Development of a muscle tendon vibrator and its application in training strength and power

A Thesis Submitted for the Degree of Doctor of Philosophy

by
Jin Luo

School of Mechanical and Manufacturing Engineering
of
Dublin City University

Supervisor Dr Kieran Moran, Dr Brian McNamara

August 2004

Declaration

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of the Degree of Doctor of Philosophy is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work

Signed ____________

Jin Luo (Student ID 50162438)

Date August 6th 2004

Table of contents

List of Figures

List of Tables

List of abbreviations and nomenclature

CMJ	counter movement jump
EMG	electromyography
EMGmpf	mean power frequency of EMG
EMGrms	root-mean-squared value of EMG
ems	eccentric mass
Hz	hertz, unit of frequency
ICC	intra-class correlation coefficient
IEMG	intergrated EMG
mm	millimeter, unit of length
ms	millisecond, unit of time
mV	millivolt, unit of voltage
MVC	maximal voluntary contraction
N	Newton, unit of force
N m	Newton meter, unit of torque
rad/s	radian per second, unit of angular velocity
RF	rectus femoris
RFD	rate of force development
RM	repetition maximum
RPM	round per minute
s	second, unit of time
S D	standard deviation
SSC	stretch-shortening cycle
TVR	tonic vibration reflex
VL	vastus lateralis
VM	vastus medialis
W	Watts, unit of power

Acknowledgements

My deepest gratitude is due to my two supervisors Dr Kieran Moran and Dr Brian McNamara, who have been guiding me in this exciting research field for the past three years

My appreciative thanks belong to the entire personnel of the School of Mechanical and Manufacturing Engineering and the School of Sport Science and Health for their friendship and kind collaboration Special thanks belong to Michael May and Martin Johnson for their professional work in the workshop, and to Javier Monedero for his kind support for all my experiments I also wish to thank Dr Garrett McGuinness for letting me use his equipments

Special thanks go to all the volunteers in my studies Without your excellent co-operation, this thesis would not have been possible

My sincere thanks are due to my parents, who have always encouraged me to pursue my study throughout these years

Finally, I want to thank Hong, my wife, who has been the source of my strength and endurance during the past three years Thank you Without your love and support, I would not have been able to finish this thesis

This study was financially supported by the grants from School of Mechanical and Manufacturing Engineering and School of Sport Science and Health of Dublin City University

Abstract

Vibration training is a novel strength training method that has gained popularity in the last five years. However, current findings on vibration training are contradictory about whether vibration training is an effective training method for strength and power development. A critical review of the relevant literature reveals that vibration training effect may be dependent on a number of factors, in particular vibration characteristics (vibration amplitude and frequency) and exercise protocol (type of exercise and exercise intensity). However, there is a lack of study of many of these factors. The aim of this study is to investigate the influence of these factors on the acute effect of vibration training on neuromuscular performance.

Methods: A portable muscle-tendon vibrator with variable vibration amplitude (0.2 to 2 mm) and frequency (30 to 200 Hz) capacity was developed in the thesis. The vibration is produced by a number of rotating eccentric masses. The vibrator is strapped to the muscle tendon during the strength training exercise. Neuromuscular performance was assessed during strength training exercise by examining EMG and various mechanical outputs. The mechanical outputs included: angular velocity, moment and power assessed in terms of peak, average, rate of development and initial (first 100 ms) measures.

Findings:

<u>Study 1</u>: The vibration amplitude on the vibrator and the muscle was affected by the eccentric mass, with a large eccentric mass (ems-II) producing significantly greater amplitude (1.2 mm) than the small eccentric mass (0.5 mm) (ems-I) ($p<0.05$). The vibration frequency on the vibrator and the muscle was not effected by the eccentric mass size ($p>0.05$). The transmissibility of vibration amplitude from the vibrator to the muscle was significantly higher with ems-I ($p<0.05$). The transmissibility of vibration peak frequency to the muscle was not affected by the eccentric mass ($p>0.05$), and was 100%. Vibration induced a significant increase in EMGrms of the biceps in sub-maximal isometric elbow flexion ($p<0.05$), with ems-II producing greater increase than ems-I (0.053 vs. 0.026 mV, $p<0.05$). All of the above results for amplitude, frequency, transmissibility and EMG response were not significantly effected by test day, joint angle or strapping force ($p>0.05$), indicating the repeatability of the vibration load under various operational conditions.

<u>Study 2</u>: The vibration peak frequency of the vibrator was determined only by the motor rotating speed ($p<0.05$). The vibration amplitude of the vibrator was determined by both the eccentric mass and the motor rotating speed ($p<0.05$). The transmissibility of the vibration amplitude to the muscle was affected by both the eccentric mass and motor speed of the vibrator ($p<0.05$). The higher the vibration amplitude (eccentric mass) and vibration frequency (motor rotating speed) on the vibrator, the lower the transmissibility of vibration amplitude to the muscle ($p<0.05$). The transmissibility of peak frequency was 100%, and was not affected by the eccentric mass and motor rotating speed ($p>0.05$). Vibration induced a significant increase in EMGrms of the biceps in sub-maximal isometric elbow flexion ($p<0.05$), with the greatest increase of EMGrms being induced by vibration with a frequency of 65 Hz and an amplitude of 1.2 mm ($p<0.05$). The above amplitude, frequency,

transmissibility and EMG results were not significantly effected by joint angle ($p>0.05$)

Study 3 Vibration training induced enhancements in EMGrms of the vastus lateralis (VL) and vastus medialis (VM) during sub-maximal isometric extension of the knee ($p<0.05$), but not of the rectus femoris (RF) ($p>0.05$) Resistance load had a significant effect on the enhancement, with the greater load (20% 1RM) producing a significantly higher EMGrms than the smaller load (10% 1RM), on both the VL (0.049 vs 0.038 mV, $p<0.05$) and VM (0.069 vs 0.049, $p<0.05$)

Study 4 During training, direct vibration did not enhance the mechanical (angular velocity, moment and power) and EMG output of a maximal isotonic bicep curl exercise ($p>0.05$) Similarly, after training there was no enhancement in the mechanical and EMG output when either the muscle was trained maximally or the muscle was rested (untrained) ($p>0.05$)

Study 5 Direct vibration did not enhance the mechanical (angular velocity, moment and power) and EMG output of a ballistic knee extension exercise during and after training On the contrary, vibration significantly increased the time to peak power (4%, 10% and 16% in set 1, 2 and 3, respectively, $p<0.05$) and decreased EMGrms of the RF (10%, 14% and 15% in set 1, 2 and 3, respectively, $p<0.05$) and EMGmpf of the VL (7% in set 2, $p<0.05$) during training, and decreased EMGrms of the RF measured 1.5 minutes (16%, $p<0.05$) and 10 minutes (15%, $p<0.05$) after training

Study 6 With both resistance loads (40% and 70% 1RM), direct vibration did not have an acute or acute residual facilitatory effect on the neuromuscular performance of a maximal isotonic bicep curl exercise ($p>0.05$) On the contrary, vibration significantly decreased mean power with the 70% 1RM load (16.8%, 13% and 18.5% in set 1, 2 and 3, respectively, $p<0.05$) and the initial power with both loads (19.5%, $p<0.05$)

Conclusion A portable muscle tendon vibrator has been successfully developed to allow investigation of the effect of vibration at different frequencies and amplitudes during sub-maximal and maximal isometric and isotonic contractions The vibrator can produce the required vibration load consistently across different operational conditions For sub-maximal isometric contractions, vibration could induce a significant increase of EMG The enhancement was greater with the increase of vibration amplitude (1.2 vs 0.5 mm) and frequency (100 and 65 Hz vs 30 Hz) In addition, the higher resistance load could induce greater EMG response to vibration training with sub-maximal isometric contraction For maximal isotonic contractions, vibration did not enhance neuromuscular performance, and in fact had a negative effect on some mechanical and EMG outputs both during and after training Vibration alone (with no exercise) had no significant acute residual effect on the mechanical and EMG outputs of maximal isotonic contractions The neuromuscular measurements in this thesis are repeatable across different test days

Publications from the thesis

Jın Luo, Bnan McNamara, Kıeran Moran A revıew of the use of vıbratıon traınıng to enhance muscle strength and power Accepted by *Sports Medıcıne*

Jın Luo, Bnan McNamara, Kıeran Moran A portable vıbrator for muscle performance enhancement by means of dırect muscle tendon stımulatıon Accepted by *Medıcal Engıneerıng & Physıcs*

Chapter 1

Introduction

Neuromuscular performance, as determined through measures of muscle strength and power, is important for successful performance of athletic activities as well as for the preservation and improvement in functional aspects of daily life Resistance training is presently the most popular way to improve muscle strength and power (1) In a search of techniques to enhance resistance training, Russian scientists have combined vibration stimulation with resistance training (2) This has been termed vibration training(3) or vibration exercise (4) During the last five years, this method of strength training has gained in popularity with a number of systems now commercially available (e g Nemes®, Nemesis, Netherland, Galileo 2000®, Novotech, Germany, PowerPlate®, Netherland)

However, current findings from vibration training studies are contradictory as to whether vibration stimulation is effective in facilitating strength and power enhancement A number of acute and chronic vibration training studies have demonstrated that conventional strength training exercise with superimposed vibration may achieve significantly more strength and power gain than the same training without vibration (3,5-7) However, some studies have not found any beneficial effect to superimposed vibration (8-10) It is thus apparent that the effect of vibration training need further investigation in order to facilitate the application of this new training method in sports and health The present study will examine the effect of vibration training on neuromuscular performance

A critical review of the literature indicates that the vibration training effect on neuromuscular capacity may be related to its methodology, which includes the vibration characteristics (vibration amplitude, frequency and the method of vibration application) and the exercise protocols (type of exercise, exercise intensity and volume). There may be optimal vibration training programs that could induce the greatest enhancement on neuromuscular performance. Investigation on this issue is the central topic of the present study.

The vibration amplitude and frequency determine the load that vibration imposes on neuromuscular system(17). The review of the literature reveals that these factors need to be high enough for vibration training to elicit an effect. However, most of the present vibration training devices employed indirect method of vibration in which vibration was transmitted from a vibrating source (e.g. vibrating platform or handle) to target muscles being trained. The disadvantage of this method is that the vibration load further away from the vibration source may not be high enough to elicit the effect because the vibration amplitude and frequency may be attenuated during the transmission through the soft tissues (22). Moreover, the agonist and antagonist muscles are both stimulated by vibration in indirect method, which may decrease the force output of agonist because of the reciprocal inhibition (8). These limitations may explain the contrasting results found with the indirect method of vibration (3,8,12). On the other hand, few studies to date have employed direct method of vibration in which vibration was applied directly to the muscle belly or the tendon of the muscle being trained (10,14,18);. Moreover, the vibration devices used in these studies are all cumbersome and not suitable for dynamic movement during strength training exercise. The present study, therefore, is going to design and construct a portable vibration training device that could stimulate the muscle-tendon directly In addition, this portable vibration training device will have the capacity to produce different vibration amplitudes and frequencies that have been employed in the vibration training studies to date, as the present study is also going to examine the effect of vibration amplitude and frequency of direct method of vibration on neuromuscular performance

The exercise protocol is also an important factor influencing the vibration training effect (3,8) However, there is a lack of study investigating the exercise protocol in vibration training with direct method The present study, therefore, will examine the influence of different type of exercises (isometric and dynamic), different intensities of exercise (sub-maximal contraction and maximal voluntary contraction) on neuromuscular response to vibration training by using the portable vibration device developed in this study

Chapter 2

Literature review

2.1 Introduction

In the only review on vibration training that could be found, Cardinale and Bosco[(11), pp4] suggest that "vibration can effectively enhance neuromuscular performance". However, their review on neuromuscular performance enhancement has a number of notable limitations. Firstly, only six studies were reviewed and half of these failed to include an appropriate control group (see inclusion/exclusion criteria below). Secondly, the review failed to include any studies where vibration training had either no effect on (8,12) or a reduction in neuromuscular performance (13,14). Finally, the authors did not address the effect of different vibration characteristics (method of application, frequency, amplitude and duration) or the time-effect (acute, acute-residual and chronic) of vibration training. In addition, the vibration training devices, especially those used in direct method of vibration were not systematically introduced in this review.

Thus, the purpose of this review is to critically examine the effect of vibration training on neuromuscular performance, with the focus on muscle strength and power, and to investigate the influence of the vibration characteristics (method of application, frequency and amplitude) and exercise protocol on this effect. The vibration training devices that have been used in vibration training studies will also be introduced. Consideration is given to the different time-effects of vibration: (i) during the application of vibration (*acute effect*), (ii) immediately after the application of vibration (*acute residual effect*) and (iii) following a series of bouts of vibration training over an extended period (*chronic training effect*). In each of these categories the effect on force, power and electromyography (EMG) during isometric and dynamic force production will be examined. Purported mechanism of vibration training will also be discussed. This review will provide sufficient detail to guide the reader on current designs of vibration training devices and their use, and clearly outline those areas that need further research in order to advance our understanding of vibration training.

