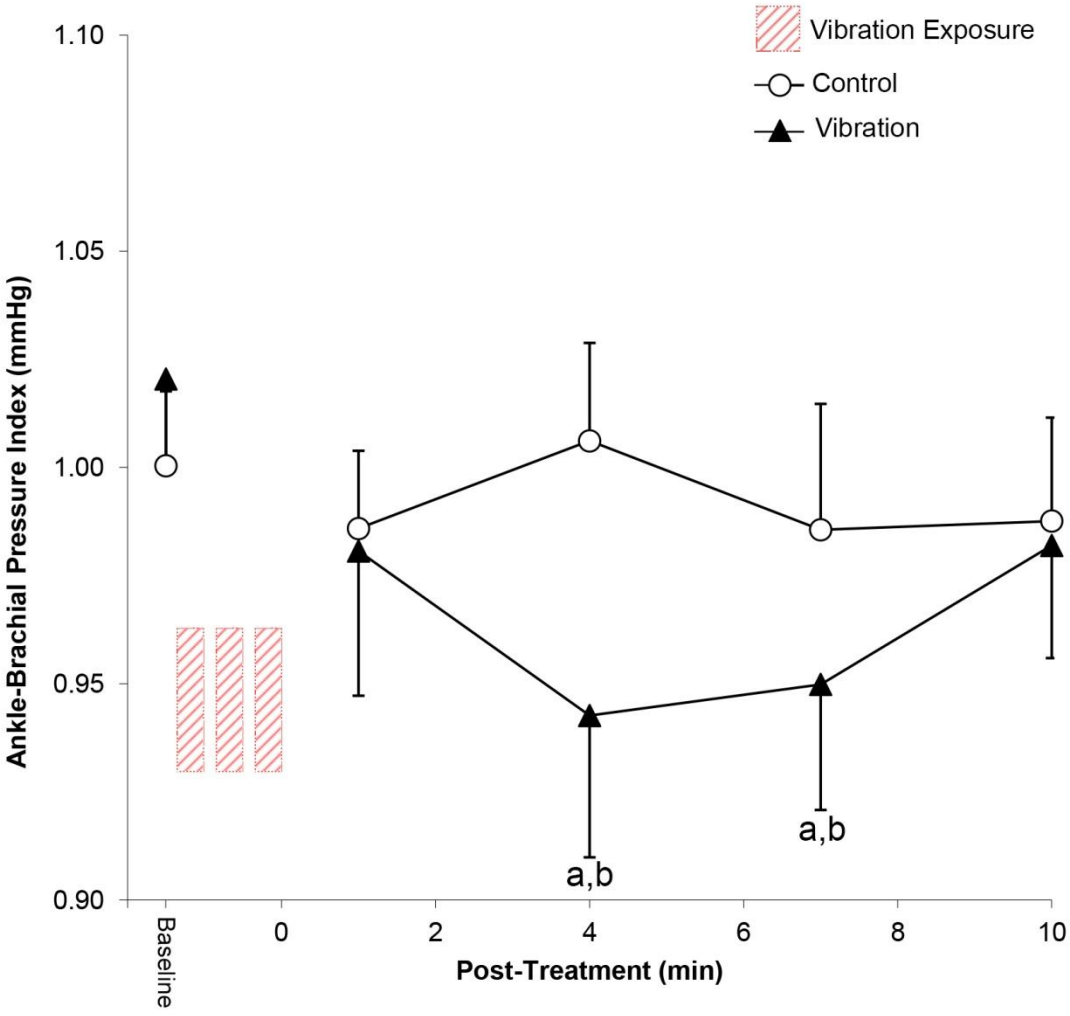


**Figure 3.5 Ankle brachial pressure index pre- and post-treatment at various time points.**

**"a" indicates significant differences below baseline for the passive vibration condition ($P < 0.05$). "b" indicates significant differences between the control and passive vibration conditions ($P < 0.05$). Data are shown as mean (n = 18) and error bars indicate SEM.**

### *3.3.7. Arm Vascular Conductance Responses*

There was no interaction between condition and time for arm vascular conductance (AVC) ($P = 0.208$). The AVC for the control was significantly higher compared with the passive vibration condition at baseline, as well as at 1 minute and 4 minutes recovery after intervention ($P < 0.05$) (Figure 3.6 A). There was no significant difference ($P = 0.052$) in AVC for either the control or passive vibration conditions at any time point when compared with the baseline. Following the intervention, at 1 minute of the recovery period, AVC tended to reduce below the baseline with the passive vibration condition but this failed to reach significance ($P > 0.05$). In contrast, AVC remained unchanged during control condition ($P > 0.05$).

### *3.3.8. Lower Leg Vascular Conductance Responses*

There was a significant interaction between condition and time for lower leg vascular conductance (LLVC) ($P < 0.05$). LLVC in both the control and passive vibration conditions was similar at baseline prior to the intervention ($P > 0.05$) (Figure 3.6 B). LLVC was significantly higher during all recovery time points post-passive vibration treatment (after 1 minute, 4 minutes, 7 minutes and 10 minutes recovery) when compared with the control condition ($P < 0.05$). In contrast, for the control condition, LLVC was observed to be significantly reduced below the baseline within all recovery time points post-intervention (1 minute, 4 minutes, 7 minutes and 10 minutes recovery) ($P < 0.05$).

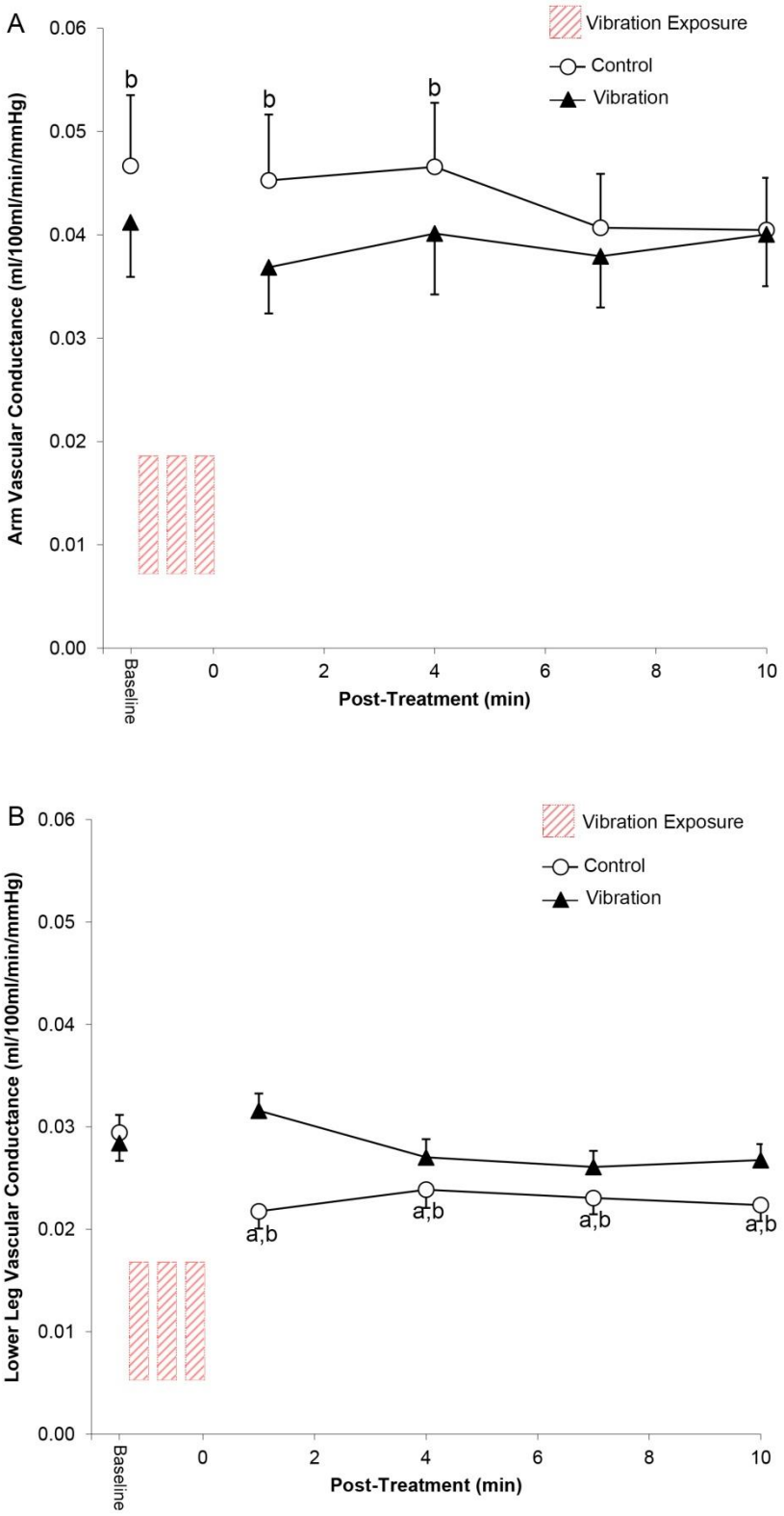


**Figure 3.6 Arm vascular conductance (A) and lower leg vascular conductance (B) pre- and post-treatment at various time points.**

**"a" indicates significant differences below baseline for the control condition ($P < 0.05$). "b" indicates significant differences between the control and passive vibration conditions ($P < 0.05$). Data are shown as mean (n = 18) and error bars indicate SEM.**

### *3.3.9. Heart Rate Responses*

There was no interaction between condition and time for heart rate (HR) ($P = 0.872$). HRs in the control and passive vibration conditions were not different at baseline ($P > 0.05$) and there was no difference in HR between the control and passive vibration conditions at any time point ($P = 0.977$) (Figure 3.7). There were also no significant differences in HR for either the control or passive vibration conditions at any time point over baseline ($P > 0.05$).

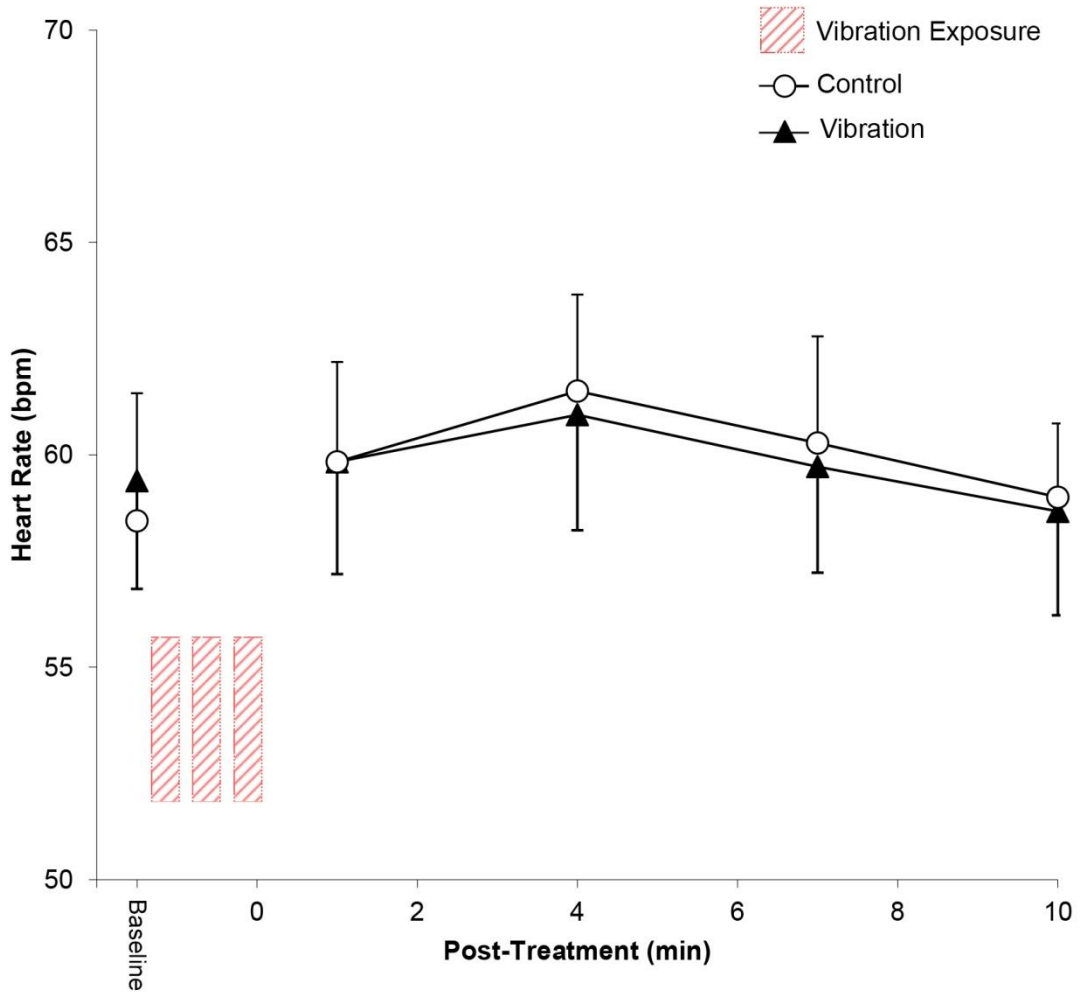


**Figure 3.7 Heart rate pre- and post-treatment at various time points.**

**None of the observed changes reached statistical significance. Data are shown as mean (n = 18) and error bars indicate SEM.**

## 3.4. Discussion

The current study examined the markers of peripheral and systemic circulating function following acute bouts of passive lower leg vibration. The main finding was that the addition of passive vibration resulted in a substantial reduction in ankle systolic blood pressure (ASBP) and a change in the ankle brachial pressure index (ABPI) during recovery following intervention: an observable effect, despite the assumed absence of skeletal muscle activation.

It has been postulated that when the subjects lie down horizontally in the supine position within the control and passive vibration conditions, and the vibration is passively applied to unloaded lower leg muscles with calves resting on the vibration platform, this would appear to provide a minimal stimulus for skeletal muscle activation. Indeed, the results relating to brachial systolic blood pressure (BSBP) and heart rate (HR) in the current study did not indicate any statistically significant difference in response to passive vibration treatment when compared to the baseline. Consequently, the unchanged in BSBP and HR is most likely due to an absence of skeletal muscle activation, suggesting that the stimulus intensity during vibration treatment was relatively low. These findings are in line with the observations made by Hazell et al. (2008), who reported that 15 minutes of acute passive vibration exposure to the feet did not show any significant difference in mean brachial arterial blood pressure and HR at any time point over baseline.

The ABPI is the ratio of the systolic blood pressure of the ankle to the brachial systolic blood pressure. In a previous study by Le Faucheur et al. (2006), it was reported that ASBP and ABPI were substantially decreased at 1 minute, 5 minutes and 10 minutes recovery post-maximal cycle ergometer exercise when compared to baseline. It is well known that if the ABPI were to fall, this would be indicative of an increased vasodilatation in the lower legs relative to the arms (Le Faucheur et al., 2006). This indeed was the case with the current results, which showed a significant decrease in ABPI during recovery after passive vibration intervention. This reduction in ABPI post-passive vibration treatment was related to the impact of a significantly decreased ASBP rather than a change in BSBP, which was negligible. Hence, the data from the present study appear to confirm and support the current hypothesis, which is that vasodilatation is increased in the lower limb, as reflected by the decreased ASBP and ABPI with passively applied vibration. A response which appears to be independent of skeletal

muscle activation and therefore, vibration appears to have a direct effect on peripheral cardiovascular system.

The present data show that passive vibration reduces ASBP and ABPI during recovery period due to a vasodilatation response; however, the underlying mechanism responsible for the increase in vasodilatation is unknown. It has been demonstrated that shear stress plays an essential role on the endothelium as the principal physiological stimulus for nitric oxide production by the constitutive nitric oxide synthase isoform; thus an increased shear stress induces vasodilatation in a blood vessel (Niebauer and Cooke, 1996, Green et al., 2005). A study by Rådegran and Saltin (1999) documented that a significant reduction, ~52 %, in femoral artery blood flow after blocking the nitric oxide production by using L-$N^G$-monomethyl arginine (L-NMMA) infusion was observed during rest and by 66 % at 10 minutes into recovery following exhaustive exercise when compared to saline infusion recovery. In contrast, this difference in femoral artery blood flow between the saline and L-NMMA infusion during submaximal exercise was absent, demonstrating that vasodilation in the contracting muscle is nitric oxide independent. Another study performed by Green et al. (2005) reported that after blocking the production of nitric oxide, blood flow was significantly decreased during rest, relative to the saline-infusion condition. The data from these studies indicate that blood flow during rest and recovery after exhaustive exercise could be related to a shear stress mediated release of nitric oxide from the endothelium. Consequently, the effects of vibration on the peripheral cardiovascular function are proposed to be due to pulsatile endothelial shear stress causing an increase in circulating nitric oxide concentration, as a result of increased endothelial nitric oxide synthase activity, which causes vasodilatation in resistant blood vessels (as described by Green et al. 2005). Thus, the most plausible explanation of the mechanism of this decrease in ABPI during recovery after vibration exposure is that it is due to a vasodilatation response that has occurred in the lower limb via inducing an increase in shear stress at the blood vessels' wall and the ASBP data appear to corroborate this suggestion.

It has been previously demonstrated that local skin blood flow significantly increased in response to passive vibration exposure. (Lohman et al., 2012, Lohman et al., 2007, Maloney-Hinds et al., 2008, Lohman et al., 2011). A study performed by Lohman et al. (2007) found that calf skin blood flow, measured by a laser Doppler imager, was significantly increased following 3 minutes of acute passive lower limb vibration.

Moreover, Maloney-Hinds et al. (2008) showed that 10 minutes of acute exposure to passive arm vibration resulted in an increase in forearm skin blood flow, measured by using a laser Doppler flow meter. Lohman et al. (2011) and Lohman et al. (2012) documented that a significant increase in calf skin blood flow, measured again by laser Doppler flowmetry, occurred in response to 10 minutes of acute passive lower leg vibration. However, 3 minutes of acute passive lower limb vibration in the present study did not result in a significant increase in local muscle blood flow [i.e. lower leg blood flow (LLBF) and lower leg vascular conductance (LLVC)]. This is might be due to a short duration of passive vibration exposure.

On the other hand, the effect of control condition in the current study resulted in a substantial decrease in LLBF and LLVC during recovery after sham exposure. Because the platform of vibration device, that used in this study, is made of metal and covered with adhesive covering film, it has been postulated that the reduction in LLBF and LLVC post-sham exposure is most likely due to a cooling effect from the vibration platform. Because of the fact that a cover might dampen a transfer of vibration to the body, adding a cover on the vibration platform was avoided. This cooling effect from the vibration platform needs to be considering in following studies by attaching a material to the vibration platform that does not dampen the transfer of vibration to the body, but avoids the cooling effect.