2.2 Inclusion/exclusion criteria for studies in this review

Studies that fulfilled the following criteria were included in this review:

- *A control group element was employed and subjects were randomly allocated to the treatment and control groups*. In those studies examining the acute and acute residual effects of vibration, the control group was the same subjects being tested under repeated measures. However, these studies were only included provided the order of testing (vibration versus non-vibration) was randomized. Moreover, studies were included provided subjects in the control group performed the same exercise as in the treatment group. This is essential as otherwise it is not possible to determine if the outcome is due to the exercise or the vibration.
- *Healthy subjects were examined.* This therefore negates those studies that examined the facilitatory effect of vibration on patients with neuromuscular disease and those which investigated the potential for neuromuscular disorder

associated with long term (years) exposure to vibration in the occupational environment,

- *The outcome measures were related to muscle force, power or EMG and a statistical analysis was undertaken*
- *The study was published in the form of full-text and in English*

2 3 Literature search

A literature search was performed on MEDLINE database (1966-2003), the Cochrane Central Register of Controlled Trails (CENTRAL) and Sports Discus The keywords used were vibration AND (muscle OR tendon OR exercise OR training) The identified papers were used to locate other appropriate research papers

A total of 14 articles met our inclusion criteria, eight of them studied the acute effect of vibration treatment, five of them studied the acute residual effect of vibration treatment, and three of them studied the chronic effect of vibration treatment Details of these studies are listed in tables 2 1 to 2 6

The vibration training studies that were specifically excluded from this review based on our criteria relating to inclusion of a control group were listed in Appendix A to 2 3 Only in the discussion of vibration training mechanism will some of these studies be mentioned (section 2 9 of this review)

2.4 Methodology of vibration training

Vibration is a mechanical oscillation that can be defined by frequency and amplitude. Frequency is defined as the cycles per unit time, and is generally measured in the unit of hertz (Hz, cycles per second) (15). Amplitude is defined as the half difference between the maximum and the minimum value of the periodic oscillation(16).

The methodology of vibration training includes the vibration characteristics and exercise protocol. Vibration characteristics include the method of vibration application, vibration amplitude, vibration frequency and the duration of vibration. The intensity of the vibration load on neuromuscular system is determined by the vibration amplitude and frequency (17). The exercise protocol includes the type of exercise, training intensity, training volume, number and duration of the rest period and the frequency of training.

There are two methods of applying vibration to the human body during exercises. In the first method, vibration is applied directly to the muscle belly (10,14,18) or the tendon (13) of the muscle being trained, by a vibration unit that may either be held by hand (13,18) or be fixed to an exterior support (10,14). In the second method, vibration is applied indirectly to the muscle being trained, i.e. the vibration is transmitted from a vibrating source away from the target muscle, through part of the body to the target muscle (3,6). For example, during the training of the quadriceps, the subject may stand on a vibrating platform that oscillates up and down in the vertical direction and perform various exercises (such as squatting); the vibration is transmitted from the platform through the lower extremities to the quadriceps (3,7,12). This method has been termed '*whole body vibration training*' (3). As another example, during the training of the biceps brachii, the subject may grasp a vibrating handle while performing a bicep curl exercise (6). Although the main direction of vibration application was different between direct method [transversal to the muscle fibers and muscle tendon (10,14,18)] and indirect method [longitudinal to the muscle fibers and muscle tendon (3,7,12)], both methods will result in longitudinal stretching (vibration) of the muscle fibers and muscle tendon. It is this longitudinal stretching that is related to the purported mechanisms of enhancement associated with vibration training.

Various vibration training devices have been used in vibration training to apply vibration directly or indirectly to muscles. These devices will be introduced in the following paragraphs.

1) Vibration devices for directly applied vibration

In the study by Humphries et al. (10), vibration was produced by using a 4KW, 3-phase electrical induction motor running at 50 Hz which was directly coupled to a 2-cylinder air conditioning compressor with exposed piston faces driven by an offset cam. The subject's leg was held against piston with Velcro straps. Jackson et al. (14) used an electromagnetic vibration unit (V201; Ling Dynamics, UK) to apply vibration directly to the femoris muscles. The size of this vibration unit was ∅102 mm (diameter) × 121 mm (height), and its weight was 1.8 kg (19). Curry et al. (18)

used a hand-held vibrator (Wahl Clipper Corp, Sterling, IL 61081, USA) to apply vibration directly to forearm muscles The former two vibration units introduced above need to be fixed to an exterior support (10,14), while the later one (18) can be held by hand during the vibration training Unfortunately, these devices are therefore not suitable for strength training where dynamic exercises are commonly executed and where it is necessary to move easily from one exercise action to another No portable device with direct vibration capabilities for strength training appears either to feature in the literature or is commercially available This may significantly reduce the widespread use of vibration training

2) Vibration devices for indirectly applied vibration

In whole-body vibration training, the person stands on a vibrating platform and performs various exercise (e g squatting) The vibration is transmitted from the platform through the lower extremities to target muscles, such as the quadriceps (3,4) There are several such devices commercially available, such as the Galileo (www galileo2000 nl), the Nemes (www nemes nl) and the Power Plate (www powerplateusa com) In the Galileo, vibration is applied by rotational oscillation around the centre of the platform (figure 2 1) The user places their feet on either side of the rotational centre of the vibration platform In the Nemes and Power Plate, vibration is applied by an up-down oscillation of the platform in the vertical direction

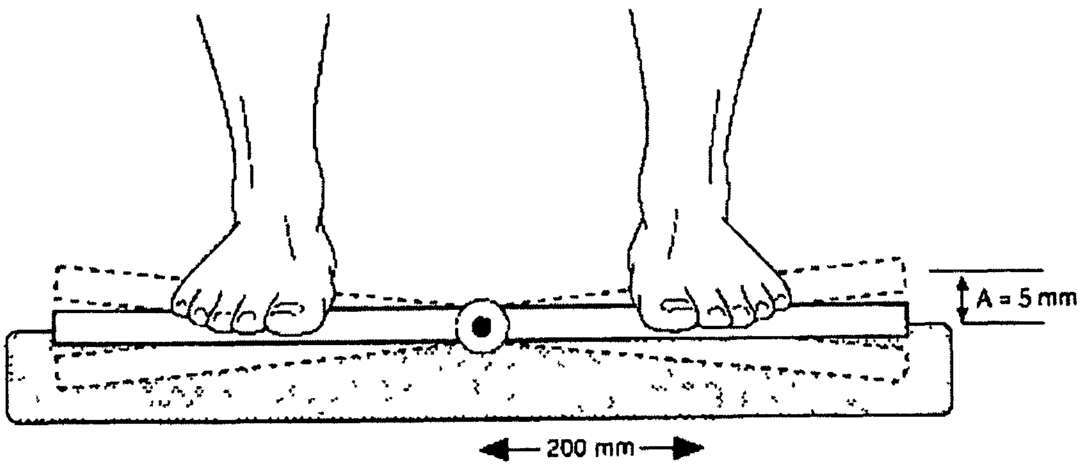


Figure 2 1 Whole-body vibration device (Galileo) [adapted from Rittweger et al (20)]

Issurin et al (6) undertook a number of studies (6,21) using a custom designed vibration device (figure 2 2) This device consisted of an electromotor (1500 W, 2800 rev/min) that rotated an axis which supported two wheels of different diameters, thus allowing speed reduction (frequencies 44 Hz and 60 Hz) Subjects were exposed to vibration by grasping a vibrating handle The center of rotation of the wheel could be displaced eccentrically to 3, 6, 9 and 12 mm A counter-weight pulley system provided the resistance for training The load was held by a stiff cable, which was passed through the eccentric wheel of the vibratory device via the pulleys Attached to the far end of the cable, a bar was used to perform bicep curl exercise

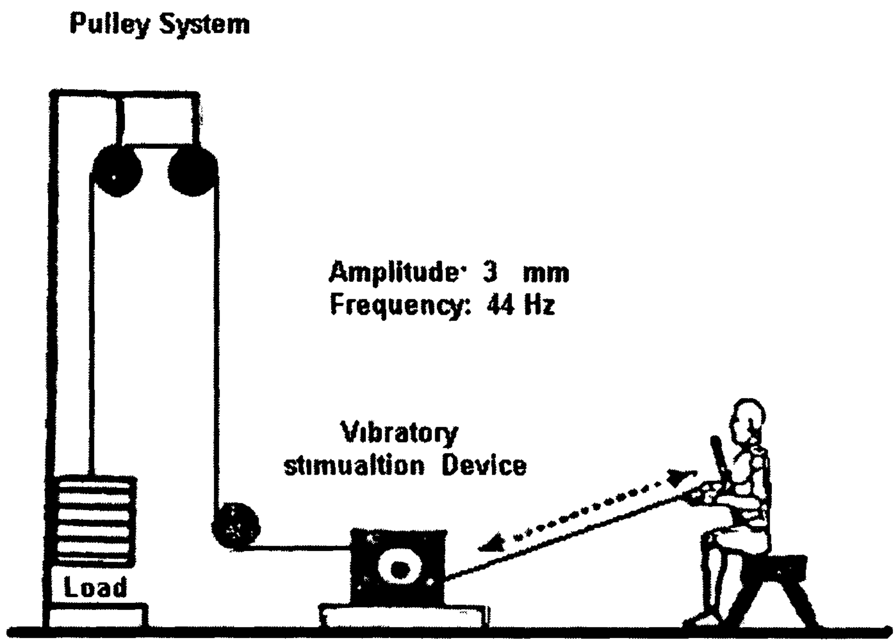


Figure 2 2 Vibration training device [adapted from Issurin et al , (6)]

While there is a clear difference between the indirect and direct methods on the way in which the vibration reaches the target muscle, both are reviewed together, as they both produce vibration to stimulate the muscle The key difference in these methods is only the magnitude of amplitude and frequency of the original vibration that reaches the target muscle With direct vibration, the amplitude and frequency does not differ notably from the reported values measured at the vibration source (13,14,18) In contrast, with indirectly applied vibration (3,6,7,12,21), the amplitude and frequency may be attenuated in a non-linear manner by soft tissues during transmission of the vibration to the target muscle (17,22) The effect of this will be addressed within the relevant sections

Duration of vibration is also a factor that should be considered in examining the effect of vibration training Its influence should be analysed in conjunction with the point of time when the neuromuscular performance was evaluated As shown in figure 2 3, if vibration stimulation is short in duration, resulting in the measurement of neuromuscular capacity without fatigue, any enhancement is indicative of an increase in neuromuscular performance by vibration stimulation [M_a(unfatigued) and M_{ar}(unfatigued) in figure 2 3a] This will be discussed as a facilitatory (positive) effect of vibration on neuromuscular performance later in this review With increases in the duration of vibration, fatigue will become more predominant Therefore an

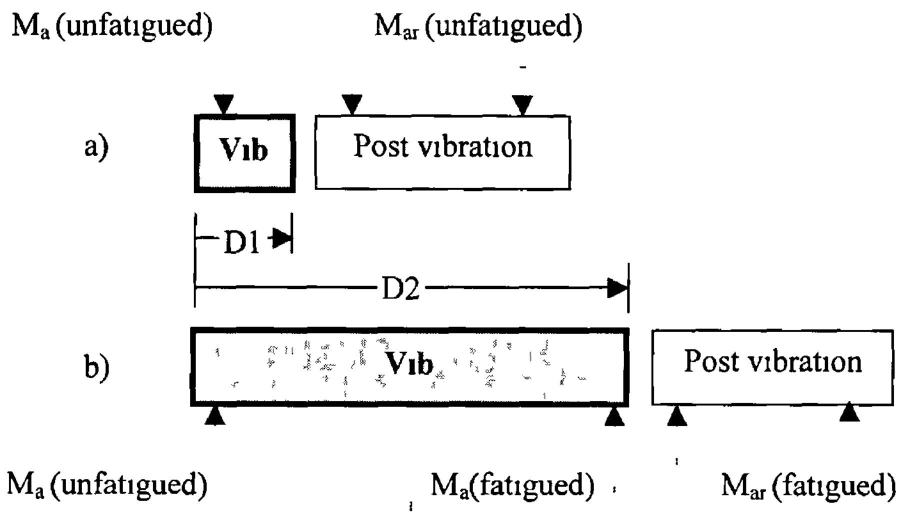


Figure 2 3 Diagram of vibration duration and the measurement of neuromuscular performance during unfatigued (a) and fatigued (b) training D1=short duration, D2=long duration, M_a=measurement of the acute effect of vibration stimulation on neuromuscular performance, M_{ar}=measurement of the acute residual effect of vibration on neuromuscular performance, vib=vibration increase in neuromuscular performance, above a no vibration condition, measured in the unfatigued state [M_a(unfatigued) in figure 2 3b], will still indicate a facilitatory effect of vibration However, a decrease in neuromuscular performance measured when fatigued [M_a(fatigued) and M_{ar}(fatigued) in figure 2 3b] may be due to either 1) an increase in neuromuscular performance earlier in the exercise, resulting in greater fatigue, which can be viewed positively, or 2) an inhibition effect of vibration on neuromuscular capacity These two effects are discussed in section 5 1 and 5 2 These factors are pertinent in both acute and acute residual effects, as shown in figure 2 3 However, these factors have no relevance in interpreting the chronic studies, as the retest is not undertaken during or immediately following vibration stimulation