Furthermore, the result of the current study showed that forearm blood flow (FBF) and arm vascular conductance (AVC) tend to decrease at 1 minute of recovery after passive vibration exposure, whereas the responses of FBF and AVC were negligible during the control recovery period. An increase in distal blood flow (i.e. FBF) has been observed in response to lower limb exercise (cycle ergometer exercise) at a moderately-high intensity (oxygen consumption ~1.8 l/min), whereas FBF reduced or was unchanged during cycling exercise at low intensity (low metabolic rate) (Green et al., 2005, Green et al., 2002). Moreover, Green et al. (2005) reported that FBF was significantly reduced after L-NMMA infusion in response to cycling exercise at low intensity, compared to saline infusion. However, this difference in FBF between the saline and L-NMMA infusion during high intensity cycling exercise was absent, indicating that vasodilation in the contracting muscle is not related to the nitric oxide production. In addition, they found that the differences in the response of FBF with varying intensities of exercise were related to the influence of retrograde diastolic flow, which was relatively larger at

low intensity of exercise, rather than antegrade systolic flow, which was modest during all exercise intensities. Green et al. (2005) concluded that the importance of an oscillatory antegrade/retrograde flow pattern may be a very potent stimulus to shear stress mediated endothelial production of nitric oxide.

These findings suggest that retrograde diastolic flow plays a central role in the FBF responses during different intensities of systemic exercise, in particular at low exercise intensity, and that lower limb exercise at low intensity is a more potent stimulus to shear stress mediated release of nitric oxide from the endothelium than at high intensity exercise. Because the subjects in the present study lay down in a supine position during both conditions and the vibration was passively applied to unloaded lower leg muscles, with calves resting on the vibration platform, this appears to provide a minimal stimulus for skeletal muscle activation, leading the intensity of treatment during the control and passive vibration conditions to be low. Therefore, the present study confirms that the slight reduction in the FBF and AVC is due to a systemic effect in response to the low intensity of vibration which was passively applied to the lower limb, possibly inducing an increase in shear stress, and thus causing increased vasodilatation to occur in the lower limb that 'steals' the blood flow from distal site (i.e. forearm) to the main site (i.e. lower limb).

Furthermore, lower leg itching was observed in some subjects during and after vibration treatment, but it was always transient, mild, and not disturbing. This symptom is comparable to the observations of previous studies by Rittweger et al. (2000), Russo et al. (2003), Cronin et al. (2004), Roelants et al. (2004b), Hazell et al. (2008) and Broadbent et al. (2010), who reported transient itching of the legs in response to whole body vibration (WBV) in some of their subjects. It has been suggested that this symptom is related to the cardiovascular function and may be strong evidence of an increase in the shear stress occurring at the wall of the blood vessel, resulting in increased vasodilatation and thereby increasing blood flow in response to the vibration stimulation (Rittweger et al., 2000, Rittweger, 2010, Broadbent et al., 2010).

Overall, this symptom and the results of the present study suggest that there was a response effect occurring on vascular function during exposure to vibration, which appears to be independent of skeletal muscle activation, and is most likely a direct effect on the peripheral cardiovascular function by increased vasodilatation. One plausible

explanation consistent with these observations is that passive vibration applied to the lower legs induced shear stress resulting in a lower limb vasodilatory effect, an alternative mechanism could be due to localised heating, which in itself would also induce vasodilation. However, evidence of a cooling effect of the vibration platform resulting in a decrease in LLBF and LLVC, as observed with the control treatment, warrants consideration when designing future investigations.

In conclusion, application of passive vibration to the lower legs resulted in a reduction in ASBP and ABPI in the post-vibration period, despite the apparent absence of skeletal muscle activation. These data provide evidence for a direct effect of WBV on the peripheral cardiovascular function via an increase vasodilatation. It has been postulated that the two possible mechanisms explain this effect; 1) a vibration induced increase in shear stress in the blood vessels or alternatively 2) a localised heating effect that induces vasodilatation. Finally, this vibration induced increase in vasodilatation may be helpful in assisting recovery from exertion and may also have potential as a novel training stimulus. The peripheral cardiovascular effects of different vibration durations, appear to be independent of skeletal muscle activation, therefore warrants further investigation.

# Chapter 4 - Effects of Varying Durations of Passive Lower Limb Vibration on the Peripheral Cardiovascular System

## 4.1. Introduction

Understanding what is an appropriate duration of exposure to low frequency whole body vibration (WBV) for any potential beneficial effect on the body is important, since we know that exposure to high frequency vibration is known to be detrimental and is limited by the Health and Safety Executive (Bovenzi, 2005, Merriman and Jackson, 2009, Brooke-Wavell and Mansfield, 2009, Totosy de Zepetnek et al., 2009b, Wilcock et al., 2009, Jordan et al., 2005, Cochrane, 2011, Dolny and Reyes, 2008). Previous studies have used different periods of vibration exposure, which have resulted in the magnitude of the effect on cardiovascular function to differ. For instance, Kerschan-Schindl et al. (2001) reported a significant increase in muscle blood flow after 9 minutes of WBV exposure. Hazell et al. (2008) observed a significant increase in mean finger arterial blood pressure and femoral artery blood flow during 15 minutes of WBV exposure. In a passive vibration study, Lohman et al. (2007) noted a significant increase in skin blood flow over the calf after 3 minutes of passive lower limb vibration while a study performed by Maloney-Hinds et al. (2008) reported an increase in forearm skin blood flow within 10 minutes of passive arm vibration, which remained higher during 15 minutes of recovery, when compared to the baseline. In a follow-up study conducted by Lohman et al. (2011), it was demonstrated that calf skin blood flow was substantially increased after 10 minutes of acute passive lower leg vibration and continued into 9 minutes of recovery. Another passive vibration study by Lohman et al. (2012) reported that calf skin blood flow was found to increase significantly, by 67 %, immediately after applying 10 minutes of acute passive lower limb vibration and remained significantly higher, by 37 %, for the following 10 minutes recovery, relative to baseline.

Furthermore, the first passive vibration study in Chapter 3 of this thesis reported a significant reduction in ankle systolic blood pressure and ankle brachial pressure index in the period following 3 minutes of passive lower limb vibration, despite the apparent absence of skeletal muscle activation. It has been concluded that vibration has a direct effect on the peripheral cardiovascular function by increasing vasodilatation, and the most likely mechanism underlying this effect is a vibration-induced increase in shear stress in the blood vessels. However, there is no study that has examined the effects of varying the durations of vibration exposure on the cardiovascular function.

The potential for vibrational stimulus to produce a greater increase in shear-stress is of interest because of its angiogenesis-inducing potential. In the current thesis, a technique has been developed to apply vibration passively to the lower limb which avoids any influence of direct skeletal muscle activation (Pollock et al., 2010), as well as focusing solely on the potential mechanism inducing effects. The aim of this study was to measure the effects of different durations of passive vibration on the peripheral circulation. The hypothesis was that acute exposure of the lower limbs to a longer duration of vibration stimulation, while lying in a supine position, would result in a greater increase in vasodilatation, causing a further increase in the peripheral blood flow when compared to that in the previous duration of exposure to passive lower limb vibration.

## 4.2. Methods

### *4.2.1. Participants*

Thirteen healthy young adults (8 males, 5 females) with an age range from 20 to 30 years were recruited to take part in the study. The subjects were recruited from the general population of the Heriot-Watt University and from personal contacts. The study was approved by the Ethics Committee of the School of Life Sciences at the Heriot-Watt University and was conducted in accordance with the Declaration of Helsinki. The participants were fully informed verbally and in writing of the purposes and protocol of the study, and of any risks and discomfort associated with the experiment before giving their written, informed consent to participate. Each volunteer completed a health screening questionnaire prior to commencing the study. Subjects completed all the varying periods of vibration treatment sessions and were randomly ordered to these treatments (described below in Experimental Sessions, section 4.2.4). The subjects were acquainted with the procedures of the study during a familiarisation session (described below in the Familiarisation Session, section 4.2.3).

As ascertained from the health screening questionnaire, with respect to regular physical activity, all volunteers were required to be active but not highly trained and subjects who had previous health issues, in particular any related to the cardiovascular system, were excluded from this experiment. Because the subject's calf was in direct contact with the vibration platform, there were further exclusionary criteria, which included subjects who had undertaken a long haul flight in the previous week as well as anyone who was positive for a Homan's sign (described below in the Familiarisation Session, section 4.2.3) as part of the health screening were excluded due to potential risk of having a deep vein thrombosis, which is a contraindication to WBV.

Subjects were asked to maintain their regular diet and normal life-style patterns during the study period. Subjects were asked to refrain from drinking alcohol and avoid the consumption of caffeine-containing beverages (e.g. tea, coffee, coca cola) for at least the night prior to participating in each test session. Subjects were also asked to refrain from participating in any heavy strenuous physical activity at least two days prior to each test session. The subjects were barefoot during the test sessions to avoid footwear dependent attenuation of the vibration.

All procedures associated with the investigation were undertaken in the Laboratory of Sport and Exercise Sciences Department located in the Sports Academy at the Heriot-Watt University. Temperature in the laboratory was regulated between 21 to 23 °C. Upon arriving at the laboratory, subjects assumed a supine position on supporting foam mats during each session.

### *4.2.2. Overview of Experimental Method*

Subjects completed four sessions on four separate occasions. Before the experimental protocol, subjects initially undertook a familiarisation session in a separate occasion in order to become accustomed to all the cardiovascular measurements, treatment procedures and vibration exposure (as described below in the Familiarisation Session, 4.2.3). The experimental protocol involved completing three separate sessions: two sessions each under a different duration of passive vibration and the last session, which involved heating the surface of the leg. There was at least one day between each of the three sessions. The experimental procedure consisted of (i) baseline measurement of lower leg blood flow (LLBF); (ii) a treatment with exposure to vibration or heating; and (iii) post-treatment measurement that was conducted in an identical manner to the baseline measurement. The key variable of interest in this study was LLBF. During all the sessions, subjects were required to lie down in the supine position with their leg resting and elevated on foam mats especially designed to be equivalent to the height of the vibration platform.

### *4.2.3. Familiarisation Session*

After the participants gave their written and informed consent, they completed the health screening questionnaire and their age, height, body mass, resting blood pressure and heart rate were recorded. The Homan's sign test was performed to assess for pain or resistance in the posterior aspect of the calf through passive dorsiflexion of the subject's ankle; if they did not pass the test then that would exclude them from the study.

Subjects then lay down in a supine position on supporting foam mats, with their calves positioned with the toes pointing outward at an angle of 30 to 45 ° to maximise the calves' contact with the vibration platform. Measurement of the circumference of the widest part of the calf was completed for the application of the strain gauge in the experimental sessions. A venous occlusion plethysmograph (Hokanson, Bellvue, WA,

USA) was demonstrated in order to familiarise the participants with the cuffs and the measurement before testing, to avoid stress and excitement on the day of testing at the experimental sessions. Finally, subjects' legs were moved slowly and comfortably by the researcher, and placed on a vibrating platform in order to familiarise the participants with the sensation of vibration that was set at a frequency of 50 Hz for a period of 30 seconds.

### *4.2.4. Experimental Sessions*

The three experimental sessions were composed of passive vibration of the lower legs and leg heating treatments. In the first two experimental sessions, the subjects were involved in completing two separate occasions under four different durations i.e. 1, 2, 4 and 8 min duration of passive lower leg vibration by means of the subjects lying down in the supine position while their lower legs rested on the vibration platform, as applied in the familiarisation session. During each session, different durations of passive vibration were applied to the lower legs, which required the completion of 1, 2, 4 or 8 bouts of vibration. The vibration was applied in 60 second-bouts, with 10 seconds rest between bouts. A Latin square design was used to assign the participants to undergo two bouts of passive vibration durations in each session, but the situation where a longer vibration duration came first was excluded, in order to minimise any carryover effect. The experimental design of the treatment administration is presented in Table 4.1. Intensity of the vibration during each of the four durations was constant, at a frequency of 50 Hz and amplitude of 3 mm for the vertical displacement, which produced a peak acceleration of approximately 10 g (i.e. 10 x 9.81 $m/s^2$) and was comparable with the protocol used in a previous study (Lohman et al., 2007). The two bouts of vibration in each session were separated by 30 minutes of supine rest. All experimental sessions were conducted in the morning, in order to avoid any potential of order effect from circadian rhythms that could affect the cardiovascular system.

On the testing day, all the equipment was set up and the room temperature pre-warmed to 21-23 °C for at least 30 minutes prior to the arrival of subjects, so that the temperature for all the supporting foam mats, equipment and walls was similar. On arrival at the laboratory, subjects lay down in the supine position on supporting foam mats for 15 minutes, to achieve a baseline blood flow prior to vascular function testing and also to acclimatise to the temperature in the room. Baseline LLBF measurement was made after 15 minutes of supine rest. Following the baseline measurement, the

subjects' legs were then passively moved slowly and comfortably from the supporting foam mats and placed on the vibration platform. Next, the subjects underwent one of the bouts of passive vibration that lasted for a total of either 1, 2, 4 or 8 min. Immediately after completing the required number of passive vibration bouts and while subjects were resting in the supine position, the subjects' legs were passively moved back slowly and comfortably from the vibration platform, and placed on the supporting foam mats for 10 minutes of recovery. The post-treatment measurement was performed after 1 minute of recovery following vibration exposure and then repeated at 3 minutes intervals for a total of 10 minutes of post-vibration recovery.

After that, subjects lay continuously in the supine position for 15 minutes before the baseline measurement was made, in order to separate the two treatments by 30 minutes. The procedures of the baseline measurement, the second set of passive vibration bouts, and post-vibration measurements were conducted in an identical manner to the procedure of the first condition and the session was then ended. The procedure of the second experimental session was conducted in an identical manner to that of the first experimental session.

In the final (third) session, surface heating was applied to the subject's lower leg with a commercial heating blanket heat (Beurer HK 45 Cosy, Beurer GmbH, Ulm, Germany) in order to elicit the maximum lower limb blood flow. This blanket heat was set at a maximum setting (Level 3) for this study. The temperature at the surface of this product reached approximately 40 °C after 10 minutes of use at the maximum heat setting. This temperature was previously used in a therapeutic study for physical therapists (Prentice et al., 2002). The blanket was pre-warmed for at least 15 minutes prior to applying it on the subjects' lower leg, to ensure that the temperature of the blanket had reached the maximum heat. The subjects assumed the supine position on supporting foam mats for 15 minutes before the baseline measurement was made. They then underwent heating on the leg for 20 minutes. The post-measurement was performed at after 1 minute of recovery following heating and then repeated at 3 minutes intervals during the total of 10 minutes post-heating recovery, after which the session was ended.

**Table 4.1 Experimental design of treatment administration.**

| Numbers of Subjects | Duration of Vibration (min) | | | |
|---|---|---|---|---|
| | 1st Session | | 2nd Session | |
| | 1st Vibration | 2nd Vibration | 1st Vibration | 2nd Vibration |
| 2 | 1 | 2 | 4 | 8 |
| 2 | 4 | 8 | 1 | 2 |
| 2 | 1 | 4 | 2 | 8 |
| 2 | 2 | 8 | 1 | 4 |
| 2 | 1 | 8 | 2 | 4 |
| 2 | 2 | 4 | 1 | 8 |
| (Total number 12) | | | | |

### *Vibration Device*

This study used the same Nemes vibration device (Nemes, Bosco System, Italy) as that employed in the initial WBV (Chapter 2) and first passive vibration (Chapter 3) studies of this thesis. Vibration stimulus was applied to the subjects' lower legs in an identical manner as in the first passive vibration study (Chapter 3) of this thesis.

It has been postulated in the discussion of the first passive vibration study, in Chapter 3, that cooling from the platform of the vibration device used in this research might affect the results and also that the cover of the vibration platform (i.e. cloth, rubber) may dampen the transfer of vibration to the body, affecting the intensity of the vibration exposure (i.e. frequency, amplitude and therefore acceleration). Thus, in order to avoid the cooling effect from this vibration platform and reduce the issue of dampening the vibration intensity, a thin wooden plate was attached on the top of the vibration platform, using industrial strength double-sided adhesive tape.

### *Accelerometer Calibration*

The frequency, amplitude and acceleration of vibration were measured using a digital accelerometer (4000A Accelerometer, Measurement Specialties, CA, USA) and the measurement was conducted in an identical manner to that in the initial WBV (Chapter 2) and first passive vibration (Chapter 3) studies of this thesis.

## *4.2.5. Measurements*

All subjects completed the vascular function assessments pre- and post-vibration and leg heating treatments. All measurements were performed initially following 15 minutes of supine rest, to establish baseline values, and then 1 minute after treatment and repeated every 3 minutes for total of 10 minutes of recovery. LLBF was measured using an automated venous occlusion strain gauge plethysmograph (Hokanson, Bellvue, WA, USA) that was also used in the initial WBV (Chapter 2) and first passive vibration (Chapter 3) studies of this thesis and the measurement conducted in an identical manner to the procedure and analysis of the first passive vibration study (Chapter 3).

### *Strain Gauge Viability*

Each strain gauge was tested for viability using a specially built apparatus of rubber tubes with an inflatable cuff and the test was conducted in an identical manner to that in the initial WBV (Chapter 2) and first passive vibration (Chapter 3) studies of this thesis.

## *4.2.6. Statistical Analysis*

All the data were analysed using Minitab 17 statistics software (version 17.1.0, Minitab). Data presented in the results are mean ± SEM. Statistical analysis was performed using analysis of variance (ANOVA) with a mixed, that is fixed and random, effects model with statistical significance accepted at $P < 0.05$. Post-hoc tests for significant differences were performed using the Bonferonni correction, with an uncorrected 1-sided alpha value of 0.05 (Kutner et al., 2005), Chapter 27, 1127-1172.

## 4.3. Results

### *4.3.1. Subject Characteristics*

Twelve (mean ± SD; age 24.2 ± 3.5 years, height 1.74 ± 0.11 m, body mass 68.7 ± 13.1 kg) out of the thirteen participants successfully completed the sessions with 100 % compliance and were free of injury. Only one subject (male), after completing the familiarisation session, withdrew from the study for reasons unrelated to the experiment. Despite the fact that the subjects did not report any severe side effects or adverse reactions related to vibration, seven subjects (4 males, 3 females) reported some transient itching and warming of the legs during and after about 1 to 2 minutes of vibration exposure, and in particular with a longer duration of passive vibration ( 4 and 8 minutes). Three of these subjects (2 males, 1 female) reported itchiness in response to 1 minute of passive vibration, whereas two subjects (males) had experienced itchiness in response to 2 minutes of passive vibration. Itchiness was also observed in five of the subjects (3 males, 2 females) in response to 4 minutes of passive vibration. In response to 8 minutes of passive vibration, six subjects (3 males, 3 females) reported itchiness and one subject (male) felt warmness. These symptoms were always temporary, mild, not disturbing, and resolved rapidly.