Both isometric (10,13,18,23,24) and dynamic(6,21,25) exercises have been employed during vibration training The intensity of these exercises range from sub-maximal contractions (3,4,7,8,12,23) to maximal contractions (6,13,18,21,24,26) The duration of exercise with applied vibration also varies among studies, ranging from only 5 seconds (10,18,21) to 30 minutes (14) in each set, and with different numbers of sets employed, ranging from one set (4,7,10,12,13,24) to several sets in a training session (3,6,8,21) The protocol appears indicative of whether or not the aim was to investigate the effect of fatigue (10,13,14,18,21,24)

2 5 Acute effect of vibration on neuromuscular performance

2 5 1 Acute effect of vibration on strength and electromyography activity (EMG) during isometric actions (Table 2 1)

2 5 1 1 Maximal isometric contraction

As shown in table 2 1, four studies have investigated the acute effect of vibration on maximal isometric contraction (10,13,18,24) The duration of vibration and contraction was short in two of these studies [5 seconds(10,18]] and prolonged in the two other studies [1 minute(13) and until exhaustion (24)] In the latter two studies, measurement of neuromuscular performance was made both in an unfatigued and fatigued state (figure 2 3b) (13,24)

When the neuromuscular system was unfatigued, only one of the four studies found that vibration had a significant facilitatory effect on maximal force (18) The authors (18) in this study found that vibration induced a 3 7% significant increase ($p<0\ 05$) in maximal isometric contraction force of the wrist extensors, and the contraction force tested without vibration had a 3 9% significant decrease ($p<0\ 05$) from their baseline force levels Thus, the net increase was approximately 7 8% Sameulson et al (24) and Humphries et al (10) also found net increases in maximal knee extensor force with vibration (6% and 17 8%), but these increases were not significant ($p>0\ 05$) due to the variability in response Bongiovanni et al (13) found that vibration induced a non-significant net decrease in maximal ankle dorsiflexion force of about 5% ($p>0\ 05$)

Table 2.1 Acute effect of vibration on isometric muscle performance

Study	Subject	Vibration characteristics			Neuromuscular performance change		
		method (location)	amp (mm)	freq (Hz)	Contraction Performed	force	EMG
Bongiovanni et al. [13]	25 UT	D (ankle dorsiflexor tendon)	1.5	150	1 min dorsiflexion (100% MVC)	Fm Fd 5% ↓ NS	NR
		Control	NA	NA	1 min dorsiflexion (100% MVC)	Fm Fd 13% ↓ +	NR
Curry et al. [18]	30 UT (15=male 15=female)	D (Wrist extentsor muscle)	1.5	120	5-second wrist extension (100% MVC)	Fm 3.7% ↑ *	NM
	30 UT (20=male 10=female)	Control	NA	NA	5-second wrist extension (100% MVC)	Fm 3.9% ↓ *	NM
Humphries et al [10]	16 UT	D (upper thigh)	0.13	50	5 second knee extension (100% MVC)	Fm 581 N $RFD_{0.01}$ 983 N/s $RFD_{0.05}$ 1349 N/s $RFD_{0.1}$ 1525 N/s $RFD_{0.5}$ 913 N/s 17.8% ↑ NS NS	EMGrms RF 84.74% NS
		Control	NA	NA	5 second knee extension (100% MVC)	Fm 493 N $RFD_{0.01}$ 658 N/s $RFD_{0.05}$ 1240 N/s $RFD_{0.1}$ 1620 N/s $RFD_{0.5}$ 786 N/s	EMGrms RF 88.1%

Note amp=vibration amplitude, D=directly applied vibration EMGrms=root-mean-squared value of EMG, Fd=decline of maximal voluntary contraction force, Fm=maximal voluntary contraction force, freq=vibration frequency, MVC=maximal voluntary contraction force, N=Newton, NA=not applicable, NM=no measurement, NR=not reported, NS=not statistically significant, N/s=Newton per second RF=rectus femoris, RFD=rate of force development UT=untrained, ↑= increase, ↓=decrease, *=statistically significant compared with pre-vibration +=statistically significant compared with control,

Table 2 1 (contınued) Acute effect of vıbratıon on ısometrıc muscle performance

Study	Subject	Vıbratıon characterıstıcs			Neuromuscular performance change			
		method (locatıon)	**amp (mm)**	**freq (Hz)**	**Contractıon Performed**	**force**	**EMG**	
Kihlberg et al.[23]	15 UT	I (hand)	8m/s^2 a	50	Hand grip and arm push (30N)	NM	IEMG	Forearm flexor Forearm extensor Triceps brachii 83 3% ↑ + 45 5% ↑ +
		Control	NA	NA	Hand grip and arm push (30N)	NM	IEMG 100% ↑ +	Forearm flexor Forearm extensor Triceps brachii 40% ↑ + 27 3% ↑ +
		I (hand)	8m/s^2 a	137	Hand grip and arm push (30N)	NM	IEMG 30% ↑ NS	Forearm flexor Forearm extensor Triceps brachii
Sameulson et al [24]	14 UT male	I (applied to one leg)	1 8	20	Sustained knee extension till exhausted (100%MVC)	Fm. 594 N 6%↑ NS Td. 15 8 s	NM	
		Control (the other leg of the subject)	NA	NA	Sustained knee extension till exhausted (100%MVC)	Fm. 561 N 30% ↓ + Td. 22.5 s	NM	

Note a=amplıtude reported ın the form of weıghted acceleratıon, amp=vıbratıon amplıtude, Fm=maxımal voluntary contractıon force, freq=vıbratıon frequency, I=ındırectly applıed vıbratıon, MVC=maxımal voluntary contractıon force, N=Newton, NA=not applıcable, NM=no measurement, NR=not reported, NS=not statıstıcally sıgnıfıcant, RFD=rate of force development, Td=tıme to exhaustıon UT=untraıned, ↑= ıncrease, ↓=decrease, WBV=whole body vıbratıon, +=statıstıcally sıgnıfıcant compared wıth control, Only one study (10) reported the EMG activity of maximal isometric contraction during vibration. The authors (10) found that vibration did not have a significant effect ($p>0.05$) on the root-mean-squared value of the EMG (EMGrms), measured on the rectus femoris muscle during maximal knee extension.

Humphries et al.(10) also examined the rate of force development (RFD) at times 0.05, 0.01, 0.1 and 0.5 seconds during a 5-second maximal isometric knee extension. The authors((10)) found that vibration did not enhance the RFD at any of these time points ($p>0.05$).

Neuromuscular performance was also measured in a fatigued state in two of the studies (13,24). In the study of Sameulson et al.,(24) subjects performed sustained maximal knee extension until exhausted. The time to exhaustion decreased significantly ($p<0.05$) by 30% in the vibration condition in comparison to a control group. In a study by Bongiovanni et al.,(13) subjects were asked to maintain their maximal contraction for 1 minute. The results showed that the decline of the maximal isometric force measured at the end of the 1 minute contraction was significantly greater (13%; $p<0.05$) when vibration was applied. These findings indicate that vibration could accentuate the muscle fatigue of sustained maximal contractions. However, as discussed above, the maximal isometric contraction force measured in both studies(13,24) at the unfatigued state did not have any significant enhancement by vibration. Thus, it is unlikely that prolonged vibration accentuate the fatigue by recruitment of more motor units during the early stage of contraction.

Bongiovanni et al.(13) suggested that vibration had a suppression effect that increased gradually with the sustained vibration on motor output of maximal voluntary contractions. This suppression effect decreased mainly the subject's ability to generate high firing rates in high-threshold motor units (13). Thus, it appears that prolonged vibration decreases the neuromuscular performance of maximal voluntary contraction by inhibiting motor units from recruitment, rather than by fatiguing the motor units by recruitment.

2.5.1.2 Sub-maximal isometric contraction

Only one study in table 2.1 investigated the acute effect of vibration on sub-maximal isometric contraction. The study could not directly determine if vibration enhances sub-maximal isometric force because the subjects were asked to maintain contraction force at a constant level during vibration treatment [e.g. 30N(23)]. However, the muscle activity measured by electromyography (EMG) showed that the integrated EMG value (IEMG) was enhanced significantly ($p<0.05$) by vibration,(23) indicating that applied vibration is likely to enhance the sub-maximal contraction force (27).

2.5.2 Acute effect of vibration on strength and power during dynamic actions (Table2.2)

2.5.2.1 Maximal dynamic contraction

Table 2 2 Acute effect of vibration on dynamic muscle performance

Study	Subject	Vibration characteristics			Neuromuscular performance change		
		method (location)	amp (mm)	freq (Hz)	contraction Performed	Performance measure	EMG
Issurin et al [21]	28 T male (14=elite 14=amateur)	I(hand)	0 3 - 0 4	44	Concentric bicep curl (MVC)	Pmax Elite 10 4%↑* , Amateur 7 9%↑* (ξ); Pmean Elite 10 2%↑* , Amateur 10 7%↑* (NS)	NM
		Control	NA	NA	Concentric bicep curl (MVC)	Pmax Elite 0 3%↑ NS, Amateur 0 9%↑ NS (NS); Pmean Elite 2 9%↓NS, Amateur 3%↓NS (NS)	NM
Liebermann et al [26]	41 T male (8=Olympic 11=National 11=amateur 11=Junior)	I(hand)	0 3 - 0 4	44	Concentric bicep curl (MVC)	1 RM strength Olympic 8 3% ↑ + #, National 4 8% ↑ +, Junior 6 2% ↑ +, Amateur 4 9% ↑ +	NM
		Control	NA	NA	Concentric bicep curl (MVC)	Olympic, National, Junior, Amateur	NM
Rittweger et al [8]	19UT (10=female 9=male)	I(WBV)	6	26	Squatting on platform with load till exhaustion	Endurance time 5 8 minutes +	NM
		Control	NA	NA	Squatting on plat-form with load till exhaustion	Endurance time 8 6 minutes	NM

Note amp=vibration amplitude, freq=vibration frequency, I=indirectly applied vibration, MVC=maximal voluntary contraction, NA=not applicable, NM=no measurement, NS=not statistically significant, Pmax=maximal power, Pmean=mean power, T=trained, UT=untrained, WBV=whole-body vibration, ↑=increase, ↓=decrease, *=statistically significant compared with pre-vibration, +=statistically significant compared with control, ξ=statistically significant compared between elite and amateur, #=statistically significant compared with national, junior and amateur

Only two studies have examined this effect, both employing indirect vibration of the biceps through a grasped vibrating handle (21,26) Maximal force (26) and power (21) during concentric elbow flexion were enhanced significantly (p<0 05) by vibration (Table 2 2) This facilitatory effect may be greater in elite athletes Issurin et al (21) found that the vibration induced a significantly larger (p<0 05) increase in maximal power for elite athletes (10 4% increase), than for amateurs (7 9% increase) consisting of participants in club or college sports Liebermann et al (26) examined the 1RM strength in four groups of athletes with different expertise levels They found that all groups could lift significantly (p<0 05) heavier loads with vibration and that the enhancement was significantly larger (p<0 05) for Olympic athletes (8 3%) than the other groups (4 8% for national senior level, 6 2% for national junior level and 4 9% for amateurs)

2 5 2 2 Sub-maximal dynamic contraction

In a study by Rittweger et al (4) subjects performed exhaustive squatting with an additional load of 40% of the body mass, both with and without whole body vibration It was found that the time to exhaustion was significantly (p<0 05) shorter with vibration than that without vibration Oxygen consumption during the squatting exercise was also enhanced significantly (p<0 05) by whole body vibration, leading the authors (4) to suggest that the shorter time to fatigue was due to greater muscle activity during squatting

From the discussion of section 2.5.1 and 2.5.2, it appears that the muscle activity in sub-maximal dynamic and isometric contractions may be enhanced by vibration. During maximal effort dynamic contractions, vibration appears to be able to facilitate force and power output. This facilitatory effect has been shown to be greater in elite athletes. It is unclear whether the maximal isometric contraction force can be enhanced by vibration. However, prolonged vibration induces more muscular fatigue in both the maximal and sub-maximal isometric and dynamic muscle contractions. This exacerbated muscle fatigue by vibration may be due to 1) a facilitatory effect of vibration on muscle contraction force and activity during the early part of exercise; and/or 2) a suppression effect of vibration on neuromuscular performance.

2.5.3 Acute residual effect of vibration on force and EMG during isometric actions (Table 2.3)

The strength of maximal voluntary contraction (MVC), EMG of MVC and rate of force development (RFD) have been assessed by four studies at different time points, from immediately after vibration (4,21) to 60 minutes after vibration(7,12) (Table 2.3). Among them, two studies measured the neuromuscular performance of muscle in an unfatigued state (7,12). Both studies were by Torvinen et al. (7,12) and examined maximal knee extension strength two minutes and 60 minutes after four-minutes of whole body vibration. The studies differed only by the amplitude of vibration [4 mm(7) vs. 1 mm(12)]. Neither study found a significant effect of vibration training 60 minutes post training. However, a small but significant

Table 2.3 Acute residual effect of vibration on isometric muscle performance

Study	Subject	Vibration and exercise characteristics					Neuromuscular Performance change				
		method (location)	amp (mm)	freq (Hz)	exercise	duration (min)	contraction performed	tp (min)	Force or torque	RFD	EMG
Jackson et al.[14]	10UT, male	D(RF)	1.5-2.0	30	None	30	Knee extension (100% MVC)	0.5	7%↓* # +	70%↓* # +	IEMG RF 1.5mv.s↓*, VL 8mv.s↓NS
		D(RF)	1.5-2.0	120	None	30	Knee extension (100% MVC)	0.5	4.2%↓* NS	30%↓* NS	IEMG RF 7mv.s↓NS, VL 7mv.s↓NS
		control	NA	NA	None	30	Knee extension (100% MVC)	0.5	2%↓*	18%↓NS	IEMG RF 2.5mv.s↓NS, VL 0mv.s↓NS
Rittweger et al.[4]	19UT (10=female 9=male)	I(WBV)	6	26	Squatting on platform with load	5.8	Knee extension (70% MVC)	0	NM	NM	EMG_{mf} VL 55.2 Hz +
								10	NM	NM	EMG_{mf} VL 50 Hz NS
		Control	NA	NA	Squatting on plat-form with load	8.6	Knee extension (70% MVC)	0	NM	NM	EMG_{mf} VL 42.4 Hz
								10	NM	NM	EMG_{mf} VL 40 Hz
Torvinen et al.[7]	16UT (8=male 8=female)	I(WBV)	4	15-30	Standing on platform with light exercise	4	Knee extension (100% MVC)	2	1.0%↑ +	NM	NM
								60	0.8%↓ NS	NM	NM
		Sham-vibration	NA	NA	Standing on platform with light exercise	4	Knee extension (100% MVC)	2	2.0%↓	NM	NM
								60	3.2%↓	NM	NM
Torvinen et al.[12]	16UT (8=male 8=female)	I(WBV)	1	25-40	Standing on platform with light exercise	4	Knee extension (100% MVC)	2	1.3%↑ NS	NM	NM
								60	1.5%↓ NS	NM	NM
		Sham-vibration	NA	NA	Standing on platform with light exercise	4	Knee extension (100% MVC)	2	0.1%↑	NM	NM
								60	0.9%↓	NM	NM

Note amp=vibration amplitude, freq=vibration frequency, D=directly applied vibration, I=indirectly applied vibration, EMG_{mf}= EMG median frequency, MVC=maximal voluntary contraction, NA=not applicable, NM=no measurement, NS=not statistically significant, RF=rectus femoris, RFD=rate of force development, tp=test time from the end of vibration, UT=untrained, WBV=whole-body vibration, VL=vastus lateralis, ↑= increase, ↓=decrease, *=statistically significant compared with pre-vibration, += statistically significant compared with control, #=statistically significant compared with 120 Hz enhancement in strength was found two minutes post vibration training in comparison to sham vibration group (1% vs –2%, $p<0.05$) when the larger amplitude of vibration was employed [4mm (7)]. No difference was evident with a 1 mm amplitude of vibration. This indicates that with sufficient amplitude, vibration has a small transient residual effect which could improve maximal isometric strength output. Two studies measured neuromuscular performance in a fatigued state (4,14). One of them assessed the maximal voluntary isometric contraction force (14) and one assessed sub-maximal contraction muscle activity (4). Jackson and Turner (14) found that both the MVC strength and the RFD were significantly reduced ($p<0.05$) following 30 minutes vibration treatment (30Hz), compared to a control group. This finding suggests that vibration can elicit greater neuromuscular fatigue.

One study by Rittweger et al (4) measured the EMG activity of a sub-maximal isometric contraction (70% MVC), performed in a fatigued state, immediately and 10 minutes after vibration. Spectrum analysis on these EMG signals found that the median frequency (EMGmf) was significantly higher than that performed by a control group (4). Similar to the force evaluation, this effect on EMG was only observed immediately after vibration (4). The authors (4) therefore suggested that the facilitatory effect of vibration observed in an unfatigued state may be due to an enhanced central motor excitability which appears to recruit predominantly large motor units as shown by the shift of EMGmf to a higher frequency (4,28,29). It is also noted that the vibration amplitude and duration in this study are 6 mm and 5.6 minutes respectively, which is similar to those in the study by Torvinen et al. [4mm and 4 minutes(7)] that found the facilitatory effect on maximal isometric strength 2 minutes post vibration This suggests that sufficient vibration amplitude is also necessary for the enhancement of central motor excitability

2 5 4 Acute residual effect of vibration on strength and power during dynamic actions (Table 2 4)

Three studies have examined the residual effect of vibration on power during dynamic actions in an unfatigued state (7,12,21), although none of them have examined the effect on strength (Table 2 4) Only one of these studies found that vibration treatment had a facilitatory effect Torvinen et al (7) found that a four-minute whole body vibration training session could induce a small but significantly larger increase in counter movement jump height than the sham-vibration group, two minutes after vibration treatment (2% vs 0%, $p<0\ 05$) Two other studies found no significant effect on dynamic muscle performance after vibration (12,21) (Table IV) The first of these two studies (12) was identical to the study by Torvinen et al (7) which found the positive residual enhancement in vertical jump performance, except the vibration amplitude was smaller [1mm(12) vs 4mm(7)] In the second study, the amplitude of vibration on the muscle was also small (less than 0 3 – 0 4 mm) and the duration of vibration was fairly short [6-7 seconds(21)] It is possible that with small amplitudes and short durations of stimulation no residual effect is produced

The facilitatory effect of vibration on dynamic muscle performance also appears transient (7) The significantly larger increase in counter movement jump height at

Table 2.4 Acute residual effect of vibration on dynamic muscle performance

Study	Subject	Vibration and exercise characteristics					Neuromuscular performance change			
		method (location)	amp (mm)	freq (Hz)	exercise	duration (min)	contraction performed	tp (min)	Performance measure	EMG
Issurin et al.[21]	28 T male (14=elite 14=amateur)	I(hand)	0.3-0.4	44	Bicep curl	0.1	Bicep curl (MVC)	0	Elite power 5%↑ NS, Amateurs power 2%↑ NS	NM
		Control	NA	NA	Bicep curl	0.1	Bicep curl (MVC)	0	Elite power 1%↓ NS, Amateurs power 3%↓ NS	NM
Rittweger et al.[4]	19 UT (10=female 9=male)	I(WBV)	6	26	Squatting on platform with load	5.8	Serial jump	0	Height NS Tg NS	NM
								10	Height Tg	NM
		Control	NA	NA	Squatting on plat form with load	8.6	Serial jump	0	NS Height NS Tg	NM
								10	Height Tg	NM
Torvinen et al.[7]	16 UT (8=male 8=female)	I(WBV)	4	15-30	Standing on platform with light exercise	4	CMJ	2	Height 2.2%↑ +	NM
								60	Height 1.9%↓	
		Sham-vibration	NA	NA	Standing on platform with light exercise	4	CMJ	2	NS Height 0%↑	NM
								60	Height 2.2%↓	
Torvinen et al.[12]	16 UT (8=male 8=female)	I(WBV)	1	25-40	Standing on platform with light exercise	4	CMJ	2	Height 2.2%↑ NS	NM
							CMJ	60	Height 4.0%↓	
		Sham-vibration	NA	NA	Standing on platform with light exercise	4	CMJ	2	NS Height 0%↑	NM
							CMJ	60	Height 3.5%↓	

Note amp=vibration amplitude, CMJ=counter movement jump, freq=vibration frequency, I=indirectly applied vibration, MVC=maximal voluntary contraction, NA=not applicable, NM=no measurement, NS=not statistically significant, T=trained, Tg=ground contact time, tp=test time from the end of vibration, T=trained, UT=untrained, WBV=whole-body vibration, ↑= increase, ↓=decrease, +=statistically significant compared with control two minutes after vibration treatment was not present at 60 minutes after vibration (7,12)

Only one study examined dynamic muscle performance following a fatiguing vibration exercise Rittweger et al (4) examined the jump height and the ground contact time of a series of continuous jumps, immediately and 10 minutes after whole body vibration The results showed that vibration treatment did not have any significant effect on these parameters (p>0 05) (4)

From the discussions in section 2 5 3 and 2 5 4, it is suggested that a bout of vibration treatment may have a small transient facilitatory residual effect on isometric and dynamic muscle performance This faciltatory effect on muscle strength and power performance could be observed in an unfatigued state and may be due to an enhanced central motor excitability to recruit predominantly large motor units during isometric and dynamic contractions (4) It appears that the vibration amplitude and duration of vibration may need to be of sufficient magnitude to elicit this facilitatory effect In addition, a bout of prolonged vibration training may exacerbate muscle fatigue, which can decrease subsequent muscle performance

2.6 Chronic effect of vibration on neuromuscular performance

2 6 1 Chronic effect of vibration on isometric strength (Table 2.5)

Table 2.5 Chronic effect of vibration training on isometric muscle performance

Study	Subject	Vibration and exercise characteristics					Neuromuscular performance change	
		method (location)	amp (mm)	freq (Hz)	exercise	timing	performance test	test results
Delecluse et al. [3]	20 UT female	I (WBV)	1.25-2.5	35-40	Standing on platform, static and dynamic knee extensor exercise	3min-20min/session 3 times/week; 12 weeks	Knee extension (100%MVC)	16.6%↑*
	21 UT female	Placebo	Negligible	35-40	Standing on platform, static and dynamic knee extensor exercise	3min-20min/session 3 times/week, 12 weeks	Knee extension (100%MVC)	5%↑NS
De Ruiter et al. [8]	10 UT 6=male 4=female	I (WBV)	4	30	Standing on platform, isometric squatting (knee angle 110°)	60s X5 sets - 60s X8 sets 3 sessions/week, 11 weeks	Knee extension (100%MVC)	MVC 0% NS RFD 3.3%↑NS
	10 UT 6=male 4=female	Control	NA	NA	Standing on platform, isometric squatting (knee angle 110°)	60s X5 sets - 60s X8 sets 3 sessions/week, 11 weeks	Knee extension (100%MVC)	MVC 5.4%↑NS RFD 4.6%↓NS

Note amp=vibration amplitude, freq= vibration frequency, I=indirectly applied vibration, MVC=maximal voluntary contraction force, NA=not applicable, NS=not statistically significant, RFD=rate of force development, UT=untrained, WBV=whole body vibration, *=statistically significant compared with pre-training level, ↑= increase, ↓=decrease

Only two studies (3,8) have appropriately examined the chronic effect of vibration on isometric strength (Table 2.5). Their results are contradictory. Deleculse et al.(3) found that 12-weeks of whole body vibration training could induce a significant increase ($p<0.05$) in knee extensor MVC strength (16.6%), while the placebo group only produced a non-significant increase (5%). In contrast, however, De Ruiter et al.(8) reported no significant difference in knee extensor isometric strength between the vibration group and the control group after 11-weeks of training. The vibration frequency was similar in these two studies [35-40 Hz (3) vs. 30 Hz (8)], but the vibration amplitude was slightly smaller in the study which found the significant increase of MVC strength [1.25-2.5 mm (3) vs. 4mm (8)]. Thus, it appears that vibration amplitudes and frequencies in both studies are sufficient to activate the muscle, and the difference in results may be due to the different exercise intensity and volume undertaken in these two studies (8). Firstly, Delecuse et al. (3) included both dynamic and isometric exercises, such as the squat, deep squat, wide-stance squat, one-legged squat, and lunge. In contrast, de Ruiter et al. (8) only asked subjects to stand on the vibrating platform with their knee angle flexed at 110°. Thus, the exercise intensity in the study of Deleculse et al. (3) appears to be significantly higher. Secondly, in the training program of Delecluse et al., (3) the total duration of vibration training of the study increased with time, initially lasting 3 minutes, but reaching 20 minutes by the end. However, in the study of de Ruiter et al., (8) the total duration of vibration training increased from 5 minutes initially, to only 8 minutes by the end of the study. Thus it seems that the exercise intensity and volume was greater in the study of Delecluse et al. (3) and may indicate that these parameters must be of significant magnitude to induce benefits associated with vibration training.