### *4.3.2. Lower Leg Blood Flow Responses*

There was a significant interaction between condition and time for lower leg blood flow (LLBF) ($P < 0.05$). At baseline, prior to the treatment, LLBF was similar for the five various conditions ($P > 0.05$) (Figure 4.1). The calculated coefficient of variation was found to be 28.2 % for the measurement of the baseline LLBF. After 2 minutes and 4 minutes of passive vibration treatment, LLBF was significantly increased above baseline at 1 minute into recovery time ($P < 0.05$) (Figure 4.1 and Figure 4.2). With 8 minutes of passive vibration, a significant increase in LLBF was observed over baseline at both 1 minute and 4 minutes into the recovery time ($P < 0.05$), whereas there was no significant difference in LLBF over baseline at any time point for either the 1 minute of passive vibration or heating conditions, ($P > 0.05$).

At 1 minute into the recovery period after treatment, LLBF was significantly higher for 8 minutes of passive vibration condition than for the other four conditions (i.e. 1 minute, 2 minutes and 4 minutes of passive vibration, and for the heating conditions) ($P < 0.05$).

LLBF after 4 minutes of passive vibration was also significantly higher 1 minute into the recovery period when compared to that after 1 minute of passive vibration ($P < 0.05$). There was no significant statistical difference in LLBF found after 1 minute of recovery time among the 1 minute of passive vibration, 2 minutes of passive vibration and heating conditions ($P > 0.05$).

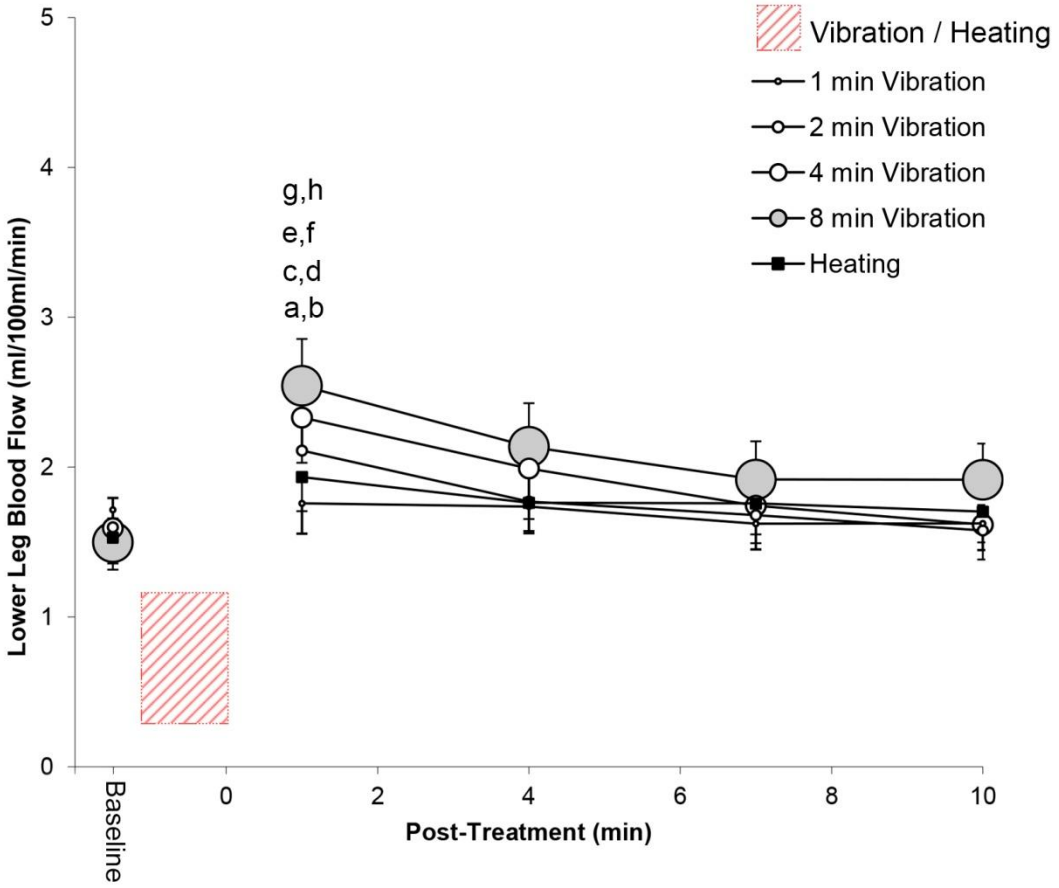


**Figure 4.1 Lower leg blood flow pre- and post-treatment at various time points.**

**"a" indicates significant increases over baseline for the 2 min of passive vibration condition ($P < 0.05$). "b" indicates significant increases over baseline for the 4 min of passive vibration condition ($P < 0.05$). "c" indicates significant increases over baseline for the 8 min of passive vibration condition ($P < 0.05$). "d" indicates significant differences between the heating and 8 min of passive vibration conditions ($P < 0.05$). "e" indicates significant differences between the 1 min and 4 min of passive vibration conditions ($P < 0.05$). "f" indicates significant differences between the 1 min and 8 min of passive vibration conditions ($P < 0.05$). "g" indicates significant differences between the 2 min and 8 min of passive vibration conditions ($P < 0.05$). "h" indicates significant differences between the 4 min and 8 min of passive vibration conditions ($P < 0.05$). Data are shown as mean (n = 12) and error bars indicate SEM.**

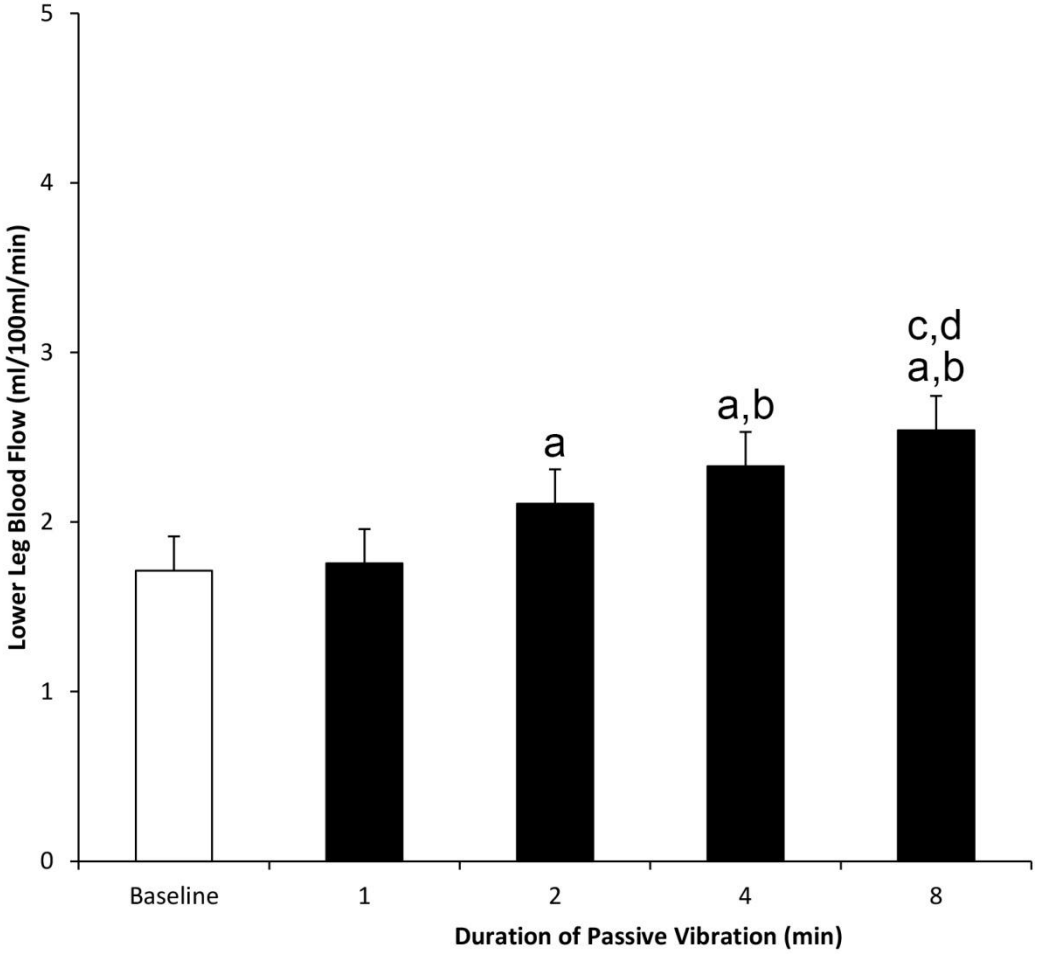


**Figure 4.2 Lower leg blood flow at baseline and 1 min post-vibration treatment for various vibration periods.**

**Open bar indicates baseline and the filled bars indicate the vibration treatment. "a" indicates significant increases over baseline ($P < 0.05$). "b" indicates significant increases over the 1 min of passive vibration condition ($P < 0.05$). "c" indicates significant increases over the 2 min of passive vibration condition ($P < 0.05$). "d" indicates significant increases over the 4 min of passive vibration condition ($P < 0.05$). Data are shown as mean (n = 12) and error bars indicate SEM.**

## 4.4. Discussion

The current study has examined the lower leg blood flow (LLBF) response to an acute bout of passive lower leg vibration with varying durations and also the response to leg heating. The main finding was that a longer duration of passive vibration to the lower leg significantly increased peripheral blood flow in the lower limb in healthy young adults. A substantial increase in LLBF was observed after 1 minute of recovery following 2 minutes, 4 minutes and 8 minutes acute passive lower limb vibration and this remained significantly higher for 4 minutes of recovery in response to 8 minutes of acute passive lower limb vibration when compared to the baseline. In contrast, LLBF remained close to baseline value following both the 1 minute of passive vibration and leg heating conditions. LLBF at 1 minute of recovery post-passive vibration treatment was progressively increased with increasing durations of passive vibration exposure.

It has been demonstrated that exposure to either whole body heating or local heating over skin can cause vasodilatation, leading to a substantial increases blood flow in healthy humans (Charkoudian, 2003, Abraham et al., 1994a, Abraham et al., 1994b, Lohman et al., 2012). Lohman et al. (2012) found that skin blood flow was significantly increased, by 193 %, after 10 minutes of moist heat and also remained significantly elevated after 10 minutes of recovery post-heating, by 164 % over baseline. Edholm et al. (1956) and Roddie et al. (1956) reported that there was a substantial increase in skin blood flow in response to body resting heat stress. However, skeletal muscle blood flow remained unchanged during body resting heat stress. Thus, all increases in limb blood flow during local heating are confined to increased skin blood flow. These observations explain the present data relating to the leg heating condition, which did not show any significant statistical change in LLBF at any time point: in the present study the LLBF was measured using automated venous occlusion strain gauge plethysmography, which measured the changing volume of the lower leg, thus determining changes in muscle blood flow more than skin blood flow changes.

The most important finding of the current study was that LLBF at 1 minute post-treatment was progressively higher with increasing durations of passive vibration and this increase continued into 4 minutes of recovery in response to the longest duration of passive vibration exposure (8 minutes). However, the shortest duration of acute passive lower limb vibration (1 minute) did not result in an increase in LLBF. This is most likely due to a minimal stimulatory effect on the peripheral vascular or neuromuscular

system. Maloney-Hinds et al. (2008) found that exposure of the arm to 10 minutes of 30 and 50 Hz frequencies of passive vibration with amplitude of 5-6 mm in vertical displacement (acceleration equal to 9.1-10.9 g and 25.5-30.2 g, respectively) with 10 seconds rest between the bouts of vibration resulted in a significant increase in forearm skin blood flow, measured using a laser Doppler flow meter, within the first 5 minutes of vibration which remained higher, but not significantly so, for the next 5 minutes of vibration, compared to baseline in young healthy adults. Consequently, this finding proposes that skin blood flow progressively increases during 5 minutes of passive vibration exposure, whereas with increasing the duration of passive vibration this increase in skin blood flow tends to decrease towards the baseline, even at varying intensities of vibration (i.e. frequency, amplitude, therefore acceleration). Conversely, the results of the present study demonstrate that LLBF becomes significantly higher with increasing durations of passive vibration. These observations suggest that a longer duration of vibration has more effect on enhancing muscle blood flow rather than skin blood flow. Therefore, the increases in blood flow of limb during longer duration of passive vibration could be due to an increased muscle blood flow through increased skeletal muscle vasodilatation.

Moreover, it has been previously demonstrated that, after blocking the production of nitric oxide by L-$N^G$-monomethyl arginine (L-NMMA) infusion, femoral artery blood flow was significantly reduced during 10 minutes of recovery post-exhaustive exercise by 66 % compared to saline infusion recovery (Rådegran and Saltin, 1999). In contrast, this difference in femoral artery blood flow between the saline and L-NMMA infusion during submaximal exercise was found to be absent, indicating that vasodilatation in the contracting muscle is not related to nitric oxide. These observations indicate that blood flow during recovery post-exhaustive exercise might be related to a shear stress mediated endothelial nitric oxide production. Alternatively they could indicate that passively applied vibration to unloaded muscles appear to provide a minimal stimulus for activation of skeletal muscle (Burke et al., 1976b). Continued activation of skeletal muscle leads to an increase in heat generation, as demonstrated by Krustrup et al. (2003), the prolonged exposure to vibration could have resulted in a higher accumulation of heat and hence vasodilatory response. Either way the present study has demonstrated that the greater amplitude of vasodilatation in the lower limb during recovery, as reflected by the increased muscle blood flow, could be due to either a greater increase in shear stress occurring with a longer duration of passive vibration: i.e.

it is nitric oxide dependent, and/or a longer passive vibration duration causing a greater stimulus for skeletal muscle activation. If exposure to passive vibration provides some skeletal muscle activity, this would result in an increase in heat production in the limb, and thereby increasing local muscle temperature and local muscle blood flow. These data provide evidence that a longer duration of vibration has a further effect on vascular function.

Moreover, several subjects reported experiencing itchiness and warmness of the legs during and following treatment of passive vibration, although it was always transient, mild, and not disturbing. As proposed by Rittweger et al. (2000), Broadbent et al. (2010) and Rittweger et al. (2010), these symptoms are related to the cardiovascular function and might therefore be an indication of an increase in the shear stress occurring at the blood vessel wall causing vasodilatation, therefore increasing blood flow in response to vibration stimulation. In the current study, most of these symptoms were visible with longer duration of passive vibration (4 minutes and 8 minutes). Therefore, these findings suggest that a longer duration of vibration may induce a greater increase in shear stress in blood vessels relative to a shorter duration of vibration.

Generally, these symptoms and the observations of the present study indicate that there was a greater influence on the function of the blood vessels by a further increase vasodilatation, as reflected by the increased muscle blood flow occurring in response to a longer period of vibration, which appears to be independent of skeletal muscle activation. There are two possible explanations consistent with these observations are that a longer duration of passive vibration applied to the lower legs has a greater effect in eliciting a further increase in shear stress at the vessel wall and/or a greater effect of skeletal muscle activation, and thus both resulting in a greater vasodilatory effect on the lower limb.

In conclusion, a passively applied vibration of longer duration to the lower legs resulted in a greater increase in LLBF in the post-vibration period, despite the apparent absence of skeletal muscle activation. These data provide evidence for a greater effect of WBV occurring with a longer period on the peripheral cardiovascular function via a further increase vasodilatation. It has been postulated that the mechanism underlying this effect is that a longer duration of vibration induces further increase in shear stress in the blood vessels but equally there might be a minimum effect of skeletal muscle activation

occurring with a longer duration of passive vibration that leads to a direct response to localised heating. This is the first study to provide evidence that a longer duration of vibration results in a further increase in the peripheral blood flow circulation. Finally, this longer duration of vibration inducing greater enhancement in peripheral blood flow may be helpful in assisting recovery from exertion and may also have potential as a novel training stimulus. However, to understand the mechanism that would explain the effect of vibration on the peripheral cardiovascular function needs further investigation.

# Chapter 5 - The Effect of Passive Vibration on Calf Muscle Activation and Blood Flow with and without Acute Vascular Occlusion of a Lower Limb

## 5.1. Introduction

Acute whole body vibration (WBV) has been reported to improve musculoskeletal function, such as increasing muscle strength (Torvinen et al., 2002a, Delecluse et al., 2003, Roelants et al., 2004a), muscle power (Cochrane and Stannard, 2005, Torvinen et al., 2002a, Delecluse et al., 2003) and speed (Bosco et al., 1999b, Torvinen et al., 2002c), improving body stability (Torvinen et al., 2002a) and flexibility (Cochrane and Stannard, 2005). It has been previously found that an increase in muscle and tendon length was found during vibration exposure (Burke et al., 1976b). Hence, it has been postulated that standing on a vibrating platform during exposure to WBV exercise (static or dynamic squat) can activate skeletal muscle, which has been reported to increase muscle strength, power, muscle blood flow, peripheral circulation, skin temperature and muscle temperature. Indeed, previous studies by Cardinale and Lim (2003) Abercromby et al. (2007a) Hazell et al. (2007) all demonstrated that electromyography activity was increased in response to WBV, thereby indicating an increase in skeletal muscle activity occurred during exposure to vibration. Furthermore, an increase in muscle blood flow has been observed after WBV exposure (Hazell et al., 2008, Lythgo et al., 2009, Kerschan-Schindl et al., 2001, Stewart et al., 2005, Herrero et al., 2011b, Herrero et al., 2011a).

It is well known that an increase in muscle fibre activity can raise skin and muscle temperature, requiring an increase in blood flow to dissipate the metabolically produced heat (Hazell et al., 2008). Several previous studies reported an increase in temperature of both skin (Hazell et al., 2008, Lohman et al., 2012, Lohman et al., 2011) and muscle (Cochrane et al., 2008, Cochrane et al., 2010) in response to acute exposure to vibration. Hazell et al. (2008) reported that during 15 minutes of acute WBV with static squat, skin temperature was significantly increased, also remaining significantly higher in the post-vibration period. Cochrane et al. (2008) compared the rate of increase in muscle temperature during acute WBV to stationary cycling and passive heating (hot water bath immersions) in healthy young adults. The change in muscle temperature elicited by the stationary cycling was matched in the WBV and passive heating treatments. Their subject had acute exposure to WBV that was combined with dynamic squatting exercise. They reported that the rise in muscle temperature was significantly greater during acute exposure to WBV than in either stationary cycling or passive heating. It

was concluded that acute exposure to WBV produces heat in a muscle more quickly than traditional forms of active and passive heating at the same the metabolic rate (oxygen uptake) when the same final muscle temperature was achieved. In a follow-up study by Cochrane et al. (2010) it was demonstrated that muscle temperature increased during 10 minutes of acute exposure to WBV in both the static squat and dynamic squat; however, the rise in muscle heat production was not significantly different between these two WBV exercises. These findings suggest that the rise in temperature of skin and muscle during WBV exposure may have occurred either due to an increase in blood flow caused by a vasodilatation or an increase in skeletal muscle activation, or both.

In a passive vibration study, Lohman et al. (2011) reported that skin temperature over a calf (gastrocnemius) muscle was significantly increased after a 10 minutes intervention of passive lower leg vibration in healthy young adults. Another study by Lohman et al. (2012) noted that 10 minutes of passive lower leg vibration combined with moist heat resulted in a significantly raised calf skin temperature in healthy older subjects. Overall, it is suggested that vibration increases skin and muscle temperatures by dampening out the effect of these vibrations within the muscle thereby transforming mechanical energy into heat.