De Ruiter et al found no chronic effect on RFD following vibration training (8), but again this may be due to insufficient training volume and intensity employed in that study (8)

2 6 2 Chronic effect of vibration on dynamic strength and power (Table 2 6)

Three studies (3,6,8) examined the chronic effect of vibration on dynamic strength and power Two studies (3,6) found that vibration enhanced the gain of dynamic muscle performance Three weeks of heavy strength training by untrained males, employing a seated bicep curl with vibration, could induce a significantly larger increase of concentric elbow flexion strength, than that in a control group where only the heavy strength training was performed (49 8% vs 16%, p<0 05) (6) Isokinetic knee extension strength and counter movement jump height were also enhanced significantly (9%, p<0 05 and 7 6%, p<0 05) after 12 weeks of training with superimposed whole body vibration, while the same training without vibration (control group) did not show any significant increase (3) However, the authors (3) did not find any significant increase in the maximal speed of ballistic knee extension with resistances of 0%, 20%, 40% and 60% of maximal isometric strength, in either the whole body vibration training group or the control group In contrast to the reported enhancement in counter movement jump height (3), de Ruiter et al (8) found no significant difference between a vibration trained group and a control group, after 11-weeks of training This lack of effect following vibration training may be due to the low level of exercise intensity and volume employed, as outlined in section 2 6 1

Table 2 6 Chronic effect of vibration training on dynamic muscle performance

Author	Subject	Vibration and exercise characteristics					Neuromuscular performance change	
		method (location)	amp (mm)	freq (Hz)	exercise	timing	performance test	test results
De Ruiter et al.[8]	10UT 6=male 4=female	I(WBV)	4	30	Standing on platform, isometric Squatting (knee angle 110°)	60s X5 sets - 60s X8 sets 3 sessions/week, 11 weeks	CMJ	Jump height 3 0%↑NS
	10UT 6=male 4=female	Control	NA	NA	Standing on platform, isometric squatting (knee angle 110°)	60s X5 sets - 60s X8 sets 3 sessions/week, 11 weeks	CMJ	Jump height 3 7%↑NS
Delecluse et al.[3]	20UT female	I(WBV)	1.25-2.5	35-40	Standing on platform, static and dynamic knee extensor exercise	3min-20min/session 3 times/week; 12 weeks	Isokinetic knee extension (100°/s) CMJ Ballistic knee extension (resistance 0%, 20%, 40%, 60% of maximal isometric strength)	Maximal strength 9%↑* Jump height 7 6%↑* Maximal speed 0%NS
	21UT female	Placebo	Negli-gible	35-40	Standing on platform, static and dynamic knee extensor exercise	3min-20min/session 3 times/week; 12 weeks	Isokinetic knee extension (100°/s) CMJ Ballistic knee extension (resistance 0%, 20%, 40%, 60% of maximal isometric strength)	Maximal strength 3%↑NS Jump height 0%NS Maximal speed 0%NS
Issurin et al.[6]	10UT male	I(hand)	0.3-0.4	44	Sitting bicep curl with (80%-100% 1RM)	6 sets, 3 times/week 3 weeks	Sitting bicep curl	Maximal strength 49.8%↑* +
	8UT male	Control	NA	NA	Sitting bicep curl with (80%-100% 1RM)	6 sets, 3 times/week 3 weeks	Sitting bicep curl	Maximal strength 16%↑*

Note amp=vibration amplitude, CMJ=counter movement jump, freq= vibration frequency, I=indirectly applied vibration, NA=not applicable, NS= not statistically significant, UT=untrained, WBV=whole body vibration, *=statistically significant compared with pre-training level, +=statistically significant compared with control, ↑=increase, ↓=decrease

Issurin et al (6) employed a heavy resistance training program in which subjects were asked to complete seated bicep curls, with a load of 80% - 100% 1RM This exercise intensity was the largest among the three studies (3,6,8) It was also noted that the gains in maximal strength in this study were also the largest, both with and without vibration [49 8% vs 16%, p<0 05(6)], although the length of this study was the shortest [3 weeks(6) vs 11 weeks(8) and 12 week(3)]

These findings indicate that vibration training can induce chronic adaptations, provided the exercise intensity and volume is sufficient to, and that the higher the exercise intensity and volume, the greater the strength and power gain that may be achieved However, it is also clear that there is a lack of research into chronic vibration training with a strict control group design This area in particular requires addressing as chronic adaptation is the main aim of resistance training

2 7 Effect of vibration characteristics on the enhancement in neuromuscular performance

The acute and chronic effects of vibration on neuromuscular performance seem to be affected by the vibration training methodology, which includes vibration characteristics (vibration amplitude, vibration frequency, the method of vibration application, vibration duration) and exercise protocols (type of exercise, intensity and volume of exercise) As shown in tables 2 1 to 2 6, there is diversity in the vibration training methodology employed among the studies to date While it is difficult therefore to identify the optimal vibration characteristics and exercise protocols for vibration training, some useful information about the effect of vibration methodology can still be obtained from these studies.

2.7.1 Influence of vibration amplitude

Two studies by Torvinen et al.(7,12) were identical except for the vibration amplitude [4 mm (7); 1 mm (12)] employed. Therefore, comparison of their findings provides insights into the influence of vibration amplitude on vibration training effect. In both studies (7,12), subjects undertook a four-minute whole body vibration training session in which light exercises (e.g. light squatting, standing in erect position, standing with knee flexed, light jumping, standing on heels) were performed on the vibrating platform. EMG activity was measured on calf muscles and thigh muscles during the vibration training process, but was not measured in the sham-vibration condition. While it is therefore not possible to determine the absolute effect of vibration training on EMG activity, it is possible to examine the relative effect of vibration amplitude on muscle EMG response by comparing these studies.

Both of the above studies measured the change of EMG activity on the soleus and vastus lateralis muscles during the four-minute vibration training process (7,12). The larger vibration amplitude (4 mm) induced a significant decrease ($p<0.05$) of mean power frequency of EMG (EMGmpf) on both muscles (soleus: 18.8%; vastus lateralis: 8.6%) and a significant increase ($p<0.05$) of EMGrms in the soleus muscle (21.6%), from the first minute to the fourth minute of the training process. The latter finding was suggested to be indicative of more pronounced muscle fatigue on soleus muscle (7) In contrast to this study, there was no significant change ($p>0.05$) of these EMG parameters on either muscle in the study with the smaller vibration amplitude (1 mm) during the four minutes training process (12) These results suggest that the larger vibration amplitude was more able to activate both muscles during training and thus induced more pronounced muscle fatigue

In addition, analysis of the acute residual effects in these two studies (table 2 3, 2 4) showed that only the vibration with the larger amplitude (4 mm) induced a significantly larger increase ($p<0.05$) in MVC strength and jump height than the sham-vibration group (7,12) These results support our above analysis that the whole body vibration with larger amplitude may activate the leg muscles more effectively, inducing a facilitatory residual effect on MVC strength and jump height It may also be suggested that the vibration amplitude may have to be of a sufficient threshold level in order to effectively activate the muscle being trained The study by Rittweger et al (4) also indicated that the enhancement of central motor excitability was elicited by whole body vibration with sufficient amplitude (6 mm) This summary finding is likely to be equally applicable to chronic based adaptations, as chronic adaptations are reflective of acute responses However, no studies to date have directly examined this

2 7 2 Influence of vibration frequency

A variety of frequencies, ranging from 15 to 137 Hz, have been used in indirect vibration studies (tables 2 1 to 2 4) In these studies, there are also differences in vibration amplitude, vibration duration and exercise protocol For indirectly applied vibration only one study has specifically investigated the effect of vibration frequency (table I) (23) Subjects gripped a vibrating handle and pushed isometrically away from their body while standing EMG activity of the forearm flexor, forearm extensor and triceps brachii muscles were examined under two vibration frequencies [50 and 137 Hz (23)] At both vibration frequencies, the integrated EMG (IEMG) of the forearm flexors and forearm extensors increased significantly more than in the control group ($p<0\ 05$) However, the amount of increase appears to be larger with the 50 Hz vibration than 137 Hz (flexor 83 3% vs 40%, extensor 45 5% vs 27 3%) For the triceps brachii muscle, only 50 Hz vibration induced a significant increase of IEMG ($p<0\ 05$) (23) This result suggests that low frequency (50 Hz) may be more effective in activating the muscle in indirectly applied vibration than high frequency (137Hz) However, care should be taken in employing frequencies that are much lower Mester et al (17) suggest that in whole body vibration training, frequency in the range less than 20 Hz should be avoided because of the resonance of human body which may induce injury effect

For directly applied vibration, only Jackson and Turner (14) have specifically examined the effect of vibration frequency In this study, vibration was applied to the muscle belly of the rectus femoris (14), and the acute residual effect on knee extension strength, following 30 minutes vibration training with two different vibration frequencies (30 and 120 Hz), was investigated The authors (14) found that the reductions of knee extension MVC strength and RFD were significantly greater in the 30 Hz vibration group, than in the 120 Hz vibration group and the control group ($p<0.05$). The IEMG was also attenuated significantly ($p<0.05$) by 30 Hz vibration only. The results of this study suggest that low frequency vibration (30 Hz) may induce more muscle fatigue, possibly by activating muscle more effectively.

The results of the above two studies suggest that low frequency (30 – 50Hz) vibration may have a greater acute effect in vibration training. As in the discussion of vibration amplitude, it is likely that the observation of greater enhancements from low frequency is applicable to chronic based adaptations, although no studies have directly investigated this.

2.7.3 Influence of method of vibration application

Two methods of vibration application have been used in vibration training studies: indirectly applied vibration (3,21,26) and directly applied vibration (10,13,14,18). The method of vibration application may influence the magnitude of vibration amplitude and frequency, i.e. the intensity of vibration load, on the muscle being trained.

Two studies on whole body vibration training by Torvinen et al., (7,12) will be examined here to demonstrate the influence of vibration application method. As introduced in section 2.7.1, the design of these two studies was identical, except for the vibration amplitude employed. In order to exclude the influence of exercise on measured EMG activity during vibration treatment, the muscles (soleus and vastus lateralis) on which EMG activity was measured in both studies will be selected in this analysis In the study with the smaller amplitude [1 mm (12)], EMGrms and EMGmpf on both the soleus and the vastus lateralis did not change significantly ($p>0.05$) during the four minutes vibration training process As discussed in section 2 7 1, this may be due to the fact that vibration amplitudes on both of these muscles was not sufficient to elicit any effect However, in the second study with the larger amplitude [4mm (7)], four minutes of vibration training did significantly decrease EMGmpf on both the soleus and the vastus lateralis ($p<0.05$) Importantly, the amount of decrease was larger on soleus (18 8%) than on vastus lateralis (8 6%) It was also found in this second study (7) that EMGrms increased significantly ($p<0.05$) only on the soleus The authors (7) suggested that fatigue of the soleus was more pronounced because the increase in EMGrms indicated that more motor units were recruited to compensate for fatigue during training This finding clearly demonstrated that the muscle group which was nearer to the vibration platform (soleus) may be more activated than the muscle group which was further away from the platform (vastus lateralis)

Kilberg et al (23) found that when employing a vibrating handle, 50 Hz vibration could induce a significant increase ($p<0.05$) in IEMG on forearm flexor, forearm extensor and triceps brachii muscles However, when vibration frequency was increased to 137 Hz, only the IEMG on the forearm flexors and forearm extensors was enhanced significantly ($p<0.05$) The IEMG of the triceps brachii did not change significantly ($p>0.05$) The authors (23) also found that 50 Hz vibration could transmit to the elbow without attenuation, while 137 Hz vibration was attenuated by about 20 dB at the wrist, and therefore would have less influence on the muscle activity of the triceps brachii.

These studies discussed above all employed the method of indirectly applied vibration. These findings suggest that with indirectly applied vibration there may have a greater vibration training effect on the muscles closer to the vibration source because of the attenuation of the vibration by the body structures during transmission. This attenuation may also result in the vibration amplitude on the muscle groups further from vibration source being less than the threshold level necessary for muscle activation, which has been discussed in section 2.7.1. Moreover, the attenuation of vibration appears to be larger with the increase of vibration frequency (22,23). This may be the reason that almost all vibration training studies with indirectly method have used a frequency less than 50 Hz (tables 2.1 to 2.4).