It has been illustrated that the rate of muscle heat production progressively increases with increasing intensity of exercise, whereas it was found to be 33 % lower in low intensity exercise with occlusion than when compared with intact circulation (Krustrup et al., 2003). It is well known that during a condition of arrested blood flow, aerobic metabolism will be minor, due to rapid emptying of local oxygen stores, leading to modest response in muscle temperature. In contrast, as the exercise progressed, during the condition of free blood flow, almost all the energy was derived from aerobic metabolism (oxidative phosphorylation), causing a substantial increase in muscle temperature (Richardson et al., 1995, Krustrup et al., 2003). In a previous study by Cochrane et al. (2010) it was reported that muscle temperature significantly increased in both the static and dynamic squatting exercises after 10 minutes, most likely due to an increase skeletal muscle activation causes a rise in muscle heat production in response to the increased metabolic rate. Furthermore, it has been documented that exposure to passive heating on the skin can cause vasodilatation, leading to a substantial increases in

blood flow in healthy humans (Charkoudian, 2003, Lohman et al., 2012, Lohman et al., 2011). Therefore, the combination of exposure to vibration either with heating, static squat, or dynamic squat complicates the effects of vibration on skeletal muscle function, causing a rise in skin and muscle temperatures.

Although in an earlier study by Burke et al. (1976b) it was reported that an activation of skeletal muscle was relatively low during passively applied vibration to a limb, it is unclear whether increases in peripheral cardiovascular function and temperature of skin and muscle is a secondary effect in response to skeletal muscle activation. The mechanism of increasing temperature would be due to functional hyperaemia and/or a direct effect of vibration induced shear stress resulting in vasodilatation in the peripheral cardiovascular function as a primary effect.

There is interest in the reported enhancement effects on the skeletal muscle blood flow via a potential shear stress mechanism in the use of exposure to vibration. The first passive vibration study (Chapter 3) in this thesis demonstrated that 3 minutes of acute vibration passively applied to the lower limb resulted in a significant reduction in ankle systolic blood pressure and ankle brachial pressure index in the period following exposure, despite the apparent absence of skeletal muscle activation. Based on these observations it was concluded that vibration has a direct effect on the peripheral cardiovascular function via an increased vasodilatation and that the most likely mechanism underlying this effect is a vibration-induced increase in shear stress in the blood vessels. Furthermore, the duration of passive vibration study (Chapter 4) in this thesis reported that lower leg blood flow (LLBF) remained significantly elevated after 1 minute of recovery following 2 minutes, 4 minutes and 8 minutes of acute passive lower limb vibration. It was only following 8 minutes of acute passive lower limb vibration that the LLBF remained substantially higher than baseline after 4 minutes of recovery. LLBF at 1 minute post-vibration treatment was progressively higher, with increasing durations of passive vibration exposure. These findings indicated that a longer vibration period is more effective in enhancing the peripheral blood flow caused by the vasodilatation response throughout the recovery period, possibly due to a longer period of vibration inducing a greater increase in shear stress in the blood vessels and/or a longer duration of vibration resulting in a greater stimulus for activation of skeletal muscle, which leads to a direct response to localised heating.

In order determine the enhancement effects on the peripheral circulation during exposure to vibration, skin temperature measurement was employed in this study as a surrogate measure of skin flow, because of the difficulties in measuring blood flow in the usual ways (e.g. via plethysmography, ultrasound, electromyography or a laser Doppler flowmetry probe) during vibration exposure, due to the interference of waves from the vibration device. In the current thesis a technique has been developed to apply vibration passively to the lower limbs that was used in the studies into first passive vibration (Chapter 3) and duration of passive vibration (Chapter 4), hence avoiding any influence of direct skeletal muscle activation (Pollock et al., 2010) as well as focusing solely on the mechanism inducing effects. Furthermore, owing to the technical barriers to making various types of measurements during the application of the vibration stimulus, changes in skin surface temperature measurements were used to make inferences on the underlying mechanisms and further, by utilising arterial occlusion, to separate out the relative contributions of muscle activation and blood flow to the observed heat transfer. The aim of this study was to investigate the effect of passive vibration on skeletal muscle activation and/or local muscle blood flow. The hypothesis was that exposure of the lower limbs to vibration stimulation, while the subject was lying in a supine position, would result in local vasodilatation that would enhance the peripheral blood flow more than either control, occlusion or occlusion plus vibration conditions.

## 5.2. Methods

### *5.2.1. Participants*

Eight healthy young adult males with an age range from 19 to 30 years were recruited to take part in the study. The subjects were recruited from the general population of the Heriot-Watt University and from personal contacts. The study was approved by the Ethics Committee of the School of Life Sciences at the Heriot-Watt University and was conducted in accordance with the Declaration of Helsinki. The participants were fully informed, verbally and in writing, of the purposes and protocol of the study, risks and discomfort associated with the experiment before giving their written informed consent to participate. Each volunteer completed a health screening questionnaire prior to participating in the study. Subjects completed all bouts of vibration, occlusion, occlusion plus vibration and the control (sham) intervention session and were randomly ordered to complete these bouts (as described below in the Experimental section). All subjects had previously participated in at least one of the vibration studies.

As ascertained from the health screening questionnaire, with respect to regular physical activity, all volunteers were required to be active but not highly trained and subjects who had previous health issues, in particular any related to the cardiovascular system, were excluded from this experiment. Because the subjects' calf was in direct contact with the vibration platform, there were further exclusionary criteria which included subjects who had undertaken a long haul flight in the previous week as well as anyone who was positive for a Homan's sign (described below in the Experimental section) as part of the health screening: these subjects were excluded due to the potential risk of having a deep vein thrombosis, which is a contraindication to WBV.

Subjects were asked to maintain their regular diet and normal life-style patterns during the study period. However, subjects were asked to refrain from drinking alcohol and avoid the consumption of caffeine-containing beverages (e.g. tea, coffee, coca cola) from at least the night prior to participating in the experimental session. Subjects were also asked to refrain from participating in any heavy strenuous physical activity from at least two days prior the experimental session. The subjects were barefoot during the test session, to avoid footwear dependent attenuation of the vibration.

All procedures associated with the investigation were undertaken in the Laboratory of Sport and Exercise Sciences Department located in the Sports Academy at the Heriot-Watt University. The temperature in the laboratory was regulated between 21 to 23 °C. Upon arriving at the laboratory, subjects assumed a supine position on supporting foam mats for the duration of the session.

### *5.2.2. Overview of Experimental Method*

Subjects were required to attend the research lab on a single occasion. The experimental protocol involved completing the session under a series of four different conditions. In order to obtain the best possible results and avoid any potential of order effect from circadian rhythms that could affect the cardiovascular system, it was preferred to carry out application of all of the four different conditions on the single occasion. The four different interventions on the single occasion were separated by 20 minutes in order to minimise any carryover effect from one intervention to another (Gomez et al., 2008). The four conditions were different on each leg. The four different conditions for the right and left legs are presented in Table 5.1. The experimental procedure consisted of (i) baseline measurement of leg bone skin temperature ($LBSk_{temp}$) (i.e. over the tibia) and leg muscle skin temperature ($LMSk_{temp}$) (i.e. over the gastrocnemius); (ii) an intervention with or without vibration exposure with or without occlusion; and (iii) measurements during and post-intervention, which were conducted in an identical manner to the baseline measurements. The key variables of interest in this study were $LBSk_{temp}$ and $LMSk_{temp}$. During the session, subjects were required to lie down in the supine position with their lower leg resting on the vibration platform.

**Table 5.1 The four different conditions for right and left legs.**

| Right Leg Condition | Left Leg Condition |
|---|---|
| Control | Control 1 |
| Occlusion | Control 2 |
| Vibration | Vibration 1 |
| Occlusion plus vibration | Vibration 2 |

### *5.2.3. Experimental Session*

Subjects completed a single experimental session that consisted of four different conditions. The four conditions applied to the right leg were different from those for the left leg. The four different conditions applied on the right leg were control, occlusion, passive vibration and occlusion plus passive vibration, whereas, the four conditions on the left leg were control 1, control 2, passive vibration 1 and passive vibration 2. Thus, when the right leg was under control or occlusion conditions, the left leg was under control conditions, (referred to as control 1 and control 2) whilst, when the right leg was under passive vibration or occlusion plus passive vibration conditions, the left leg was undergoing passive vibration (vibration 1 and vibration 2). During the application of the four conditions, the subjects lay down in the supine position with their lower legs resting on the vibration platform. The total length of the test was one hour and 47 minutes. The application of each condition consisted of 5 minutes lying supine plus 2 minutes of baseline measurements, 8 minutes of intervention for each pair of conditions and 8 minutes for the final recovery period (i.e. the total length of each condition was 23 minutes), with an additional 5 minutes break between each condition in order to allow for adequate recovery time between application of each condition. A Latin square design was used to randomly order the participants each underwent all conditions.

An arterial occlusion curved thigh cuff (CC22$^{TM}$, Hokanson, Bellvue, WA, USA) was attached around the right thigh and connected to an adjustable arterial occlusion air pressure source (E20 Rapid Cuff Inflator and AG101 Cuff Inflator Air Source, Hokanson, Bellvue, WA, USA). The arterial occlusion cuff was inflated to 200 mmHg, which is higher than systolic blood pressure, for 8 minutes in two of the right leg trial conditions (i.e. occlusion and occlusion plus passive vibration) in order to occlude the blood flow to the leg. Vascular occlusion manoeuvres have previously performed in a manner similar to this study (Fellahi et al., 2014, Gomez et al., 2008) and it was found that while there was a transient local tissue hypoxia, it was rapidly reversed in normal, healthy subjects. The application of an inflated pressure cuff to the right thigh was comparable to the procedure used to occlude arterial blood flow in the upper arm in order to determine blood pressure.

The passive vibration was applied at a constant frequency of 50 Hz, with an amplitude of 3 mm with the vertical displacement, which produced a peak acceleration of approximately 10 g (i.e. 10 x 9.81 m/s$^2$), and was comparable with the protocol used in a previous study (Lohman et al., 2007). Moreover, it was found from a pilot test, conducted specifically to prepare for the current study, that allowing 10 seconds breaks between the bouts of vibration exposure influenced the skin temperature response, which declined during the break, most likely due to a reduction in blood flow. Therefore, in order to avoid the influence of the breaks between the bouts of vibration exposure, which would affect the results, the vibration in this study was applied continuously. The control intervention, which was a sham treatment, was conducted in an identical manner to the passive vibration intervention, but without exposure to vibration.

On the testing day, all the equipment was set up and the room temperature was pre-warmed to 21-23 °C for at least 30 minutes prior to the arrival of subjects, so that the temperature of all of the supporting foam mats, items of equipment and walls was similar. On arrival at the laboratory, subjects remained in the lab room for 15 minutes to acclimatise to the temperature in the room. During this thermal acclimatisation, subjects were initially given their information sheet and then filled in the consent form. After giving their written and informed consent, the participants completed the health screening questionnaire and their age, height, body mass, resting blood pressure and heart rate were recorded. The Homan's sign test was performed to assess for pain or resistance in the posterior aspect of the calf, through passive dorsiflexion in the subject's ankle; if they did not pass the test then they would be excluded from the study.

The subjects then lay down for 5 minutes in the supine position on the supporting foam mats with their lower leg resting on the vibration platform. This was to achieve a baseline blood flow prior to vascular function testing, and their calves were positioned with the toes pointing outward at 30 to 45 °, to maximise the calves' contact with the vibration platform. After the 5 minutes of supine rest, the baseline $\mathrm{LBSk_{temp}}$ and $\mathrm{LMSk_{temp}}$ measurements were measured for 2 minutes. Following the 2 minutes of baseline measurements, the subjects underwent one of the interventions for 8 minutes.

It had been detected from the pilot testing that exposure to vibration had an effect in cooling the lower limb via the vibration of the limb in the air during the exposure to

vibration, which resulted in cooling the legs. Hence, the cooling effect from convection was negated by covering both lower legs with a cloth during each intervention, in order to avoid any issue that might affect the regulation of blood flow. Immediately after completing one of the 8 minutes interventions, the covers were removed from both legs and the subjects were continuously rested in the supine position for an 8 minute recovery period, after which the condition was completed.

Immediately after completing one of the conditions, each subject had a 5 minutes break where they transferred to a seating position before commencing the next condition, and separated the two interventions by 20 minutes (i.e. 8 minutes of recovery + 5 minutes break + 5 minutes lying supine + 2 minutes of baseline measurements). After that, subjects underwent another condition and the procedures for each condition were conducted in an identical manner to the procedure of first condition, and repeated respectively at 3 time intervals thereafter for the total of 4 conditions, after which the session was ended.

### *Vibration Device*

This study used the same Nemes vibration device (Nemes, Bosco System, Italy) as that employed in the initial WBV (Chapter 2), first passive vibration (Chapter 3) and duration of passive vibration (Chapter 4) studies of this thesis. Vibration stimulus was applied to subjects' lower legs in an identical manner as that used in the first passive vibration (Chapter 3) and duration of passive vibration (Chapter 4) studies of this thesis.

### *Accelerometer Calibration*

The frequency, amplitude and acceleration of vibration were measured using a digital accelerometer (4000A Accelerometer, Measurement Specialties, CA, USA) and the procedures were conducted in an identical manner to the initial WBV (Chapter 2), first passive vibration (Chapter 3) and duration of passive vibration (Chapter 4) studies of this thesis.

## *5.2.4. Measurements*

All the subjects completed the vascular function assessments pre-, during and post-vibration and control (sham) interventions both with and without acute arterial occlusion of the lower limb. All measurements were performed for 2 minutes following

5 minutes of supine rest, to establish baseline values, then during the 8 minutes of intervention and immediately after the intervention for 8 minutes of recovery, and then repeated at 3 time intervals thereafter for the total of 4 conditions. While the right leg was the main leg of interest (and the only one subject to the occlusion), the vibration stimulus was applied equally to both lower legs, so a partial set of skin temperature measurements were made on the left leg for comparison purposes. The $LBSk_{temp}$ and $LMSk_{temp}$ were measured using thermocouple probes connected into a data logger (Squirrel SQ800, Grant Instruments, Cambridgeshire, England). The data logger was connected via Bluetooth (BTL-578, BTLink, Taiwan) into a standard laptop in order to record the skin temperatures via using SquirrelView software (SquirrelView Software, England). Six thermocouple probes were applied on the warmest sites of the medial side of centre of the subjects' right and left tibia and gastrocnemius, determined via the thermal camera (FLIR i7, FLIR Systems, OR, USA). Two of the thermocouple probes were located over the right tibia (about 2 cm above and below the warmest site); two other thermocouple probes were located over the right gastrocnemius (about 2 cm above and below the warmest site); another thermocouple probe was located over the warmest site of the left tibia, and one was located over the warmest site of the left gastrocnemius. The calculated coefficient of variation was found to be 0.7 % for the readings of the two thermocouple probes over the right tibia and gastrocnemius. Therefore, it was decided to use the mean of these two thermocouples.

### *5.2.5. Statistical Analysis*

All the data were analysed using Minitab 17 statistics software (version 17.1.0, Minitab). Data presented in the results are mean ± SEM. Statistical analysis was performed using analysis of variance (ANOVA) with a mixed, that is fixed and random, effects model with statistical significance accepted at $P < 0.05$. Post-hoc tests for significant differences were performed using the Bonferonni correction, with an uncorrected 1-sided alpha value of 0.05 (Kutner et al., 2005), Chapter 27, 1127-1172.

## 5.3. Results

### *5.3.1. Subject Characteristics*

Eight participants (mean ± SD: age 22.4 ± 3.3 years, height 1.81 ± 0.09 m, body mass 77.5 ± 10.2 kg) successfully completed the single session free from injury. Although the subjects did not report any severe side effects or adverse reactions that were related to the vibration, two subjects reported some transient itching and one reported redness of the leg during and after about 1 to 2 min of vibration intervention. These symptoms were always temporary, mild, not disturbing, and resolved rapidly.

Furthermore, some subjects experienced a modest degree of discomfort, transient itching (1 subject) and numbness (2 subjects) during the condition of occlusion, but these symptoms quickly disappeared as soon as the pressure was relieved, after 8 minutes of inflation. Four subjects reported some transient itching (2 subjects), tingling (1 subject) and numbness (1 subject) of the leg during the occlusion plus vibration condition; however, these symptoms rapidly disappeared as soon as the pressure was relieved and vibration stopped, after 8 minutes.

### *5.3.2. Absolute Changes in Left Leg Bone and Muscle Skin Temperatures*

The left leg bone skin temperature ($LBSk_{temp}$) and left leg muscle skin temperature ($LMSk_{temp}$) starting with different temperatures (absolute changes) for the four various conditions are shown in Figure 5.1. This figure is an example of the actual response of skin temperature, which started at a different temperature for each condition.