There are two ways to apply vibration directly to a muscle. One is by applying vibration on the muscle belly (10,14,18), the other is by applying vibration on the muscle tendon (13). Compared with indirectly applied vibration, there are few studies employing the direct vibration method (4 studies with direct vibration vs. 11 studies with indirect vibration, as shown in tables 2.1 to 2.6). There have been no chronic vibration training studies to date employing direct vibration. Although it has been suggested that indirectly applied vibration may be able to stimulate more muscle groups at the same time (6), the method of direct vibration may have its advantage in stimulating the target muscle without signal attenuation. Thus, given the same amplitude of vibration source, direct vibration may facilitate more effective utilization of this amplitude In addition, vibration with a higher frequency may be employed in direct vibration Some studies (30) have suggested that the most effective location to stimulate the muscle by vibration is the muscle tendon

2 7 4 Influence of vibration duration in a training session

The duration of vibration was normally the same length as the duration of exercise employed It may be an important factor to influence the vibration training effect when sub-maximal contractions were performed with vibration Available chronic vibration studies suggest that the longer duration of vibration in a training session may achieve more strength gain when sub-maximal contractions are performed during training (3,8) This was shown in the studies by Delecluse et al [maximal duration of 20 minutes(3)] and de Ruiter [maximal duration of 8 minutes(8)] in which only the study with longer duration whole body vibration training achieved significant gain in knee extension strength and jump height ($p<0.05$) Delecluse et al (3) suggested that prolonged vibration stimulation may result in full motor unit activation, which may be necessary for strength gain While it is tempting to conclude that increased vibration training duration is necessary for chronic enhancement when sub-maximal contractions are employed, these two studies(3,8) also had differences in vibration amplitude and the training exercises employed Clearly this issue requires direct investigation

2 7 5 Influence of exercise protocol

Acute studies have shown that it is unclear whether the maximal isometric contraction force can be enhanced by vibration (10,13,18,24), but vibration may increase the sub-maximal isometric contraction force, as evident by increased EMG activity during vibration (23) For dynamic contractions, vibration can increase the maximal voluntary contraction force (26) and power (21) The exercise protocols used in chronic vibration training studies appear to be consistent with the above findings on exercise type and intensity (see section 2 6 1 and 2 6 2) To date, however, maximal isometric contractions have not been employed in chronic vibration training studies In whole body vibration training studies, sub-maximal isometric and dynamic contractions were always used, such as standing on the platform with knee flexed (8), squatting (3), and light jumping (7,12) Maximal effort has only been used with dynamic exercises in chronic vibration training studies (6), and the results showed that this kind of exercise protocol, with applied vibration, could achieve significantly more strength gain (p<0 05) (6)

As discussed in section 2 6 1 and 2 6 2, the increase in exercise intensity and volume tends to induce greater muscle performance improvement in chronic vibration training (3,8) However, because of the lack of chronic vibration training studies and the diversity of the training programs employed, the optimal vibration training programs remains unclear

2 8 Summary of vibration treatment on neuromuscular performance

Although there is a lack of strictly controlled studies, the available studies on vibration training to date still allow us to make some conclusions about this new training method. It appears that vibration training can induce enhancements in strength and power, both acute and chronic (3,6,7,18,21,23,26). However, vibration training may also have some limits, e.g. it is still unclear whether the maximal isometric contraction force can be enhanced by vibration. Moreover, the inhibition effect of vibration on motor unit recruitment should be taken into consideration. It also seems that the methodology of vibration training, both the vibration characteristics and exercise protocols, plays an important role in eliciting this enhancement (8,12).

Vibration amplitude and frequency are very important in vibration training because they determine the load that vibration imposes on the neuromuscular system during training (17). Present studies indicate that vibration amplitude may need to be of a sufficient magnitude if it is to elicit an enhancement of strength and power (7,12). Due to the lack of studies directly comparing different amplitudes, it is not currently possible to stipulate the specific optimum magnitude of this minimum amplitude for either direct or indirect vibration methods. There may also be a frequency range (e.g. 30-50 Hz) that is able to activate the muscle most effectively (14,23). However, there is a lack of study examining the effect of vibration frequency, especially in direct vibration method. These findings need further investigations.

The vibration amplitude and frequency that are delivered to a muscle being trained are influenced by the method of vibration application. With indirectly applied vibration, a situation may exist where the vibration amplitude and frequency on a muscle close to the vibration source may be sufficient to activate the muscle effectively, but they may not be sufficient when they reach a muscle further away from the vibration source (7,23). This is because vibration amplitude and frequency may be attenuated during its transmission through soft tissues (17,22). Moreover, this attenuation is increased with the increases in vibration frequency (22). In contrast, direct vibration may stimulate a specific muscle group more effectively because the distance of transmission is shorter and the amount of attenuation is less. However, the effect of direct vibration is more localized and indirect vibration may be able to activate more muscle groups during its transmission (6). Compared with indirect method of vibration, there have been far fewer studies examining the effect of the direct method of vibration.

Vibration duration appears to be an important factor when vibration is employed with the exercise of sub-maximal effort, a sufficient duration may be needed to fully activate motor units (3) and enhance central motor excitability (4).

The exercise protocol employed in vibration training appears influence on the training effect. Insufficient exercise intensity and volume may reduce or prevent any vibration effect (8).

Vibration appears to induce greater strength and power gain in elite athletes than non-elite athletes. Although this vibration training effect was only examined in two studies, which investigated the acute responses (21,26), it suggests that vibration training may have a great potential for use with elite athletes, as it is harder to produce an enhancement in neuromuscular performance in elite athletes than non-elite athletes when conventional strength training methods are used

2 9 Purported mechanism for vibration training effect

Currently there is no clear consensus on the mechanism by which vibration may enhance neuromuscular performance, and in fact there is a lack of research in this area However, a number of mechanisms have been postulated upon, which are discussed below It should be noted that only in this section will some of those studies that did not fulfil our inclusion/exclusion criteria be reported because some purported mechanisms for vibration training were suggested by these studies In the following discussions, the neuromuscular mechanisms will be discussed first (section 2 9 1 to 2 9 3), followed by the hormonal mechanisms (section 2 9 4)

2 9 1 Superimposed vibration increases muscle activity and contraction force during strength training

1) Tonic vibration reflex (TVR)

Mechanical vibration applied to a skeletal muscle produces a sustained discharge of the Ia afferent and a tonic reflex contraction in the muscle being vibrated This phenomenon is called tonic vibration reflex (TVR) (30,31) Park and Martin (32) found that sub-maximal contraction force and neural activity of a muscle could be enhanced by TVR

2) Vibration induced afferents facilitate maximal voluntary muscle

Motor units need to fire at a very high frequency (60 to 120 Hz) in the initial phase of a maximal voluntary contraction performed as fast and hard as possible (33) In addition, an excitatory inflow of Ia afferents are needed for the generation of the high motor unit firing rates (34) Thus the continuous firing of Ia afferents induced by vibration may facilitate the high firing rates of motor units that are needed in maximal voluntary contractions Cardinale and Bosco (11) suggest that vibration may stimulate the secondary endings and Golgi tendon organs of the muscle, and the joint receptors and cutaneous mechanoreceptors The afferent signals from these sensory organs may facilitate the activity of γ motoneurons (11), which may increase the sensitivity of the primary endings, leading to enhanced force and power output in maximal voluntary contractions

3) Increased synchronization of motor units

There is some evidence that, in elite power and strength athletes, motor units are activated synchronously during maximal voluntary efforts (35) It has also been found that the increased mechanical output of muscle induced by short-term training might have been brought about by the neural adaptations in terms of greater muscle activation levels and more synchronous activation patterns (36)

Muscle vibration may drive motor units to fire more synchronously (37,38) Martin & Park (38) and Lebdev & Polyakov (37) studied the synchronization of motor units under vibratory stimuli by using spectral analysis of the EMG Their results showed that there were peaks in EMG power spectrum at the vibration frequency and its harmonics, which indicated that the discharge of motor units became synchronized with vibration pulses (37,38) Issurin et al (6) suggested that the synchronization of motoneurons by vibration may result in a more efficient use of the force production potential of the muscle being trained

4) Muscle tuning

Muscle has an ability to damp the vibration or shock input from the lower limbs during running (39) A 'muscle tuning' hypothesis has been suggested to explain this phenomenon (39,40) This hypothesis suggests that the soft tissues of the lower limbs may damp vibrations with the frequencies of 10 to 20 Hz (resonance frequency of lower limb) by increasing the muscle stiffness of lower limb (40) This 'muscle tuning' hypothesis has also been suggested to be a possible mechanism for whole body vibration training effect (41) Cronin et al (42) found that the muscle stiffness of lower limbs tended to increase after a bout of whole body vibration training Therefore, it is possible that the increase of muscle stiffness to damp vibration may also be a reason for the enhancement of contraction force and power

5) Decreased sense of effort

Liebermann et al (26) found that when subjects performed the same isotonic elbow flexion exercise with and without vibration, their perception of effort was lower when there was applied vibration during exercise The authors also found that maximal strength during elbow flexion was greater with superimposed vibration The authors (26) thus suggested that the improved maximal isotonic contraction force associated with vibration may in part be due to the decreased sense of effort, as people have the feeling of lifting lighter loads (26)

2 9 2 Vibration has a residual effect to facilitate the subsequent contraction

As discussed above in section 2 5 3 and 2 5 4, muscle contraction force and power may be enhanced immediately after the vibration treatment This faciliatory effect may be due to the following mechanisms

1) Increased motoneuron excitability

TVR may induce a facilitatory after-effect which decreases motor unit recruitment thresholds during the subsequent voluntary contraction (43) This post-vibration facilitation has been interpreted as a post-tetanic potentiation of the motoneurons, since Granit (44) has demonstrated that the muscle spindle Ia afferents can produce an effect of this kind A remanent sensitization of the muscle spindles is also suggested as a mechanism for this post-vibration facilitation effect (43)

Several studies also report that the stretch reflex could be potentiated after vibration treatment (30,45) Eklund et al (30) found that the TVR in the quadriceps muscle could be facilitated by a preceding 90 seconds vibration applied to the patellar tendon In addition, tendon reflex elicited in the soleus muscle of normal human is markedly potentiated after 1-2 minutes duration of Achille tendon vibration

(30,45,46) It is suggested that the enhanced stretch reflex after vibration treatment results in the improved counter movement jump (CMJ) performance because the CMJ is characterised by the so-called stretch-shortening cycle (SSC) which could be potentiated by the stretch reflex activity (35)

Rittweger et al (4) suggests that the motor unit recruitment pattern may be changed after vibration treatment The authors (4) undertook spectral analysis on the EMG signal recorded during isometric contraction (70% MVC) after an exhaustive exercise with and without vibration It was found that the median frequency was significantly higher in the vibration group than the control group (4) It has been demonstrated that the EMG median frequency may be an indicator of central nervous recruitment patterns, as smaller motor units have a smaller conduction velocity (and hence EMG frequency) and amplitude (and hence EMG power) than larger units (28) This finding on EMG median frequency suggests that a central nervous recruitment of predominantly larger motor units occurs after vibration training (4) Therefore, the after vibration facilitation of isometric and dynamic muscle performance may be due to an enhanced central motor excitability, particularly with respect to the fast twitch fibres and motor units (4)

Furthermore, the study by Kossev et al (47) demonstrated that muscle vibration caused augmentation of motor evoked potentials (MEPs) following transcranial magnetic stimulation (TMS) but not following transcranial electrical stimulation, indicating that cortical excitability was altered by muscle vibration Cardinale and Bosco (11) suggested that vibration training may influence the excitatory state of the peripheral and central structures, which could facilitate subsequent voluntary movements. This may be one of the mechanisms for improvement in acute muscle performance following a bout of vibration training.

2) Increased neuromuscular efficiency by increased muscle blood flow after vibration

Bosco et al. (48) found that the neural efficiency index, which is the EMGrms divided by mechanical power, decreased significantly after a bout of vibration treatment (48). The authors (48) therefore suggested that the neuromuscular efficiency was significantly enhanced by vibration. This increase of neuromuscular efficiency after vibration treatment may probably be the result of increased muscle blood flow and muscle temperature (48), which could accelerate the supply of substrates and removal of the waste substances produced by the muscle contractions and therefore decrease fatigue (49).

The increase of muscle blood flow and muscle temperature after vibration treatment was found in a number of studies (50-52). Nakamura et al. (51) found that muscle vibration can induce vasodilation. Kerschan-Schindl et al. (50) found that whole-body vibration training may increase the muscle blood volume, as power doppler indices indicated that muscular blood circulation in the calf and thigh significantly increased after 3 minutes of whole-body vibration exercise. With localized vibration, Oliveri et al. (52) found that after 15 min of 100 Hz vibration applied to the forearm muscle, the skin temperature increased significantly. The authors (52) also noted that all subjects had an erythematous reaction around the area where the vibrator was placed, which suggested that there was vasodilation of cutaneous vessels from vibration stimulation

3) Inhibition of antagonist muscle

Tonic vibration reflex (TVR) may also induce a decrease in the excitability of the motoneurons innervating the antagonist muscle through reciprocal inhibition (31) Cardinale and Bosco (11) suggested that vibration may alter the inter-muscular coordination patterns leading to a decreased braking force However, no study appears to have analysed antagonist muscle EMG to date In order to clarify this mechanism, further studies are needed

2 9 3 Muscle hypertrophy by vibration training

To date there have been no reports on the effect of vibration training on human muscle hypertrophy However, some animal experiments have shown enlargement of the muscle fibres following vibration Applying vibration 5 hours a day for 2 days to the hindlimb of rat, Necking et al (53) found increased cross-section areas of the vibrated muscle fibres, which, he suggested, may be due to increased intracellular oedema Flamping et al (54) found that 192-seconds of mechanical vibration each day for 14 days applied to the Achilles tendon of rat during hindlimb unloading significantly reduced the decrease in soleus muscle mass and fibre size when compared with the control soleus It is possible that vibration may also have a similar effect on human muscle hypertrophy

2.9.4 Hormonal response to vibration training

Several hormones secreted by different glands in the body affect skeletal muscle tissue. These effects are classified as either catabolic, leading to the breakdown of muscle proteins, or anabolic, leading to the synthesis of muscle proteins from amino acids. Among the anabolic hormones are testosterone, growth hormone, and somatomedins (35,54).