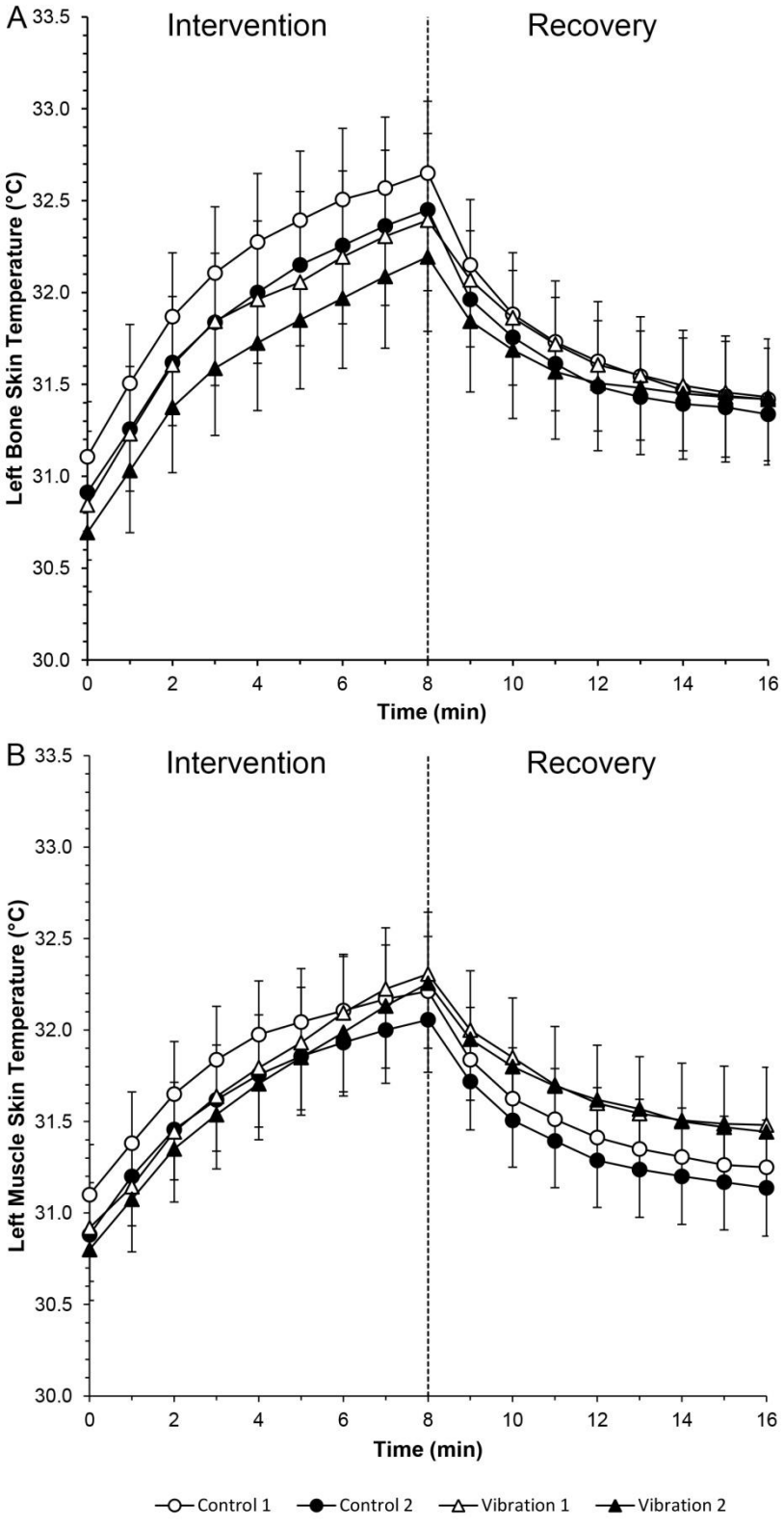


**Figure 5.1 Absolute changes of left leg bone skin temperature (A) and muscle skin temperature (B) during (0-8 min) and post- (8-16 min) intervention at various time points.**

**Data are shown as mean (n = 8) and error bars indicate SEM.**

### *5.3.3. Relative Changes of Delta Left Leg Bone Skin Temperature*

The delta left $LBSk_{temp}$ plotted with same starting temperature (relative changes) for the four various conditions is shown in Figure 5.2 A. There was a significant interaction between condition and time for the left $LBSk_{temp}$ ($P < 0.05$). A significant statistical difference was found between the control 1 and vibration 2 conditions for the left $LBSk_{temp}$ at several time points during recovery following intervention (14, 15 and 16 minutes) ($P < 0.05$). There was no significant statistical difference in the left $LBSk_{temp}$ during or after intervention between conditions of control 1 and control 2, control 1 and vibration 1, control 2 and vibration 1, control 2 and vibration 2, and vibration 1 and vibration 2 ($P > 0.05$).

During intervention, control 1 and 2, and vibration 1 and 2 all resulted in a significant rise in skin temperature over the tibia by 1.5 °C when compared to the baseline. However, the skin temperature over the tibia remained elevated above the baseline during recovery in response to additional passive vibration 1 and 2 relative that recorded for control 1 and 2. The skin temperature of the subjects in control 1 and 2 during recovery decreased by 1.2 °C and 1.1 °C, respectively, towards the baseline, whereas skin temperature post-vibration 1 and 2 interventions reduced by only 0.9 °C and 0.8 °C, respectively.

### *5.3.4. Relative Changes of Delta Left leg Muscle Skin Temperature*

The delta left $LMSk_{temp}$ plotted with same starting temperature (relative changes) for the four various conditions is shown in Figure 5.2 B. There was a significant interaction between condition and time for left $LMSk_{temp}$ ($P < 0.05$). A significant statistical difference in the left $LMSk_{temp}$ was observed between the vibration 1 and control 1 conditions after intervention at all recovery time points (9, 10, 11, 12, 13 14, 15 and 16 minutes), and for vibration 1 and control 2 conditions at several time points of recovery (10, 15 and 16 minutes) ($P < 0.05$). There was also a significant statistical difference between the vibration 2 and both control 1 and 2 conditions on left $LMSk_{temp}$ at the last time point during intervention (8 minutes) as well as all recovery time points post-intervention (9, 10, 11, 12, 13 14, 15 and 16 minutes) ($P < 0.05$). There was no significant statistical difference in left $LMSk_{temp}$ during or after intervention

between the control 1 and control 2 conditions, or between the vibration 1 and vibration 2 conditions ($P > 0.05$).

The temperature rise was ~0.2 °C higher over the gastrocnemius during exposure to passive vibration 1 and 2 when compared with that for control 1 and 2. Skin temperature rose during passive vibration 1 and 2 interventions by 1.4 °C and 1.5 °C, respectively, whereas skin temperature within the control 1 and 2 interventions reached only 1.1 °C and 1.2 °C, respectively. The effect of removing the cover resulted in a reduction in skin temperature over the gastrocnemius toward the baseline in response to control 1 and 2, while skin temperature remained elevated in the period following the vibration 1 and 2 interventions. During recovery after control 1 and 2 the skin temperature decreased by 0.9 °C whilst skin temperature after the vibration 1 and 2 interventions reduced by only 0.8 °C.

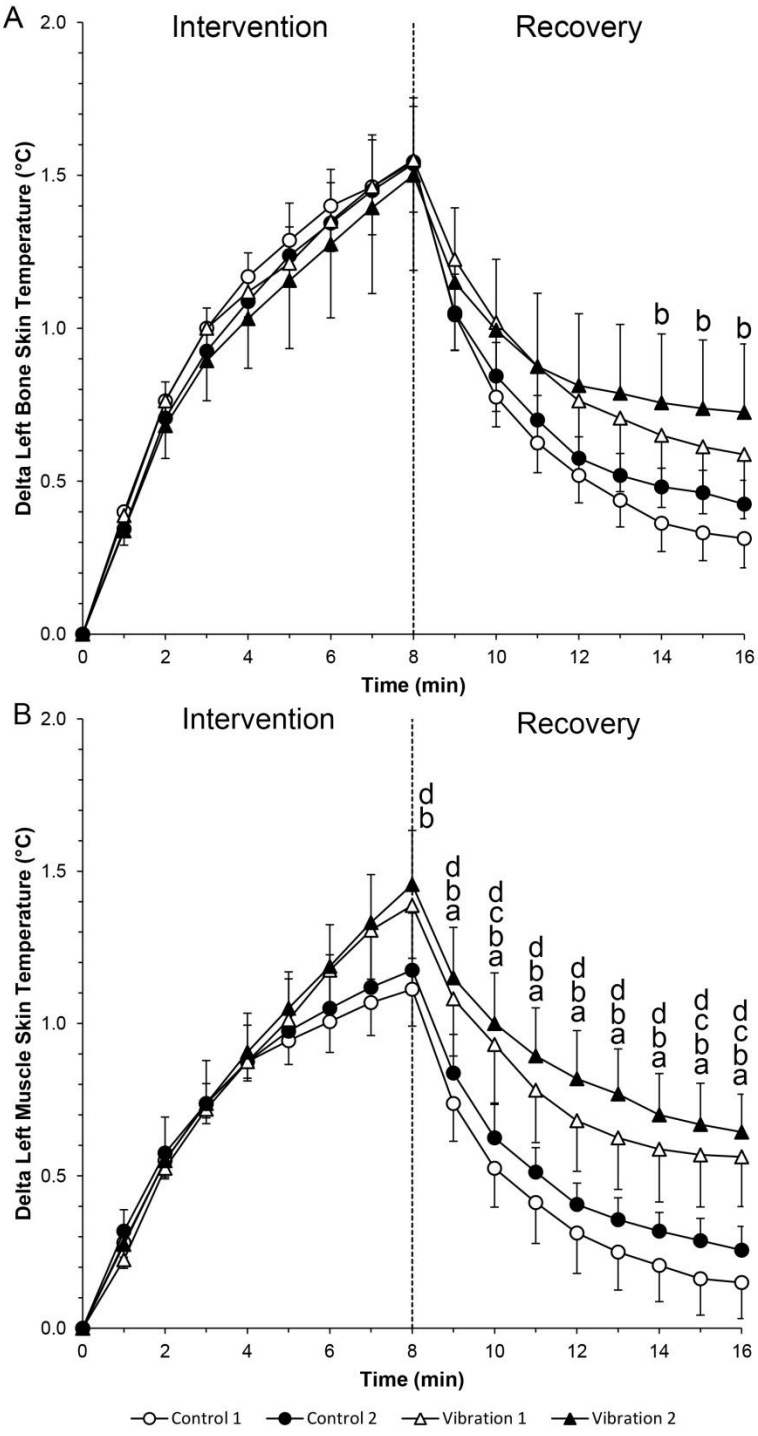


**Figure 5.2 Relative changes of delta left leg bone skin temperature (A) and muscle skin temperature (B) during (0-8 min) and post- (8-16 min) intervention at various time points.**

**"a" indicates significant differences between the control 1 and vibration 1 conditions ($P < 0.05$). "b" indicates significant differences between the control 1 and vibration 2 conditions ($P < 0.05$). "c" indicates significant differences between the control 2 and vibration 1 conditions ($P < 0.05$). "d" indicates significant differences between the control 2 and vibration 2 conditions ($P < 0.05$). Data are shown as mean (n = 8) and error bars indicate SEM.**

### *5.3.5. Absolute Changes in Right Leg Bone and Muscle Skin Temperatures*

The right $LBSk_{temp}$ and right $LMSk_{temp}$ starting with different temperatures (absolute changes) for the four various conditions are shown in Figure 5.3. This figure is an example of the actual response of skin temperature, which started at a different temperature for each condition.

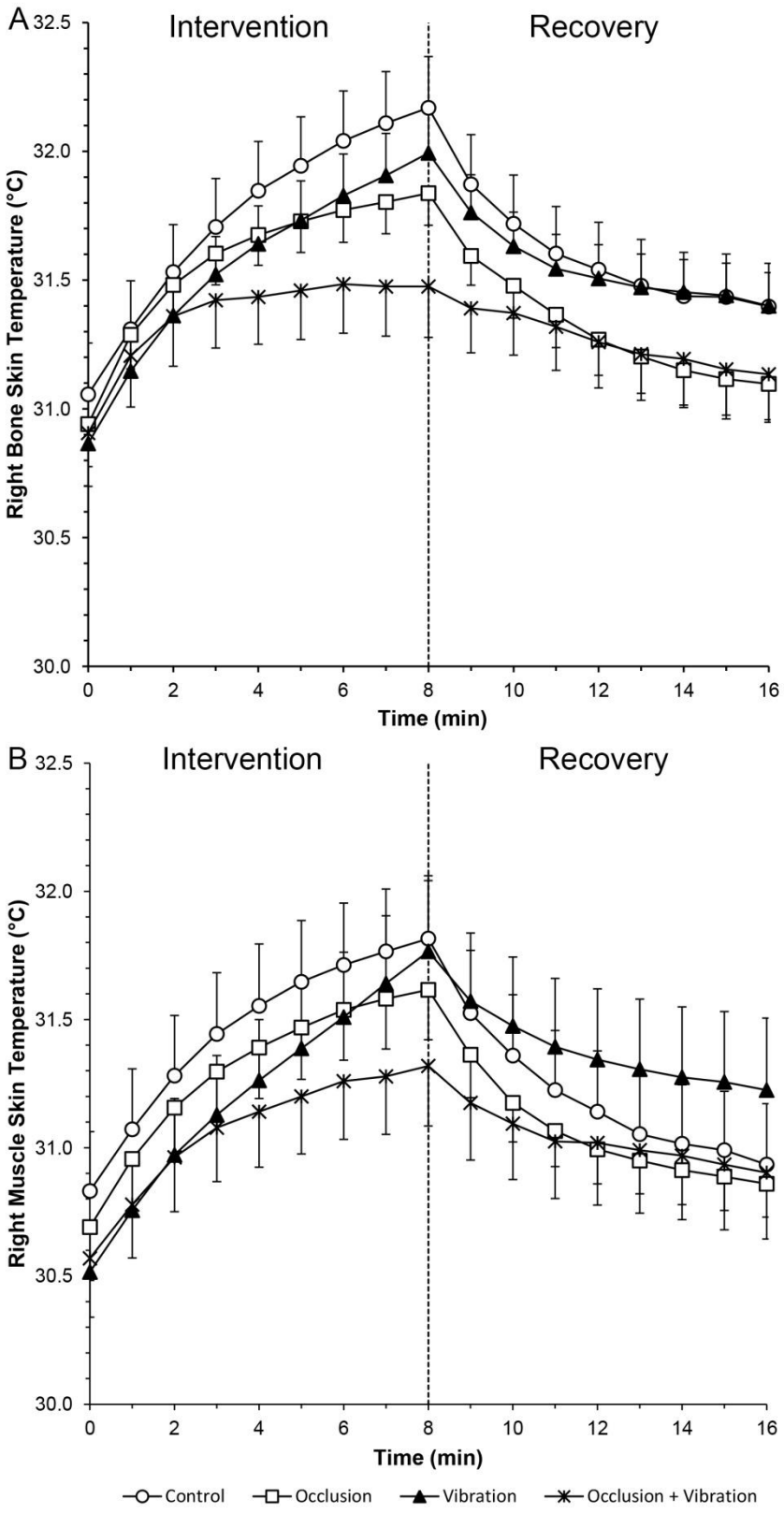


**Figure 5.3 Absolute changes of right leg bone skin temperature (A) and muscle skin temperature (B) during (0-8 min) and post- (8-16 min) intervention at various time points.**

**Data are shown as mean (n = 8) and error bars indicate SEM.**

### *5.3.6. Relative Changes of Delta Average Right Leg Bone Skin Temperature*

The delta average right $LBSk_{temp}$ plotted with same starting temperature (relative changes) for the four various conditions is shown in Figure 5.4 A. There was a significant interaction between condition and time for the right $LBSk_{temp}$ ($P < 0.05$). There was a significant statistical difference between the control and occlusion plus vibration conditions on the right $LBSk_{temp}$ at several time points during intervention (4, 5, 6, 7 and 8 minutes) and at the first time point of recovery after intervention (9 minutes) ($P < 0.05$). A significant statistical difference in the right $LBSk_{temp}$ was also found post-intervention between the occlusion and vibration conditions at several time points of recovery (9, 11, 12, 13, 14, 15 and 16 minutes) ($P < 0.05$). During intervention there was also a significant statistical difference in the right $LBSk_{temp}$ between the conditions of occlusion and occlusion plus vibration at several time points (6, 7 and 8 minutes) ($P < 0.05$). A significant statistical difference was also observed between the vibration and occlusion plus vibration conditions on the right $LBSk_{temp}$ at several time points during intervention (4, 6, 7 and 8 minutes) as well as all recovery time points post-intervention (9, 10, 11, 12, 13 14, 15 and 16 minutes) ($P < 0.05$). There was no significant statistical difference in the right $LBSk_{temp}$ during or after intervention between conditions of control and occlusion, and control and vibration ($P > 0.05$).

The addition of passive vibration resulted in a substantial rise in skin temperature over the tibia when compared with covering the limb alone. The effect of occlusion and occlusion plus vibration resulted in a depression in the effect of removing convective heat loss, such that the skin temperature was lower after 6 minutes of occlusion and vibration compared to either the control or vibration intervention. Skin temperature over the tibia rose by 1.1 °C during the control and vibration interventions, whereas within the occlusion and occlusion plus vibration interventions it increased by only 0.9 °C and 0.6 °C, respectively. The effect of removing the cover resulted in a decrease in skin temperature over the tibia toward the baseline in response to control and occlusion while the skin temperature following vibration with and without occlusion remained elevated above the baseline. During recovery, the skin temperature after the control and occlusion interventions fell by 0.8 °C and 0.7 °C, respectively, whilst after vibration and

occlusion plus vibration interventions the skin temperature fell by only 0.6 °C and 0.4 °C, respectively.

### *5.3.7. Relative Changes of Delta Average Right Leg Muscle Skin Temperature*

The delta average right $LMSk_{temp}$ plotted with same starting temperature (relative changes) for the four various conditions is shown in Figure 5.4 B. There was a significant interaction between condition and time for right $LMSk_{temp}$ ($P < 0.05$) There was a significant statistical difference between the control and vibration conditions on right $LMSk_{temp}$ after intervention at all recovery time points (9, 10, 11, 12, 13 14, 15 and 16 minutes) ($P < 0.05$). A significant statistical difference was also observed between the occlusion and vibration conditions on right $LMSk_{temp}$ at the last time point during intervention (8 minutes), as well as at all recovery time points post-intervention (9, 10, 11, 12, 13 14, 15 and 16 minutes) ($P < 0.05$). There was also a significant statistical difference in right $LMSk_{temp}$ between the conditions of vibration and occlusion plus vibration at several time points during intervention (6, 7 and 8 min) as well as all recovery time points after intervention (9, 10, 11, 12, 13 14, 15 and 16 minutes) ($P < 0.05$). There was no significant statistical difference in the right $LMSk_{temp}$ during or after intervention among the conditions of control and occlusion, control and occlusion plus vibration, and occlusion and occlusion plus vibration ($P > 0.05$).

The temperature rise was ~0.3 °C higher over the gastrocnemius during exposure to passive vibration, when compared with the control and occlusion. However the rise in skin temperature was 0.5 °C lower in response to the occlusion plus vibration intervention when compared with that for the passive vibration. Skin temperature rose by 1.25 °C during passive vibration intervention, whereas skin temperature within the control, occlusion and occlusion plus vibration interventions increased by only 1.0 °C, 0.9 °C and 0.75 °C, respectively. Furthermore, during recovery skin temperature over the gastrocnemius remained elevated above the baseline in response to additional passive vibration with and without occlusion compared to that for control and occlusion alone. The control and occlusion resulted in a decrease of 0.9 °C and 0.7 °C, respectively during recovery, whilst skin temperature in the recovery period after the

vibration and occlusion plus vibration interventions reduced by only 0.55 °C and 0.45 °C, respectively.

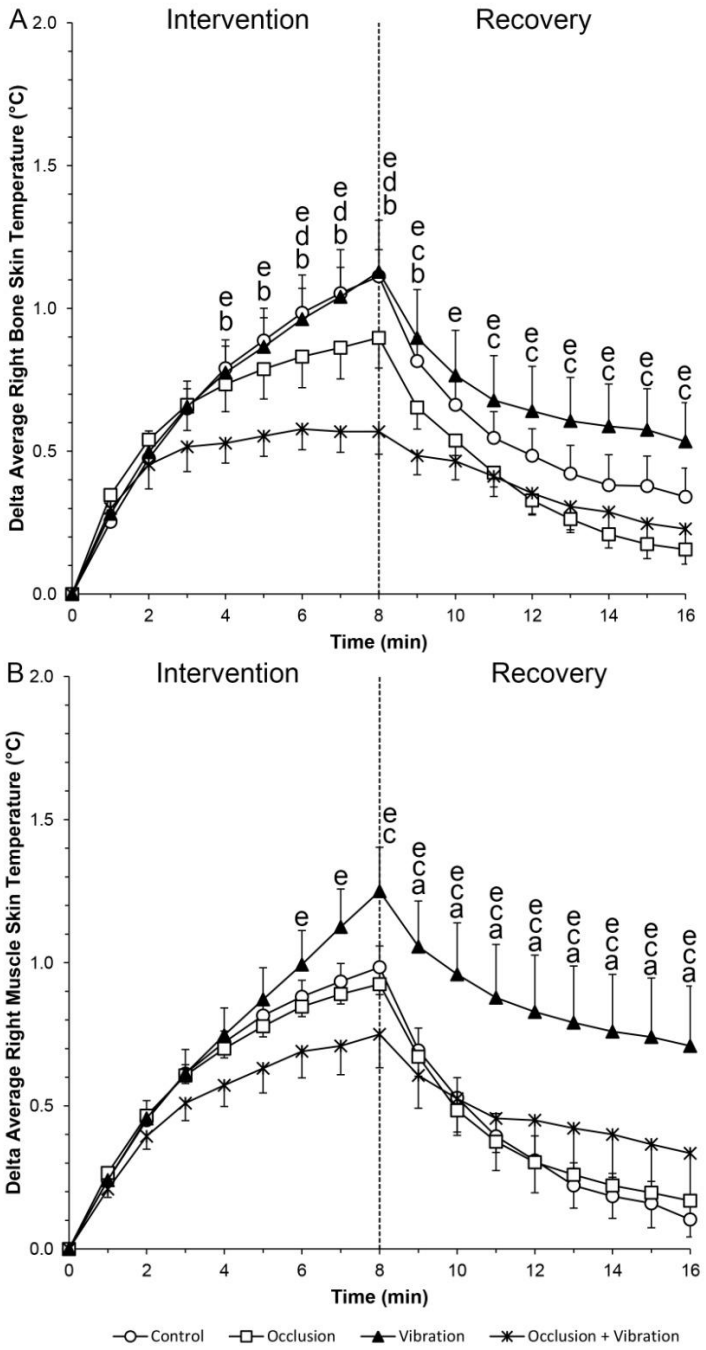


**Figure 5.4 Relative changes of delta average right leg bone skin temperature (A) and muscle skin temperature (B) during (0-8 min) and post- (8-16 min) intervention at various time points.**

**"a" indicates significant differences between the control and vibration condition ($P < 0.05$). "b" indicates significant differences between the control and occlusion plus vibration conditions ($P < 0.05$). "c" indicates significant differences between the occlusion and vibration conditions ($P < 0.05$). "d" indicates significant differences between the occlusion and occlusion plus vibration conditions ($P < 0.05$). "e" indicates significant differences between the vibration and occlusion plus vibration conditions ($P < 0.05$). Data are shown as mean (n = 8) and error bars indicate SEM.**

## 5.4. Discussion

The current study examined the leg bone skin temperature ($LBSk_{temp}$) and leg muscle skin temperature ($LMSk_{temp}$) during 8 minutes of control, vibration, occlusion, and occlusion plus vibration and during 8 minutes of subsequent recovery with intact circulation. The main finding from this study was that the addition of passive vibration resulted in a substantial rise in skin temperature over the tibia when compared with covering the limb alone. The effect of occlusion and occlusion plus vibration resulted in a depression in the effect of removing convective heat loss, such that the skin temperature was lower after 6 minutes of occlusion and vibration compared to either the control or vibration interventions. This was in contrast to the rise in skin temperature over the gastrocnemius that was observed during exposure to passive vibration. During vibration, the rise in skin temperature was higher by ~0.3 °C in comparison to the control and occlusion conditions. However, the effect of vibration and occlusion resulted in a dramatic attenuation in the rise of skin temperature, of about 50 %. The exact nature of the differences in skin temperature responses appears to be due to alterations in flow-mediated vascular response as a consequence of low flow conditions and abnormal flow patterns, as discussed below. Furthermore, skin temperature remained elevated over both the tibia and gastrocnemius during recovery in response to additional passive vibration with and without occlusion compared to the control and occlusion conditions.

It is well known that if blood flow is arrested in the vessel, the shear stress in this vessel will be absent and this reduction will lead to vasoconstriction (Anderson and Mark, 1989). In contrast, if there is more blood flow in the vessel, the shear stress in this vessel will increase and will lead to vasodilation (Anderson and Mark, 1989). Accordingly, if there is vasoconstriction, which causes less blood flow in the vessel, the temperature in this local vessel will reduce (Richardson et al., 1995, Krustrup et al., 2003). Conversely, if there is vasodilatation, which causes an increase in blood flow, the temperature in this local vessel will rise (Richardson et al., 1995, Krustrup et al., 2003). Therefore an increase in blood flow could be regulated via increased shear stress, which causes vasodilatation, and/or other factors, e.g. increases the activation of skeletal muscle (Rådegran and Saltin, 1999). Therefore, the increase in temperature might be due to an increase in skeletal muscle activation and/or an increase blood flow.

The most interesting finding was that exposure to passive vibration with occluded blood flow resulted in a dramatic attenuation in the rise of skin temperature relative to occlusion or control and vibration interventions over both the tibia (by about 30 %, 50 %, and 50 %, respectively) and the gastrocnemius (by about 15 %, 25 %, and 50 %, respectively). It has been previously demonstrated that a disturbed pattern of blood flow results in vasoconstriction in order to re-regulate endothelial dysfunction and this includes recirculation eddies, flow separation and reattachment, and reciprocating flow (Chiu and Chien, 2011). It is postulated that an abnormal flow pattern is the most likely cause of the response to the occluded blood flow with addition of exposure to passive vibration. These observations suggest that the combination of blood flow occlusion and vibration results in further vasoconstriction to reduce the abnormal flow of blood (i.e. eddies) and an attenuation in the rise in skin temperature. Furthermore, the plateau in skin temperature over the gastrocnemius appears to contradict the possibility of skeletal muscle activation during exposure to passive vibration. These findings suggest that passively applied vibration can result in an increase in skin temperature during exposure, in response to increased blood flow due to a vasodilatation response independent of skeletal muscle activation, suggesting therefore that vibration has a direct effect on the muscle vascular bed.

In order to avoid any issue that might affect the regulation of blood flow, i.e. the cooling effect from convection was negated through covering both lower legs with a cloth during each intervention. While the right leg was the main limb of interest, the skin temperature measurements made on the left leg were completed for reliability purposes. Indeed, the results of this study showed that there were no significant differences in left $LBSk_{temp}$ and $LMSk_{temp}$ during or after intervention between the control 1 and control 2 conditions, nor between the vibration 1 and vibration 2 conditions. The effect of eliminating convective heat loss resulted in a ~1.0 °C rise in skin temperature when the thermistor was located over the tibia, irrespective of any applied vibration (see Figure 5.2 A). In contrast, when examining the effect of removing convective heat loss but with the thermistor located over the gastrocnemius there was a difference between vibration exposure and no vibration, such that the temperature rise was about 25 % higher with vibration. It has been previously demonstrated that passive vibration will increase muscle spindle and Golgi tendon organ activity, which could be indicative of an increase in skeletal muscle activity (Burke et al., 1976b). However, this

circumstantial evidence does not directly reflect an increase muscle fibre activity, only that vibration exposure increases the afferent output of the organelles detecting muscle and tendon length. Nevertheless the data from the left leg illustrates that passive vibration leads to an elevated increase in skin temperature, indicating either a direct effect on the muscle vascular bed or a secondary effect from increasing muscle activity.

The main focus of the present study was the intervention on the right leg, showing that the skin temperature data over the tibia and gastrocnemius for both the control and vibration intervention during the intervention and in the post-intervention period were comparable to the data from the left leg (i.e. the control 1 and control 2, and the vibration 1 and vibration 2). Therefore, these findings indicate that the effects of control and vibration in skin temperature over the tibia and gastrocnemius on the right and left legs are repeatable. It was observed that, similarly to the left leg data, skin temperature rose during the control intervention by 1.1 °C over the tibia and by 1.0 °C gastrocnemius. These rises in skin temperature over the bone and muscle are most likely due to the absence in convective heat lost with the cover on. Moreover, the difference in skin temperature between the control and vibration during intervention was absent when the thermistor was located over the tibia. There are two possible explanations consistent with this observation. One of the possible explanations is that vibration has no effect on the skin over the bone while the other possible explanation is that the bone dampens the vibration stimulus and so reduces the influence of vibration exposure on the skin. It is postulated that the rise in the skin temperature over the bone during the vibration intervention is most likely due simply to the absence of convective heat loss.

Conversely, with the thermistor located over the gastrocnemius there was a greater rise in skin temperature due to the vibration exposure compared to that for control, occlusion and occlusion plus vibration interventions (by approximately 25 %, 35 %, and 50 %, respectively). It has been previously reported that exposure to vibration can cause changes in muscle and tendon length (i.e. muscle spindle and Golgi tendon organ activity) (Burke et al., 1976b). Stimulating short, fast changes in the length of muscle and tendon, which is called a tonic vibration reflex, during exposure to vibration can raise the temperature of the muscle, requiring an increased blood flow to the skin to dissipate the metabolically produced heat (Hazell et al., 2008). However, Burke et al. (1976b) found that muscle fibre activity was relatively low when vibration was

passively applied to the leg. This finding suggests that vibration applied to unloaded muscles appears to provide a minimal stimulus for skeletal muscle activation.

On the other hand, it has been documented that increasing intensity of exercise results in an increased muscle blood flow and therefore the temperature within the muscle would progressively rise (Krustrup et al., 2003). Indeed, Lohman et al. (2011) noted that both skin blood flow, measured by a laser Doppler flow meter, and skin temperature over a calf muscle (gastrocnemius) significantly increased in response to 10 minutes of acute passive lower leg vibration. In another passive vibration study by Lohman et al. (2007) found, by using a laser Doppler imager, that 3 minutes of acute vibration passively applied to a lower limb significantly increased calf skin blood flow. In a follow-up passive vibration study, Maloney-Hinds et al. (2008) documented that forearm skin blood flow, which was also measured using a laser Doppler flow meter, increased within 10 minutes of starting acute passive arm vibration. Another study performed by Lohman et al. (2012) reported a significant increase in calf skin blood flow, measured again by laser Doppler flowmetry, occurring after 10 minutes of acute passive lower leg vibration. These observations suggest that passively applied vibration to a limb increases local skin blood flow over muscle, thereby most likely leading to increases in skin temperature. Since there was evidence that skin blood flow increases over muscle during passive vibration exposure and might be a minimum effect of skeletal muscle activation occurring during vibration intervention, it is therefore suggested that the rise in skin temperature over the muscle in the current study is due to either an increase in blood flow as a direct effect on the muscle vascular bed, or to skeletal muscle activation as a secondary effect from increasing muscle activity (if there was skeletal muscle activation), or both.

As expected, a difference was found among occlusion, and vibration exposure and control on skin temperature when the thermistor was located over the right tibia, such that the temperature was approximately 20 % lower with occluded blood flow. It has been previously demonstrated that brachial artery blood flow was significantly reduced during 10 minutes of occluded the blood flow to the forearm (Anderson and Mark, 1989). Therefore, the reduction in skin temperature during the occlusion intervention of the present study appears to be due to the arrest of blood flow in the right leg. In contrast, there was no difference in skin temperature during intervention between the

control and occlusion when the thermistor was located over the gastrocnemius. A possible explanation consistent with this observation is that there was residual heat stored in the muscle that resulted in a similar rise in skin temperature during occluded blood flow.

Other important findings were that, when examining the effect of removing the cover with the thermistors located over both the tibia and gastrocnemius there was a reduction in skin temperature toward the baseline after interventions of control and occlusion alone, whereas this reduction in skin temperature was absent in the subsequent period of exposure to vibration with and without occlusion intervention. The decrease in skin temperature towards the baseline after the control intervention is most likely due to a cooling effect in the lower limb in response to removing the cover. Conversely, skin temperature remained elevated above the baseline in the post-intervention period in response to vibration exposure. In a previous passive vibration study, Lohman et al. (2011) found that there were significant increases in both skin temperature and skin blood flow in a calf muscle over the baseline with 9 minutes of recovery following a 10 minutes intervention of acute passive lower leg vibration. Another study by Lohman et al. (2007) noted that calf skin blood flow substantially increased over the baseline with 10 minutes recovery after 3 minutes of acute passive lower limb vibration. A follow-up passive vibration study by Maloney-Hinds et al. (2008) reported that forearm skin blood flow remained above the baseline during 15 minutes of recovery in response to 10 minutes of acute vibration passively applied to the arm. Lohman et al. (2012) found a significant increase in calf skin blood flow over the baseline with 10 minutes of recovery post-10 minutes of acute passive lower leg vibration exposure. These findings support the observations of the present study that a rise in skin temperature during recovery from acute passive vibration intervention is most likely due to a vasodilatation effect resulting in an increase in skin blood flow.

In a previous study by Anderson and Mark (1989) it was reported that deflating the forearm occluding cuff after 10 minutes significantly increased brachial artery blood flow (reactive hyperaemia) by about 50 % compared to the baseline prior to arresting the blood flow. Thus, the increase in blood flow during reactive hyperaemia would necessitate a rise in skin temperature. Indeed, a rise in skin temperature over both the tibia and gastrocnemius relative to the baseline was observed in response to occlusion

with additional vibration exposure indicating a reactive hyperaemia. In contract, after releasing the leg occluding cuff alone, the skin temperature reduced towards baseline. It seems that a cooling effect has impacted the lower limb during recovery from the occlusion intervention alone as reflected by a falling skin temperature. Whereas this cooling effect was absent in the occlusion with vibration exposure, for which the response was comparable to that following the vibration exposure intervention. These data suggest that the addition of vibration exposure and occluded blood flow results in a rise in skin temperature as a function of a reactive hyperaemia. The resulting vasodilatation induces a greater increase in blood flow than that observed in post-occlusion alone.

Similarly to the results of the studies of initial passive vibration (Chapter 3) and duration of passive vibration (Chapter 4), it was observed in the current study that itchiness and redness of the lower limb were visible on some subjects during and after vibration treatment, but it was always transient, mild, and not disturbing. These symptoms are related to the cardiovascular function and might also be a strong indication of an increase in the shear stress occurring at the vessel wall, leading to vasodilatation, therefore increasing blood flow in response to exposure to vibration, as suggested by Rittweger et al. (2000), Broadbent et al. (2010) and Rittweger et al. (2010).

Generally, these symptoms and the results of the present study indicate that the rise in skin temperature during exposure to vibration that continues into recovery, independent of skeletal muscle activation, is due to an increase in blood flow by increasing vasodilatation in the vascular function. An explanation consistent with these observations was that passive vibration applied to the lower legs, independent of skeletal muscle activation, induced shear stress resulting in a general vasodilatory effect on the lower limb, therefore increasing blood flow.

In conclusion, passively applied vibration to the lower legs resulted in a rise in skin temperature during exposure and in the post-exposure period, despite the absence of skeletal muscle activation. Therefore, the findings propose that vibration produces more heat than the other conditions, as reflected by the higher skin temperature observed during exposure to vibration, and continuing into recovery. These data provide evidence for a direct effect of WBV on the peripheral cardiovascular function during and post-

exposure, via increased vasodilatation. Furthermore, these findings indicate that there is a vibration-induced increase in shear stress in the blood vessel walls, resulting in an enhanced blood flow. This is the first study to provide evidence that passive vibration has a direct effect on the peripheral circulation and the induced shear stress factor; this is evidence that was not previously available. Hence, these findings suggest that vibration induces an enhancement in skeletal muscle blood flow by increasing vasodilatation and thereby could be used in assisting recovery from exertion and also using as a training stimulus, this despite the absence of skeletal muscle activation.

# Chapter 6 - General Discussion

Whole body vibration (WBV), which could be employed as a novel form of exercise, is receiving increasing interest in physical training (Delecluse et al., 2005, Cochrane and Stannard, 2005) and rehabilitation applications (Ebersbach et al., 2008, Bautmans et al., 2005). It has been previously demonstrated that an increase in skeletal muscle activity is observed during vibration exposure (Burke et al., 1976b). Indeed, several studies have shown that electromyographic activity increased in response to WBV, thereby indicating an increase in skeletal muscle activity occurring during exposure to vibration (Cardinale and Lim, 2003, Abercromby et al., 2007a, Hazell et al., 2007). Consequently, the increases in the activation of skeletal muscle during exposure to vibration should lead to an increase in blood flow to the activated muscle bed. An increase in local skeletal muscle blood flow has been observed after WBV exposure (Hazell et al., 2008, Lythgo et al., 2009, Kerschan-Schindl et al., 2001, Stewart et al., 2005, Herrero et al., 2011b, Herrero et al., 2011a) but there are no data describing the mechanism to explain the response from WBV on skeletal muscle blood flow. Thus, the effects of WBV on peripheral cardiovascular function are poorly understood.

Since there is currently no study that has detected the potential mechanism that would explain the effect of WBV on the peripheral cardiovascular function, it would be beneficial to investigate this area to provide a clearer understanding of the relationship between WBV and cardiovascular function. The main aim of this thesis was to investigate the effect of WBV on peripheral cardiovascular function. A secondary aim was to detect the potential vasodilatory effects of vibration via induced shear stress, resulting in an increased vasodilatation that enhances the peripheral blood flow in assisting recovery from exertion and also to explore its potential as a novel training stimulus. The first study in this thesis (the initial WBV study, in Chapter 2) aimed to investigate the effects of WBV on the systemic blood flow response. The second study (the first passive vibration study, in Chapter 3) aimed to investigate the potential effects of passive vibration on the peripheral circulation. The third study (the duration of passive vibration study, in Chapter 4) examined the effects of different durations of passive vibration on the peripheral circulation. The fourth study (the occlusion of blood flow study, in Chapter 5) attempted to distinguish the effects of passive vibration on skeletal muscle activation from those on the peripheral vascular system.

Green et al. (2002) documented that exercise at a sufficiently high intensity involving a substantially large muscle group can have effects on the whole cardiovascular system

via an increased skeletal muscle blood flow distal to the main muscle activation site (i.e. a systemic effect on the circulation). A follow-up study carried out by Green et al. (2005) reported that lower limb exercise (cycle ergometer exercise) at a moderately-high intensity (oxygen consumption ~1.8 l/min) resulted in an increase in distal blood flow (i.e. forearm blood flow), while forearm blood flow (FBF) fell or was unchanged during cycling exercise at low intensity (a low metabolic rate). Moreover, Green et al. (2002) and Green et al. (2005) found that brachial antegrade systolic flow progressively increased with increasing workloads of cycle ergometer exercise, whereas brachial retrograde diastolic flow increased substantially during all cycling exercise workloads. These observations indicate that the differences in the response of FBF with different workloads of exercise were related to the impact of retrograde diastolic flow, which was relatively larger at lower workloads of exercise, rather than antegrade systolic flow, which was modest during all exercise intensities. The responses in antegrade and retrograde flow during cycling exercise were in contrast to those observed during forearm exercise, where antegrade flow in the brachial artery was higher than in leg exercise and retrograde flow was extremely low. To date, there are no data reporting any systemic effects of WBV on blood flow. Understanding the mechanism that would explain the effect of vibration on the systemic blood flow thus warrants further investigation.