Hormonal response to vibration training was examined by a number of studies (55-57). However, it should be noted that none of these studies employed an appropriate control. Thus the influence of the exercise associated with vibration can not be excluded. In two of these three studies, increased hormonal secreation was found after vibration treatment (55,57). Bosco et al. (55) found that immediately after a bout of 10-minutes whole body vibration training (10 sets of 1-minute treatment with 1-minute rest in between, except after fifth set where the rest time between the fifth and sixth set was 6-minutes), there was a significant increase of blood levels of testosterone (7%) and growth hormone (460%). McCall et al. (57) found that after 10-minutes of muscle vibration (100Hz, 1.5mm) applied to the tibialis anterior muscle of human subjects, plasma growth hormone concentration determined by bioassay (BGH) was elevated significantly by 94%. However, in another study by Bosco et al. (56), it was found that hormonal levels (the serum testosterone) decreased significantly after a bout of 7-minute vibration training (7 sets of 1-minute treatment with 1-minute rest in between). The possible reason for the above contrasting results may be the different vibration training protocols employed. It has been found that the change of anabolic hormone concentrations after a resistance exercise workout is determined by factors such as intensity of the workout, amount of rest between sets and exercises, volume of total work and training level of the individual (1). Thus, the different vibration training durations and rest times may induce different hormonal responses after a bout of vibration treatment.

It was also noted that the different hormonal profile corresponded to the different neuromuscular performance in the two studies by Bosco et al. (55,56). In the study which demonstrated decreased serum testosterone, both counter movement jump and continuous jump height tested immediately after vibration treatment decreased significantly (56). However, in the study which demonstrated increased serum testosterone, both counter movement jump height and dynamic leg press power increased significantly (55).

The decrease of testosterone in blood accompanied by the decrease in neuromuscular performances suggests that vibration treatment may act on the biological system in a similar manner to heavy resistance training (56). According to training theory, at the beginning of heavy resistance training both neuromuscular performances and testosterone concentration in the blood decrease (56). After several weeks, a period of overcompensation follows, where enhancement of the muscle performance and an increase of serum testosterone are found (56). On the other hand, Bosco et al. (56) suggested that an adequate male sex hormone level may compensate for the effect of fatigue by ensuring a better neuromuscular efficiency in the fast twitch fibres, which supports the finding that the potentiated neuromuscular performance after vibration treatment was accompanied by the increase of testosterone.

2.10 Justification of the present study

It is clear from this review that the contradictory findings on vibration training are evident and they may be related to training factors including vibration characteristics (amplitude, frequency and method of application) and exercise protocols (type of exercise and exercise intensity). However, there is a lack of research into many of these factors. Therefore, investigation on this issue is the aim of the present study. In particular, the following factors will be examined:

Firstly, the review of literature suggests that vibration amplitude needs to be high enough to activate a muscle during vibration training (7,12). There also appears to have a frequency range that may activate the muscle most effectively (14,23). Therefore, the vibration load (amplitude and frequency) on a muscle may be closely related to the vibration training effect. However, the vibration load on a muscle is affected by the method of vibration application. To date, most vibration training studies have employed the indirect method of vibration, which may limit the vibration load on a muscle further away from the vibrating source because of the vibration attenuation. In addition, it is very difficult to examine the relationship between the vibration load and vibration training effect on a muscle by indirect method because the actual vibration and frequency on the muscle is unquantifiable after the transmission of vibration through soft tissues.

Few vibration training studies to date have employed direct method of vibration (10,14,18,49). None of them have examined the influence of vibration amplitude. Only one of them directly examined the influence of vibration frequency (14).

Moreover, the vibration devices used in these studies are cumbersome and not suitable for dynamic movement during strength training (10,14,18) Therefore, the present study will develop a portable vibration training device that can directly stimulate the muscle during training exercise This device should also have the capacity to produce different ranges of vibration amplitude and frequency to allow the present study to examine the influence of vibration characteristics (amplitude and frequency)

Secondly, the present review indicates that superimposed vibration may enhance the strength and power of maximal isotonic contractions (6,21,25) This is of great potential in strength training because of the general acceptance that dynamic training is more beneficial to neuromuscular performance in athletes than isometric training However, only three studies to date with appropriate control have examined vibration training with maximal isotonic effect (6,21,25) All of these studies employed an indirect method of vibration Therefore, the present study will investigate the effect of vibration training with a direct method, on the neuromuscular performance of maximal isotonic contractions

Finally, it is evident from the review that exercise intensity may have an influence on the vibration training effect (3,8) However, no vibration training studies to date have directly examined this possibility Therefore, this will be undertaken in the present study

Chapter 3

Development of a portable muscle-tendon vibrator with variable amplitude and frequency for vibration training

3 1 Introduction

Although vibration training gained popularity in the last five years as a novel strength training method (11,17) The study results in this area are not consistent as to whether vibration has facilitatory effect on strength and power development A number of acute and chronic vibration training studies have demonstrated that vibration training could achieve significantly more strength and power gain than the same conventional training without vibration (3,6,7,12,21,26) However, some studies did not find any beneficial effect to superimposed vibration (8,9) A critical review of the literature suggested that the vibration training effect may be dependent on the methodology employed

The methodology of vibration training includes the vibration characteristics and exercise protocol Vibration characteristics include vibration amplitude, frequency and the method of vibration application Vibration load imposed on neuromuscular system during vibration training is determined by vibration amplitude and frequency (17) The review of the literature reveals that these factors need to be high enough for vibration training to elicit an effect However, the method of vibration application could influence the vibration amplitude and frequency that imposed on the target muscle during vibration training There are two methods of applying vibration to the muscle during strength training In the direct method, vibration is applied directly to the muscle belly or the tendon of the muscle being trained (14,18,49) In the indirect method, vibration is applied indirectly to the muscle being trained, i.e. the vibration is transmitted from a vibrating source away from target muscles, through part of the body to the target muscle (5,6).

Although the indirect method has the advantage of stimulating more muscle groups during vibration transmission (6), there are some disadvantages with this method. Firstly, the energy of vibration, especially vibration of high frequency, may be attenuated when transmitted through the soft tissues. This attenuation may elicit the effect that the vibration load (amplitude and frequency) on the muscle groups further away from vibration source may not be high enough for muscle activation. Secondly, both the agonist muscle and antagonist muscle are stimulated by vibration in indirect method, which may induce some amount of inhibition on the activation of agonist muscle (8,58).

Compared with indirect method, vibration training with direct method may stimulate specific muscle group more effectively because the distance of transmission is shorter and the amount of attenuation is less. To date, however, there have been few vibration training studies with appropriate control design used this method (10,14,18). The results of these studies are inconsistent because different vibration load was imposed. No study to date has examined the relationship between the vibration load and the vibration training effect in direct method. In addition, the vibration unit used in direct method to date either has to be held by another person (18) or needed to be fixed to an exterior support (14) during their operations. Thus they are not suitable for strength training where dynamic exercises are normally executed and where it is necessary to move easily from one exercise action to another.

It is thus the primary objective of this study to develop a vibrator that was firstly portable and could stimulate the muscle-tendon directly during strength training exercise, and secondly, provide varied amplitude and frequency capacity to investigate the effect of the different vibration loads on neuromuscular performance

3 2 Methods

3 2 1 Requirements for the muscle-tendon vibrator

1) Size and weight As the vibrator will stimulate the muscle-tendon directly during strength training exercise, a key design criterion was to make it as small and light as possible so that it can be attached to the muscle-tendon conveniently and accommodate the movement necessitated by different training exercises

2) Vibration characteristics (amplitude and frequency ranges) Another important requirement for the vibrator design was its ability to produce vibrations with an amplitude and frequency range appropriate for vibration training It is expected that the vibrator could encompass the ranges of amplitudes and frequencies that have been employed in the vibration training studies to date This could facilitate our study for searching the optimum vibration amplitudes and frequencies for vibration training To establish these ranges of amplitudes and frequencies, a review was made on the vibration characteristics applied in the vibration training studies reported to date This review was limited to studies employing direct method because the studies with indirect vibration only reported the vibration characteristics of the vibration source(3,5-7,12) which were attenuated by the

time they reach the target muscle group(59) Frequencies were found to range from 30 Hz(14) to 200 Hz(32), while amplitudes ranged from 0 2 mm(32) to 3 3 mm(30) It was reported however, that vibration with amplitude greater than 2 mm induced discomfort for subjects(30) Thus it was decided that our vibrator design should encompass an amplitude and frequency range of 0 2 mm to 2 mm, and 30 Hz to 200 Hz respectively to facilitate optimization of the design for vibration training applications

3) Repeatability The output of vibration characteristics should be repeatable during various operation conditions in strength training exercises

3 2 2 Concept generation of the vibrator design

1) Selection of the methods to develop vibrator

The common types of vibration machine were reviewed and their advantages and disadvantages were compared in order to select the methods to build our vibrator

a) Direct-drive mechanical vibration machine

The direct-drive vibration machine consists of a rotating eccentric or cam driving a positive linkage connection which force a displacement between the base and output table of the machine (figure 3 1) The frequency can be changed by employing a direct-coupled variable-speed motor with electronic speed control(60)

The advantage of this method

- low operating frequencies and large displacement can be provided conveniently

The disadvantage of this method

- the machine must be designed to provide a stiff connection between the ground or floor support and the table This is not suitable for our vibrator because we want to develop a portable vibrator that can be used in dynamic strength training exercises
- The allowable range of operating frequencies is small in order to remain within bearing loading ratings
- The waveform of acceleration is normally sufficiently distorted The fundamental driven frequency is usually un-recognizable

The application of this kind of method in vibration training device

- In the study by Issurin et al (6,21), this method was used to build a vibration device for indirect vibration training The device has to be fixed to the ground and can produce vibration with frequencies of 44 Hz and 60 Hz The detail of this vibration device can be found in section 2 4
- In the study by Warman et al (49), this method was used to build a vibration device for direct vibration training The device also has to be fixed to an exterior support and can only produce vibration with frequency of 50 Hz The detail of this vibration device can be found in section 2 4

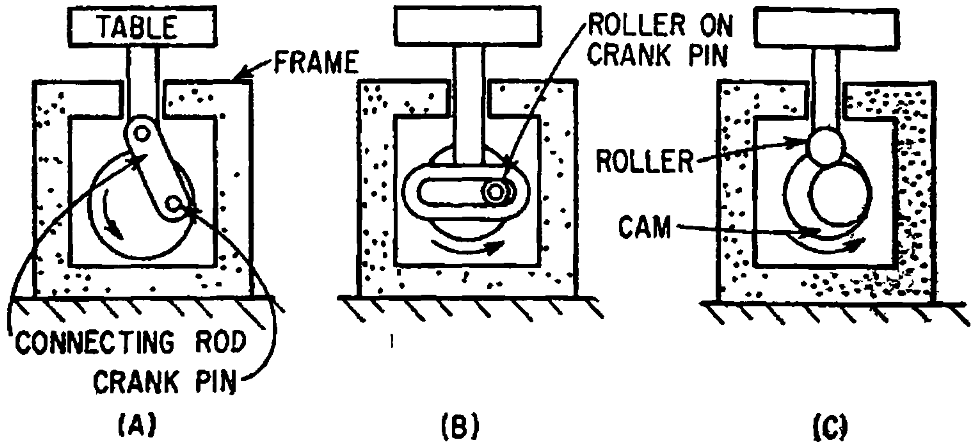


Figure 3 1 Example of direct-drive mechanical vibration machines

(A) Eccentric connecting link (B) Scotch yoke (C) Cam and follower [Adapted from Unholtz (60)]

b) Reaction-type mechanical vibration machine

This kind of vibration machine using a rotating shaft carrying a mass whose center-of-mass is displaced from the center-of-rotation of the shaft for the generation of vibration (figure 3 2) The force resulting from the rotating unbalance is transmitted through bearings directly to the table mass, causing a vibratory motion without reaction of the force against the base (60)

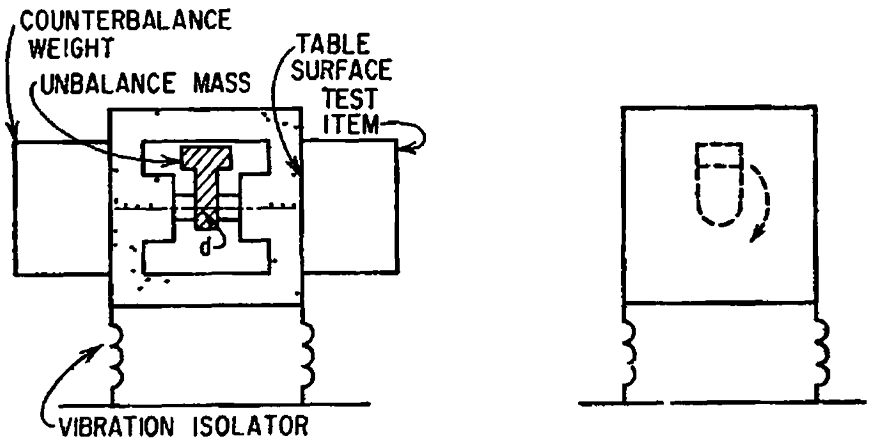


Figure 3 2 Example of reaction-type mechanical vibration machine [Adapted from Unholtz (60)]