The initial WBV study in this thesis (reported in Chapter 2) investigated the effects of WBV on the systemic blood flow response. The effects of WBV exposure during the completion of dynamic squat exercise on the FBF response was compared to the squatting exercise alone, in healthy young adults. This involved subjects performing 2 minutes of dynamic squatting exercise at varying intensities (unloaded and loaded) with and without WBV on the vibrating platform. The study was designed to address any potential systemic effect on the circulation in a similar manner to the studies by Green et al. (2002) and Green et al. (2005). The results failed to show any statistically significant differences in the post-exercise FBF, mean brachial arterial pressure or heart rate between the various conditions (i.e. unloaded squats alone, unloaded squats with WBV, loaded squats alone and loaded squats with WBV).

However, there was a trend towards differences in FBF at the first post-exercise time point (1.5 minute) where FBF appeared to increase in the unloaded squats alone condition but this did not reach significance. However, this increase in FBF was lower

in response to unloaded squats with WBV treatment. In contrast, with loaded squats alone this increase in FBF was absent compared with the baseline and although it appeared to increase from loaded squats alone to loaded squats with WBV exposure, this apparent change did not reach significance.

A possible explanation consistent with these observations is that the sensitivity of the equipment to detect a change in upper limb blood flow may have been too small or the effect only lasted for a very short duration. Another possible explanation is that vasodilatation in the activated skeletal muscle of the lower limb could 'steal' the blood flow from a distal site (i.e. forearm) to the main site (i.e. lower limb), as described by Green et al. (2005). It was concluded that the intensities in both unloaded and loaded squats exercise were in all likelihood higher than the lower exercise intensities used in Green's studies (2005, 2002), and therefore the blood flow response is in all probability different in the distal limb during higher intensity exercise. Furthermore, it is postulated that retrograde diastolic blood flow in FBF was relatively high during all the conditions of this study, which resulted in no statistical significant difference between these conditions in terms of FBF. Overall, although it appears that WBV might have an effect on systemic blood flow, the effects of WBV on vascular function, although, were not clear enough to indicate any potential vasodilation. Therefore, it was hard to detect the effects of vibration on peripheral cardiovascular function because, most likely due to the higher exercise intensity, skeletal muscle activation could have resulted in redirecting blood flow from the forearm to the lower limb. These results were considered preliminary but indicated that the potential vasodilatory effects of cardiovascular system warrants further investigation and a new model of the effects of vibration exposure or better methods of analysis needed to be developed for future studies.

Standing on the vibrating platform during exposure to vibration is reported to be an effective method of inducing skeletal muscle activation, whereas this increase in skeletal muscle activity was found to be relatively low during passively applied vibration to a limb (Burke et al., 1976b). The finding by Burke et al. (1976) proposes that vibration applied to unloaded muscles appears to provide a minimal stimulus for skeletal muscle activation. In order to focus solely on the mechanism inducing effects and avoid complications due to skeletal muscle activation (Pollock et al., 2010), in the current research a technique was developed to apply vibration passively to the lower limbs and is a technique employed during all subsequent studies. This technique

involved subjects lying in a supine position with their calves resting on the vibrating platform.

The first passive vibration study (Chapter 3) in this thesis investigated the potential vasodilatory effects of this model of vibration. The experimental model was hypothesised to be independent of muscle activation, since vibration was applied in a passive manner to the lower limbs with the effect being confined to the peripheral circulation, in order to gain an understanding of the effects of this vibration stimulus in healthy young adults. The passive vibration treatment consisted of three 60 seconds bouts with 10 seconds rest between bouts. This study was designed to be comparable with the protocol used in a previous study (Lohman et al., 2007), which reported that after 3 minutes of acute vibration passively applied to a lower limb, the stimulus resulted in a significant increase in calf skin blood flow (gastrocnemius), by 250 %, which remained significantly elevated (200 %) above baseline during 10 minutes of recovery. Other studies have found a substantial increase in skin blood flow observed in response to acute passive vibration exposure (Lohman et al., 2011, Lohman et al., 2012, Maloney-Hinds et al., 2008). Whether this increase is a secondary effect in response to skeletal muscle activation due to functional hyperaemia or a direct effect of vibration-induced shear stress on the peripheral cardiovascular system is not known. The data reported in Chapter 3 demonstrated that passively applied vibration to the lower legs resulted in a significant reduction in ankle systolic blood pressure (ASBP) and ankle brachial pressure index (ABPI) in the post-vibration period, an observable effect despite the absence of skeletal muscle activation. However, there was a substantial reduction in lower leg blood flow (LLBF) and lower leg vascular conductance observed at 1 minute into recovery after control treatment, the sham exposure, and this was postulated to be most likely due to a cooling effect from the platform of the vibration device.

Le Faucheur et al. (2006) found that ASBP and ABPI were lower than the baseline measurement within 10 minutes of recovery after maximal cycle ergometer exercise. It is well known that, if the ABPI were to fall, this would be indicative of an increased (Le Faucheur et al., 2006) vasodilatation in the lower legs relative to the arms. This was indeed the case, with a significantly reduced ASBP and ABPI observed in the current study after passive vibration.

Moreover, Rådegran and Saltin (1999) reported that after blocking the production of nitric oxide by L-$N^G$-monomethyl arginine (L-NMMA) infusion, femoral artery blood flow was significantly reduced within rest and after 10 minutes of recovery post-exhaustive exercise, by ~52 % and 66 %, respectively, compared to recovery after saline infusion. However, this difference in femoral artery blood flow between the saline and L-NMMA infusion conditions during submaximal exercise was absent, demonstrating that vasodilation in the contracting muscle is nitric oxide independent. In a separate study, Green et al. (2005) documented a significant decrease in blood flow during rest, after blocking the production of nitric oxide, compared to that in a saline-infusion condition. The observations from these studies indicate that blood flow during rest and recovery after exhaustive exercise might be related to a shear stress-mediated release of nitric oxide from the endothelium. Consequently, the effects of vibration on peripheral cardiovascular function are proposed to be due to pulsatile endothelial shear stress causing an increase in circulating nitric oxide concentration, as a result of an increase in endothelial nitric oxide synthase activity, which then causes vasodilatation in resistant blood vessels (as described by Green et al. (2005). Thus, the most plausible explanation of the mechanism of this substantial reduce in ABPI during recovery post-exposure to vibration is due to a vasodilatation response that occurred in the lower limb, possibly inducing an increase in shear stress at the blood vessel's wall, and ASBP data also appear to corroborate this suggestion.

Furthermore, the present study confirms that the slight reduction in the upper limb blood flow (i.e. FBF and AVC) at 1 minute of recovery post-exposure is due to a systemic effect in response to a low intensity of vibration passively applied to the lower limb that might be induced an increase in shear stress, resulting in an increase vasodilatation occurring in the lower limb that 'steals' the blood flow from distal site (i.e. forearm) to the main site (i.e. lower limb), as described by Green et al. (2002) and Green et al. (2005). Moreover, it has been demonstrated that retrograde diastolic flow, rather than antegrade systolic flow, plays a central role in the responses of blood flow in distal limb during different intensities of systemic exercise, in particular at lower intensity of exercise, (Green et al., 2005, Green et al., 2002). Green et al. (2002) and Green et al. (2005) concluded the importance of an oscillatory antegrade/retrograde flow pattern may be a very potent stimulus to shear stress-mediated endothelial production of nitric oxide. Overall, the results of the present study provide evidence that vibration stimulus, which appears to be independent of skeletal muscle activation, has a

direct effect on the peripheral cardiovascular function and that this is most likely due to an increase in shear stress.

Another possible indication of the increased shear stress in response to vibration is that some subjects reported experiencing transient and mild itching of the legs during and after vibration treatment. A number of studies have reported that itchiness, redness, erythema, and oedema occurred transiently during the first few sessions of WBV exposure (Kerschan-Schindl et al., 2001, Roelants et al., 2004b, Rittweger et al., 2000, Hazell et al., 2008, Russo et al., 2003, Broadbent et al., 2010, Cronin et al., 2004). In a previous study by Rittweger et al. (2000), it was proposed that the main contributor of these symptoms is the increase in blood flow. Moreover, it has been postulated that the vibration-induced shear forces in the skin promote vasodilatation, which is believed to be mediated by liberation of histamine from mast cells (Rittweger, 2010). In a follow-up study, Broadbent et al. (2010) found that histamine levels were lower after exposure to vibration following muscle soreness from downhill running compared to sham exposure. Accordingly, they speculate that vibration may increase the clearance rate of histamine via increased blood flow and conclude that acute exposure to vibration may stimulate mast cells to produce histamine, leading to increased vasodilatation, therefore increasing blood flow, which promotes these symptoms. Overall, it seems that the most likely mechanism causing these symptoms is a vibration-induced increase in shear stress at the vessel wall, causing vasodilatation and thereby increasing blood flow. Factors promoting these symptoms in response to vibration exposure remain unidentified by the scientific community; however, studying such factors is beyond the scope of this research.

Based on the observations of the present study it was concluded that vibration has a direct effect on the peripheral cardiovascular function via an increased vasodilatation and that the most likely mechanism underlying this effect is a vibration-induced increase in shear stress in the blood vessels, an alternative mechanism might be due to localised heating, which in itself would also induce vasodilation.. It could be hypothesised that WBV may be of use to enhance blood flow during recovery routines and may also have potential as a novel training stimulus. In order to explore this further, it was decided to conduct further investigation of the effects of different durations of vibration on the peripheral blood flow warrants further investigation.

The duration of passive vibration study (described in Chapter 4 in this thesis) followed a similar design to the first passive vibration study (Chapter 3), but with the intention of investigating the effects of varying durations of passive vibration on the peripheral circulation in healthy young adults. The subjects were involved in completing four different durations of passive vibration i.e. 1, 2, 4 and 8 60-second bouts with 10 seconds rest between each bout. The cooling effect from the platform of the vibration device was avoided by attaching a thin wooden plate on the top of the vibration platform. The results reported in Chapter 4 demonstrated that LLBF was significantly increased at 1 minute of the recovery period following 2 minutes, 4 minutes and 8 minutes of acute passive lower limb vibration and this remained substantially higher above baseline for 4 minutes of the recovery period post-8 minutes of acute passive lower limb vibration, despite the apparent absence of skeletal muscle activation. LLBF at 1 minute post-vibration treatment was progressively increased with increasing durations of passive vibration exposure.

As illustrated by Rådegran and Saltin (1999), competitive inhibition of nitric oxide production reduces blood flow during the recovery period following exercise. Moreover, Burke et al. (1976b) reported that skeletal muscle activity was relatively low in response to passive vibration exposure. Continued activation of skeletal muscle results in an increase in heat generation, as reported by Krustrup et al (2003), the prolonged exposure to vibration might have resulted in a higher accumulation of heat and hence vasodilatory response. Therefore, the greater amplitude of vasodilatation in the lower limb during recovery, as reflected by the increased muscle blood flow, might be due to either a longer duration of passively applied vibration inducing a greater increase in shear stress: i.e. it is nitric oxide dependent, and/or a greater stimulus for activation of skeletal muscle occurring with a longer duration of passive vibration These data provide evidence that a further effect on vascular function occurring with a longer duration of vibration.

Furthermore, transient and mild itching and warming of the legs were visible on some participants in response to a longer exposure to vibration duration (4 and 8 minutes). As discussed above, in the first passive vibration study, these symptoms also indicate that a greater increase in shear stress in blood vessels may occur in response to longer vibration duration. Based on the observations of the present study it was concluded that a longer vibration period is more effective in enhancing the peripheral blood flow

caused by the vasodilatation response throughout the recovery period, possibly due to a longer period of vibration inducing a greater increase in shear stress in the blood vessels but equally a longer duration of passive vibration could have a minimum effect of skeletal muscle activation, which leads to direct response to localised heating. This longer vibration duration induced a further enhancing effect on the peripheral cardiovascular function and could be used as a novel training stimulus and also might be helpful in assisting recovery from exertion. It was considered further investigation was needed to understand the mechanism that would explain the effect of vibration on the peripheral cardiovascular function.

The occlusion of blood flow study (Chapter 5) in this thesis investigated the potential enhancement effects of vibration during and in the post-exposure period on the peripheral circulation in healthy young adults. Whether this enhancement is a secondary effect in response to skeletal muscle activation due to functional hyperaemia and/or a direct effect of vibration-induced shear stress resulting in vasodilatation of the peripheral cardiovascular function was unknown. The cooling effect from convection was negated through covering both lower legs with a cloth during each intervention, in order to avoid any issue that might affect the regulation of blood flow. In addition, any complication caused by the intermittent nature of applying the bouts of vibration exposure on the blood flow regulation was avoided by exposing volunteers to continuous vibration. The study involved subjects completing four different conditions in randomised order, each trial lasted 8 minutes and consisted of: control, vibration, occlusion, and occlusion plus vibration and was followed by 8 minutes of recovery with intact circulation. Because of the difficulties in measuring blood flow in the usual ways (e.g. via plethysmography, ultrasound, electromyography or a laser Doppler flowmetry probe) during vibration exposure, due to the interference of waves from the vibration device, skin temperature measurement was employed in this study as a surrogate measure of skin flow.

The results reported in Chapter 5 demonstrated that after preventing convective heat loss there was a difference between the vibration, control and occlusion interventions, such that the temperature rise was ~0.3 °C higher with vibration exposure. Through increasing muscle fibre activity, skin and muscle temperature will rise, requiring an increase in blood flow to dissipate the metabolically produced heat (Hazell et al., 2008). Krustrup et al. (2003) noted that increasing the intensity of exercise results in an

increased muscle blood flow and therefore the temperature within the muscle would progressively rise. However, a previous study reported that muscle fibre activity was relatively low when vibration was passively applied to the limb (Burke et al., 1976b). Indeed, a significant increase in skin blood flow and skin temperature over a calf muscle (gastrocnemius) has been observed after 10 minutes of acute passive lower leg vibration (Lohman et al., 2011). Since there was evidence that skin blood flow increases over muscle in response to passive vibration exposure and might be a minimum effect of skeletal muscle activation occurring during exposure to vibration, therefore it seems likely that the rise in skin temperature over the muscle during passive vibration in the present study is due to either a direct effect on the muscle vascular bed or a secondary effect from increasing muscle activity. The rise in skin temperature during the control intervention was most likely due to the absence of convective heat lost with the cover on. In a previous study by Anderson and Mark (1989), it was demonstrated that brachial artery blood flow significantly reduced during 10 minutes of occluding the blood flow to the forearm. Nevertheless, in this study, no difference in skin temperature was found between the control and occlusion interventions. It is proposed that there was residual heat stored in the muscle that resulted in a similar rise in skin temperature during the occluded blood flow.

Interestingly, the rise in skin temperature was attenuated by about 50 % in response to occlusion plus vibration intervention, when compared with the passive vibration. Chiu and Chien (2011) documented that a disturbed pattern of blood flow causes vasoconstriction in order to re-regulate endothelial dysfunction, and this includes recirculation eddies, flow separation and reattachment, and reciprocating flow. Consequently, it is proposed that the combination of blood flow occlusion with additional exposure to passive vibration results in further vasoconstriction to reduce the abnormal blood flow (i.e. eddies) and an attenuation in the rise in skin temperature. Furthermore, the plateau in skin temperature appears to contradict the possibility of skeletal muscle activation during exposure to passive vibration. These findings indicate that passively applied vibration can result in a rise in skin temperature during exposure, in response to increased blood flow due to a vasodilatation response independent of skeletal muscle activation, suggesting, therefore, that vibration has a direct effect on the muscle vascular bed.

On the other hand, skin temperature remained elevated during recovery in response to additional passive vibration with and without occlusion, relative to the control and occlusion conditions. The decrease in skin temperature towards the baseline after the control intervention is most likely due to a cooling effect in the lower limb in response to removing the cover and restoring convective heat loss. In contrast, a rise in skin temperature above baseline during recovery from acute passive vibration intervention is most likely due to a vasodilatation effect resulting in an increase in skin blood flow. This data is in line with the observations made by Lohman et al. (2011), who reported that skin temperature and skin blood flow over calf muscle were significantly increased above baseline at 9 minutes recovery after 10 minutes of acute exposure to passive lower leg vibration.

Anderson and Mark (1989) demonstrated that brachial artery blood flow significantly increased by about 50 % when deflating the forearm occluding cuff after 10 minutes (reactive hyperaemia) compared to the baseline prior to arresting the blood flow. Thus, the increase in blood flow during reactive hyperaemia necessitates a rise in skin temperature. The elevated skin temperature following occlusion with additional vibration, compared to the baseline, followed a comparable response of the post-passive vibration exposure during the 8 minutes of recovery in the decline in skin temperature. Therefore, these data suggest that the addition of vibration exposure to occluded blood flow results in a rise in skin temperature during recovery could be a function of reactive hyperaemia, and would result in vasodilatation causing a greater increase in blood flow than post-occlusion alone.

Because the subjects in the present study lay down in the supine position during all conditions and the vibration was passively applied to unloaded lower leg muscles with calves rested on the vibration platform, the absence of skeletal muscle activation and the occlusion plus vibration data suggest that the intensity during vibration intervention was relatively low. It is therefore suggested that the effects of vibration on the peripheral cardiovascular function is due to pulsatile endothelial shear stress causing an increase in circulating nitric oxide concentration, as a result of increase endothelial nitric oxide synthase activity, which causes vasodilatation in resistant blood vessels, as described by Rådegran and Saltin (1999), and Green et al. (2005). Thus, the most plausible explanation of the mechanism of this rise in skin temperature during exposure to passive vibration that continues into recovery to greater degree than for recovery after control

and occlusion, is that it is due to a vasodilatation response that occurred in the lower limb via inducing increase in shear stress at the blood vessels' wall, leading to an increase in circulating blood; the occlusion with additional passive vibration data adds further weight to this proposal.

Similarly to the first passive vibration (Chapter 3) and duration of passive vibration (Chapter 4) studies, it has been observed that transient and mild itching and redness of the lower limb were visible on some participants in response to vibration intervention. As discussed above, in the first passive vibration study, these symptoms are related to the cardiovascular function as well as being a strong indication that an increase in the shear stress has occurred at the vessel wall, leading to vasodilatation and therefore increasing blood flow in response to vibration exposure.

Overall, the findings of this study indicate that vibration produces more heat than the other conditions, as reflected by the higher skin temperature during vibration and continuing into recovery. The results indicate that vibration has a direct effect on the peripheral cardiovascular function during and post-exposure by increasing vasodilatation. Furthermore, these data provide evidence that the mechanism for the increase in blood flow in response to vibration exposure is due to an induced increase in shear stress in the blood vessels, resulting in increased vasodilatation during exposure that continues into recovery. Therefore, these finding suggest that vibration-induced enhancement in the peripheral circulation has beneficial effects in use as a training stimulus and also in assisting recovery from exertion.

## Conclusion

In conclusion, the findings of this thesis provide information regarding a previously unknown aspect of the peripheral circulation during and post-exposure to WBV. Overall, the findings from the first passive vibration (Chapter 3), duration of passive vibration (Chapter 4) and occlusion of blood flow (Chapter 5) studies in this thesis provide evidence that vasodilatation occurs during and after exposure to vibration and appears to be a process that is independent of skeletal muscle activation. It was hypothesised that the stimulus has a direct effect on the blood vessels via inducing an increase in shear stress in the blood vessel that results in vasodilatation and an increase in blood flow. Therefore, these observations have demonstrated that vibration has a direct effect on the muscle vascular bed as a primary effect. Furthermore, transient and

mild itching, warming and redness of the legs were observed on some subjects in the studies of current thesis during and after exposure to vibration that might be strong evidence that an increase in shear stress has occurred at the wall of the vessel, causing vasodilatation and therefore increased blood flow. Hence, these findings indicate that vibration induced enhancement in the skeletal muscle blood flow could have a beneficial effect in assisting recovery from exertion and could also be used as a training stimulus. Taken together, these studies have highlighted a novel form of stimulus and provided a further understanding of the mechanism of vibration on the peripheral cardiovascular function that may improve our understanding of the benefits of WBV on the human body.

## Limitations

In order to reach the research aim, this required specific research design and careful consideration of the procedures for executing each stage of the thesis. However, it is an impossible to produce a perfect output in order to achieve the research aim; therefore this thesis has a number of constraints which are outlined as follows:

- The measurement of the blood flow immediately following intervention by using an automated venous occlusion strain gauge plethysmograph was impossible, because of the moving subject limb from the vibration platform into the supporting foam mats and the placing the strain gauge around the limb. Therefore, the time for the first measurement of the blood flow by using an automated venous occlusion strain gauge plethysmograph post-intervention is limited.

- The blood flow was measured using automated venous occlusion strain gauge plethysmography, which measured the changing volume of the limb, thus it is unknown whether this changes in the limb volume is due to a response in skin blood flow and/or skeletal muscle blood flow. Consequently, determine the response of blood flow in skin or skeletal muscle via using automated venous occlusion strain gauge plethysmography is limited.

- The measurement of blood flow in the usual ways (e.g. via plethysmography, ultrasound or a laser Doppler flowmetry probe) during vibration exposure is limited, due to the interference of waves from the vibration device.

Consequently, skin temperature measurement was employed in the occlusion of blood flow study (Chapter 5) in this thesis as a surrogate measure of skin flow.

- All subjects were asked to maintain their regular diet and normal life-style patterns during each study period. Subjects were asked to refrain from drinking alcohol, avoid the consumption of caffeine-containing beverages and refrain from participating in any heavy strenuous physical activity for a specific period prior to each test session. Subjects were also asked at least four hours since last meal to avoid any issue that induced effect in cardiovascular system. Therefore, the control in the subjects is limited.

- There might be a potential of order effect from circadian rhythms, which could affect the cardiovascular system, for each study.

## Future Studies

Future studies are needed to examine the potential enhancement effects of passive vibration on the peripheral circulation, in an identical manner to the occlusion of blood flow study in this thesis, but using intramuscular temperature measurement sensors in order to confirm and support the findings and inferences of this thesis or reject them. Moreover, an electromyographic recording could be used in future studies to determine the potential activation of skeletal muscle in response to passive vibration exposure in order to confirm and support the findings and inferences of this thesis or reject them. Furthermore, further investigation is needed to assess the potential enhancement effects of passive vibration on the peripheral circulation in different age groups, which are expected to respond differently, due to ageing effects. A comparison of the potential enhancement effects of passive vibration on the peripheral cardiovascular function between genders is also needed, for further investigation. In addition, the effects of different combinations of frequency and amplitude (e.g. 30 Hz versus 50 Hz, 3 mm versus 6 mm) of passive vibration on the peripheral circulation could be further investigated. Moreover, investigation of the effects of vibration training on the cardiovascular function for a certain number of weeks might be of interest to help improve vascular function.

# Publications

# Submission for the Physiological Society Main Meeting 2012

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**CURRENT SUB-CATEGORY:** None

**PRESENTATION TYPE:** General Communication

**TITLE:** Potential Systemic Shear-Stress Inducing Effect of Whole Body Vibration

**AUTHORS (FIRST NAME, LAST NAME):** Alasdair G. Thin[1], Mahmoud Gholoum[1], Alice Mitchell[1], Colin Gilbertson[1], Derek Ball[1]

**INSTITUTIONS (ALL):** 1. School of Life Sciences, Heriot-Watt University, Edinburgh, United Kingdom.

**ABSTRACT BODY:** There is growing interest in the use of whole body vibration (WBV) for physical training and rehabilitation applications. Subjecting the body to prolonged periods of high-frequency vibration have long been known to be potential injurious, whereas lower frequencies and durations of exposure may have potentially beneficial effects (Rittweger, 2010). Neuromuscular activation appears to be highest in the frequency range 15-20 Hz (Wakeling *et al*., 2002). WBV has been reported to increase local muscular blood flow (Kerschan-Schindl *et al*., 2001) but there are no data reporting any systemic effects of WBV on blood flow. Vibration induced shear stress is of interest for its angiogenesis inducing potential. The aim of this study was to investigate the potential shear stress effects of WBV, its effect on skeletal muscle blood flow distal (forearm) to the main site (lower limbs) of muscle activation was investigated. Ten (8 male) healthy young adults aged (mean±SD) 20±1 years, height 1.76± 0.08 m, body mass (BM) 76.1±6.8 kg undertook bouts of squatting exercise under four separate conditions, completing 60 squats in two minutes at a constant rate. The conditions were unloaded, loaded with a mass added to a back pack equivalent to 15 %BM and with and without WBV (30 Hz, 3 mm amplitude). A latin square design was used and subjects undertook two exercise conditions separated by 30 minutes in each of two separate sessions on different days. Immediately after completing each exercise bout, subjects moved to a supine position on an examination couch. Forearm blood flow (FBF) was measured in triplicate using venous occlusion plethysmography pre-exercise commencing 1½ minutes post-exercise and at 3 minutes intervals thereafter until 23 minutes had elapsed. Blood pressure was measured using an automated monitor on the opposite arm. Data were analysed using repeated measures ANOVA. Overall there were no significant differences in the post-exercise FBF (Fig 1) or mean arterial pressure (MAP) (Fig 2) between the various conditions. However, there was a trend towards differences in FBF at the first post-exercise time point (2 minutes) where FBF appears to increase in the unloaded condition. In contrast, with 15 %BM loading this increase in FBF was absent, most likely due to a selective reduction in lower limb peripheral resistance in response to the increased metabolic load which was associated with a trend towards a lower MAP (Fig 2). However, with the addition of WBV, it appears that this partially restored the observed increase in FBF. One tentative explanation consistent with this observation is that WBV induced shear stress resulted in a general systemic vasodilatory effect that partially counteracted the increased lower limb vasodilatation. These results should be considered preliminary, but indicate that the potential systemic effect of WBV induced shear stress warrant further investigation.

**Reference 1:** Kerschan-Schindl K, Grampp S, Henk C, Resch H, Preisinger E, Fialka-Moser V & Imhof H (2001). Whole-body vibration exercise leads to alterations in muscle blood volume. *Clin Physiol* **21**, 377–382.

**Reference 2:** Rittweger J (2010). Vibration as an exercise modality: how it may work, and what its potential might be. *Eur J Appl Physiol* **108**, 877–904.

**Reference 3:** Wakeling JM, Nigg BM & Rozitis AI (2002). Muscle activity damps the soft tissue resonance that occurs in response to pulsed and continuous vibrations. *J Appl Physiol* **93**, 1093–1103.

# Poster Presentation of Potential Systemic Shear-Stress Inducing Effect of Whole Body Vibration

## Potential Systemic Shear-Stress Inducing Effect of Whole Body Vibration

Alasdair G. Thin, Mahmoud Gholoum, Alice Mitchell, Colin Gilbertson, and Derek Ball
School of Life Sciences, Heriot-Watt University, Edinburgh, UK

### OVERVIEW

There is growing interest in the use of whole body vibration (WBV) for physical training and rehabilitation applications. Subjecting the body to prolonged periods of high-frequency vibration have long been known to be potential injurious, whereas lower frequencies and durations of exposure may have potentially beneficial effects (Rittweger, 2010). Neuromuscular activation appears to be highest in the frequency range 15-20 Hz (Wakeling *et al.*, 2002).

### BACKGROUND

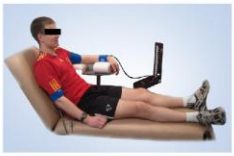
WBV has been reported to increase local muscular blood flow (Kerschan-Schindl *et al.*, 2001) but there are no data reporting any systemic effects of WBV on blood flow. Vibration induced shear stress is of interest for its angiogenesis inducing potential.

### PURPOSE

The aim of this study was to investigate the potential shear stress effects of WBV. Its effect on skeletal muscle blood flow distal (forearm) to the main site (lower limbs) of muscle activation was investigated.

### METHOD

Ten (8 male) healthy young adults aged (mean ± SD) 20 ± 1 years, height 1.76 ± 0.08 m, body mass (BM) 76.1 ± 6.8 kg undertook bouts of squatting exercise under four separate conditions, completing 60 squats in two minutes at a constant rate. The conditions were unloaded, loaded with a mass added to a back pack equivalent to 15 %BM and with and without WBV (30 Hz, 3 mm amplitude).



A Latin square design was used and subjects undertook two exercise conditions separated by 30 minutes in each of two separate sessions on different days. Immediately after completing each exercise bout, subjects moved to a supine position on an examination couch.

Forearm blood flow (FBF) was measured in triplicate using venous occlusion plethysmography pre-exercise commencing 1½ minutes post-exercise and at 3 minutes intervals thereafter until 23 minutes had elapsed. Blood pressure was measured using an automated monitor on the opposite arm. Data were analysed using repeated measures ANOVA.

### RESULTS

Overall there were no significant differences in the post-exercise FBF (Fig. 1) or mean arterial pressure (MAP) (Fig. 2) between the various conditions.

There was a trend towards differences in FBF at the first post-exercise time point (2 minutes) where FBF appears to increase in the unloaded condition.

In contrast, with 15 %BM loading this increase in FBF was absent, most likely due to a selective reduction in lower limb peripheral resistance in response to the increased metabolic load which was associated with a trend towards a lower MAP (Fig. 2). However, with the addition of WBV, it appears that this partially restored the observed increase in FBF.

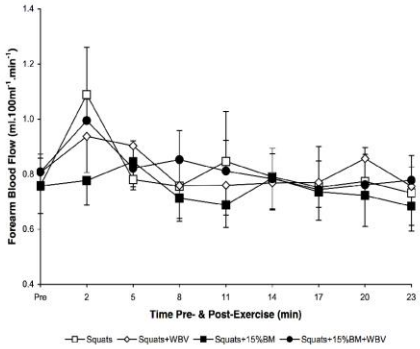



Figure 1. Forearm Blood Flow (FBF) pre- and post-exercise at various time points. Data are shown as mean (n=10) and error bars indicate SEM.

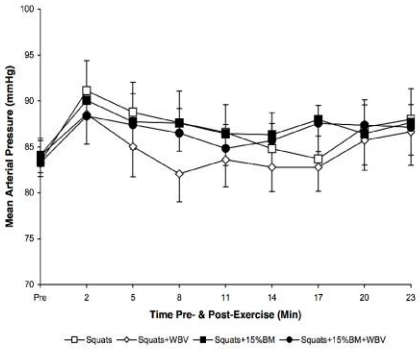



Figure 2. Mean Arterial Blood Pressure (MAP) pre- and post-exercise at various time points. Data are shown as mean (n=10) and error bars indicate SEM.

### CONCLUSION

One tentative explanation consistent with these observations is that WBV induced shear stress resulted in a general systemic vasodilatory effect that partially counteracted the increased lower limb vasodilatation. These results should be considered preliminary, but indicate that the potential systemic effect of WBV induced shear stress warrants further investigation.

### REFERENCES

Kerschan-Schindl K, Grampp S, Henk C, Resch H, Preisinger E, Fialka-Moser V & Imhof H (2001). Whole-body vibration exercise leads to alterations in muscle blood volume. *Clin Physiol* **21**, 377–382.

Rittweger J (2010). Vibration as an exercise modality: how it may work, and what its potential might be. *Eur J Appl Physiol* **108**, 877–904.

Wakeling JM, Nigg BM & Rozitis AI (2002). Muscle activity damps the soft tissue resonance that occurs in response to pulsed and continuous vibrations. *J Appl Physiol* **93**, 1093–1103.

### CORRESPONDENCE

Mahmoud Gholoum - msg6@hw.ac.uk

## Submission for the European College of Sport Science 2013



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Msg6@hw.ac.uk

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1st Dr Alasdair G Thin and 2nd Dr Derek Ball

**Effects of Passive Lower Limb Vibration on Peripheral Cardiovascular System**

M. Gholoum, T. Edmond, S. Woods, D. Ball and A.G.Thin

Whole body vibration (WBV) has been observed to increase muscle blood flow. Whether this is in response to skeletal muscle activation or a separate effect on the cardiovascular system is not known. The aim was to investigate the potential vasodilatory effects of vibration independent of muscle activation by applying it in a passive manner. Eighteen subjects visited the lab on two separate occasions and vibration and control treatments were applied in a randomised order. Leg blood flow (LBF), brachial blood pressure (BP) and ankle systolic BP were made at rest and then made immediately after treatment and repeated at 3 min intervals. Mean (±SEM) LBF at baseline was 2.2±0.1 ml/100ml/min and was increased after vibration relative to control values by +31.0±7.9, +6.2±5.2, +6.1±6.6, and +9.9±5.2% at 1, 4, 7, and 10 min respectively ($P<0.05$). Mean ankle-brachial pressure index at baseline was 1.01±0.01 and was reduced by –0.8±2.9, –6.5±3.3, –3.5±3.7, and –0.6±2.1% at the same time points relative to control values ($P<0.05$). The results provide evidence for body vibration having cardiovascular effects independent of skeletal muscle activation. This means that WBV may be of use in helping to enhance blood flow during recovery and have potential as a novel training stimulus.

# Poster Presentation of Effects of Passive Lower Limb Vibration on Peripheral Cardiovascular System

## Effects of Passive Lower Limb Vibration on Peripheral Cardiovascular System

**Mahmoud Gholoum, Tania Edmond, Stephanie Woods, Derek Ball and Alasdair G. Thin**

*School of Life Sciences, Heriot-Watt University, Edinburgh, UK*

### OVERVIEW

Whole body vibration (WBV) has been used as a novel form of exercise for both physical training and rehabilitation applications. WBV exercise at lower frequencies (<60 Hz) for short periods has been reported to have beneficial effects on the human musculoskeletal system (Torvinen *et al.*, 2002). WBV has been observed to increase muscle blood flow (Kerschan-Schindl *et al.*, 2001). Whether this is a secondary effect in response to skeletal muscle activation or a separate effect on the cardiovascular system is not known.

### METHODS

Eighteen (9 male) healthy young adults aged (mean ± SD) 22.0 ± 2.3 years, height 1.72 ± 0.09 m, body mass 70.1 ± 13.0 kg were recruited to the study. Skeletal muscle activation was avoided by having subjects lie in a supine position on supporting foam mats with their lower legs resting on the vibrating platform (Nemes, Bosco System) as shown in Fig. 1.

Subjects visited the lab on two separate occasions and vibration and control treatments were applied in a randomised order. Vibration consisted of three 60 s bouts with 10 s between (40 Hz, 3 mm amplitude, 6.8 g RMS acceleration).

Lower leg blood flow (LLBF) was measured using venous occlusion plethysmography (Hokanson System) (Fig. 2). Brachial blood pressure (BP) was measured using an automated monitor (Tango+, SunTech Medical) and ankle systolic BP measured manually in duplicate. Baseline measurements were made following 15 min of supine rest. All measurements were then made immediately after treatment and repeated at 3 min intervals thereafter. Data were analysed using repeated measures mixed model ANOVA.

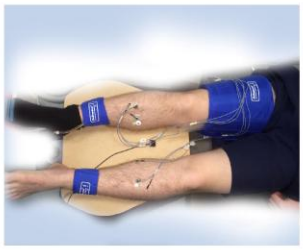

Figure 1. Application of passive vibration to lower legs.

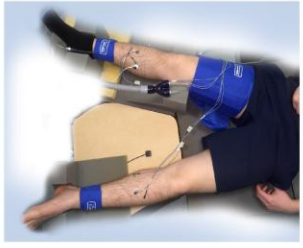

Figure 2. Measurement of lower leg blood flow (LLBF) measured using venous occlusion plethysmography.

### RESULTS

There was an overall significant increase in LLBF due the vibration and also a significant interaction effect of Treatment and Time immediately after vibration (Fig. 3).

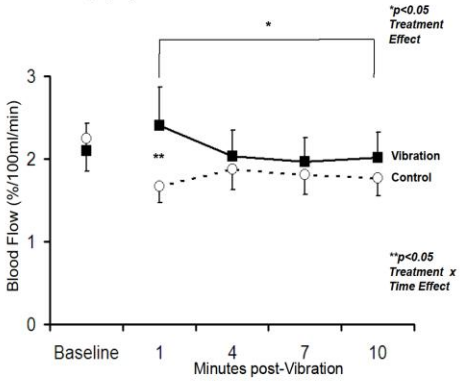


Figure 3. Lower Leg Blood Flow (LLBF) pre- and post-treatment at various time points. Data are shown as mean (n=18) and error bars indicate SEM.

If the ankle brachial pressure index (ABPI) were to fall, this would be indicative of a increased vasodilatation in the lower legs relative to the arms. This indeed was the case with a significant overall treatment effect of vibration observed compared to the sham condition (Fig. 4).

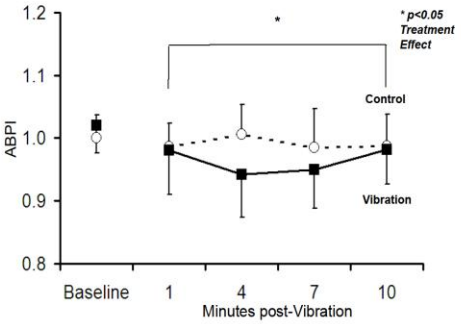


Figure 4. Ankle Brachial Pressure Index (ABPI) pre- and post-treatment at various time points. Data are shown as mean (n=18) and error bars indicate SEM.

### CONCLUSION

Passively applied vibration to the lower legs resulted in an increase in LLBF and a reduction in ABPI in the post-vibration period, despite the absence of skeletal muscle activation. These data provides evidence for a direct effect of WBV on the peripheral cardiovascular system. We postulate that the most likely mechanism underlying this effect is a vibration induced increase in shear stress in the blood vessels.

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Kerschan-Schindl *et al.* (2001). Clin Physiol, 21, 377–382.
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