The advantage of this method

- The force generated by the rotating unbalance are transmitted directly to the table without dependence upon a reactionary force against a heavy base or rigid ground connection Thus, there is no need to fix the vibration machine to an exterior support when it is used on stimulating muscles during vibration training, i e vibration machine could be portable by using this method
- The output waveform of vibration is superior to that attainable in the direct-drive type of vibration machine

The disadvantage of this method

- frequencies up to 120 Hz and higher can only be obtained for smaller machines

The application of this kind of method in vibration training device

To date, there has been no vibration training device that employed this kind of method

c) Electrodynamic vibration machine

This kind of vibration machine system is comprised of an electrodynamic vibration machine, electrical power equipment which drives the vibration machine, and electrical controls and vibration monitoring equipment The force which causes motion of the table is produced electrodynamically by the interaction between a current flow in the armature coil and the intense magnetic dc field which passes through the coil(60)

The advantage of this method

- A wide range of operating frequencies is possible, from 0 to above 30,000Hz
- Frequency and amplitude are easily controlled
- Good output waveform can be generated at all frequencies and amplitudes

The disadvantage of this method

- Exterior rigid support is needed for the operation
- The size is usually too big and the weight is too heavy for portable operation
- Quite expensive

The application of this kind of method in vibration training device

- In the study by Jackson et al (14), a vibrator of this kind (Ling Dynamics, V201, Ling Dynamics, UK) was used to apply vibrations with two different frequencies (30 and 120 Hz) directly to the femoris muscles The size of the vibration unit is ∅102 mm (diameter) × 121 mm (height), and its weight is 1 8 kg(19)

d) Hydraulic vibration machine

The hydraulic vibration machine produces vibration by flow of high-pressure fluid from a pump to the vibration output device Usually, an electrohydrolic valve is used to deliver the high-pressure fluid(60)

The advantage of this method

- Large generated force and large amplitude of vibration can be produced relatively easily

The disadvantage of this method

- A rigid connection to firm ground or a large massive base is necessary to anchor the machine in place
- Hydraulic fluid cleanliness, seepage and leakage are problems
- Quite expensive (electrohydraulic valve, hydraulic source)

The application of this kind of method in vibration training device

No vibration training device has used this method

A comparison of the above mentioned four methods was made as shown in table 3 1 After the comparison, the method of reaction-type vibration machine was selected as small size can be achieved by this method

Table 3 1 Comparison of different types of vibrator

Type of vibrator	**Frequency**	**Amplitude**	**Waveform**	**Size**	**Exterior support structure**	**Application in vibration training**
Direct-drive	Operating frequency low and variable	Variable	Bad	Big	Needed	Yes(6)
Reaction-type	Operating frequency can reach more than 120Hz and variable	Variable	Superior to that of direct-drive type	Small	Not needed	No
Electrodynamic	Wide range operating frequency and variable	Variable	Good	Big	Needed	Yes(14)
Hydraulic	Wide range operating frequency and variable	Variable	Good	Big	Needed	No

2) Two concepts of vibrators and their attachment methods

<u>1st concept:</u> The vibrator is in the shape of a cylinder, with a motor housed inside it There are two eccentric masses attached to the front and rear shaft respectively The

vibrator was fastened to the muscle-tendon with elastic Velcro strap The orientation of the longitudinal axis of the vibrator was perpendicular to the arm or leg (figure 3 3)

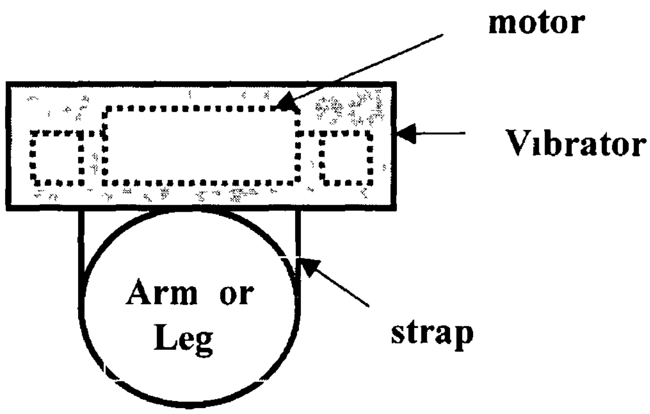


Figure 3 3 Sketch of the first concept

<u>2nd concept</u> The shape of the vibrator is a cylinder, with the motor housed inside it There is only one eccentric mass attached to the front shaft of the motor Thus the length of the vibrator can be shorter compared with the first concept The vibrator is fastened to the muscle-tendon with elastic Velcro strap Because the vibrator is shorter, the orientation of the longitudinal axis of the vibrator is parallel to the arm or leg (figure 3 4)

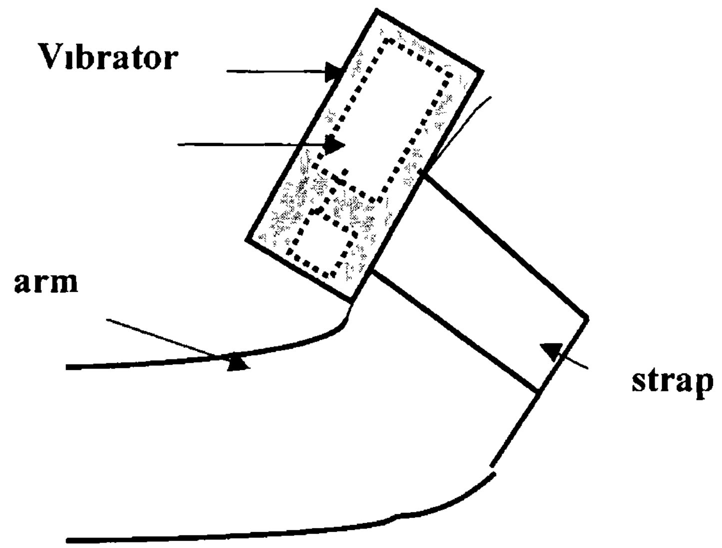


Figure 3.4 Sketch of the second concept

Compared with the first concept, the advantages and disadvantages of the second concept are as follows

Advantage

a) The vibrator can be made shorter in 2nd concept

b) The rear shaft of the motor is not needed and the price of the motor is lower

c) The attachment by the elastic strap is easier

Disadvantage

a) It may influence the training exercise because the longitudinal axis of the vibrator is parallel to the arm or leg

b) The balance of the vibrator is poor because there is only one eccentric mass on one side of the shaft

The first concept was chosen for the vibrator design.

3.2.3 Detailed design of vibrator

1) Eccentric mass

Different vibration amplitudes are to be produced by different eccentric mass sizes that attached to the shaft of motor. In order to produce the vibration amplitude consistent with the required range, an estimation of the eccentric mass that should be used for the vibrator was made. A single degree-of-freedom system model was used for this estimation calculation (figure 3.5). Eccentric mass Mu was mounted on to the mass M (mass of the motor and housing, i.e. 430 g). The eccentric radius (e) was 8.4 mm, and ω the angular velocity of the eccentric mass (frequency of vibrator). K and C represented the stiffness and damping coefficient of the muscle-tendon under the vibrator. A was the displacement amplitude of the mass M in the X-direction.

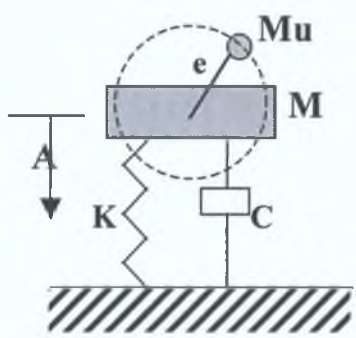


Figure 3.5 Single degree-of-freedom system model of vibrator

The displacement amplitude of the vibrator can be calculated as follows(61):

$$A = \frac{Mu}{M} \times e \times Ra \qquad \text{(Equation 3.1)}$$

where

M_u = eccentric mass

M = mass of the motor and housing

e = eccentric radius

Ra = dimensionless response factor, and is calculated as

$$Ra = \frac{(\omega^2/\omega_n^2)}{\sqrt{(1-(\omega^2/\omega_n^2))^2 + (2\times\xi\times\omega/\omega_n)^2}} \qquad \text{(Equation 3 2)}$$

where

ω_n = natural frequency of muscle-tendon under the vibrator

ξ = fraction of the critical damping

To identify the values of ω_n and ξ for muscle-tendon, the data from Wakeling et al (62) which investigated the free vibration behavior of quadriceps muscles were used The damped natural frequency ranged from 8 85 Hz to 30 39 Hz (62) An average value of 19 8 Hz was used in this study The fraction of the critical damping in the study of Wakeling et al (62) ranged from 0 14 to 0 73 and thus an average value of 0 44 was used in our study According to the calculation using Equation-3 2, *Ra* ranged from 1 24 at 30 Hz to 1 01 at 200 Hz Using these values, the eccentric mass could be calculated from Equation-3 1 The calculation showed that if the amplitude ranged from 0 2 to 2 mm at frequencies between 30 and 200 Hz, the eccentric mass should range from 8 g to 100 g (table 3 2)

Table 3.2 Estimation of eccentric mass at required range of vibration amplitude and frequency

Frequency (Hz)	Ra	Eccentric mass (g) (amp=0.2mm)	Eccentric mass (g) (amp=1mm)	Eccentric mass (g) (amp=2mm)
30	1.24	8.29	41.46	82.91
50	1.09	9.34	46.70	93.41
70	1.05	9.76	48.78	97.57
90	1.03	9.94	49.71	99.42
110	1.02	10.04	50.19	100.38
130	1.01	10.09	50.47	100.94
150	1.01	10.13	50.65	101.29
170	1.01	10.15	50.77	101.53
200	1.01	10.18	50.88	101.77

Note: amp = vibration amplitude

Three different materials, i.e. plastic, aluminium and copper were used to make eccentric masses. For each material, there were four pieces which functioned as eccentric masses, i.e. two eccentric masses on each side of the shaft. The thickness of each eccentric mass was 4mm. The weight of each eccentric mass was 3.5 g (plastic), 8 g (aluminium), and 26 g (copper) respectively. Therefore, the amplitude that could be produced ranged from 0.14 mm (with only one plastic eccentric mass on each side of shaft) to 2 5 mm (with 2 copper eccentric masses on each side of shaft) Moreover, in order to fine-tune the weight contribution of the eccentric mass, there will be one piece of eccentric mass attached to each end of the motor shaft by set screw, and another one piece of adjustable eccentric mass attached to each fixed eccentric mass The angle between the fixed and adjustable eccentric masses constituting the eccentric masses on each side of the shaft could be adjusted to several different angles (figure 3 6) 0°, 83°, 120°, 150°, 173° and 180°

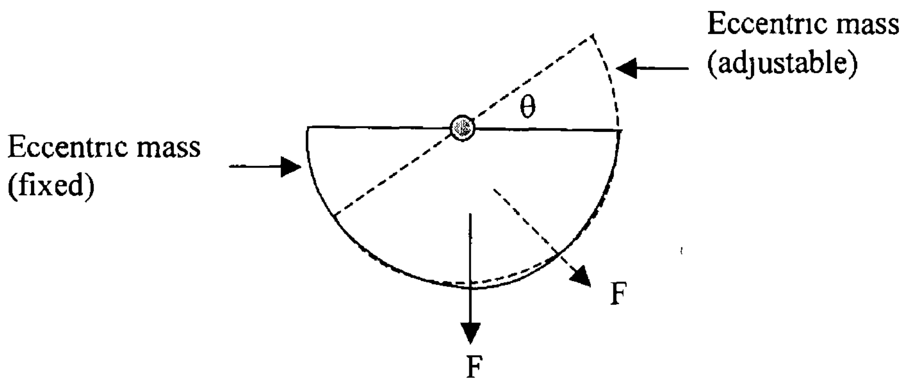


Figure 3 6 Sketch of fixed and adjustable eccentric masses

Note F = eccentric force produced by one eccentric mass

Therefore, the eccentric force will vary with the angle, which could be calculated by the following equation

$$Ft = F \times \sqrt{2 \times (1 + \cos\theta)} \qquad \text{(Equation 3 3)}$$

where

Ft = total eccentric force produced by the fixed and the adjustable eccentric masses

F = eccentric force produced by one eccentric mass

θ = the angle between the fixed eccentric mass and the adjustable one

According to the calculation of equation 3.3, the produced eccentric force at angles of 0°, 83°, 120°, 150°, 173°, and 180° were 100%, 75%, 50%, 25%, 6.25% and 0% of full eccentric force respectively.

3) Selection of motor

Several factors will decide the motor selected, which will be discussed as follows.

a) Weight and size: The size should be as small as possible, and the weight as light as possible

b) Rotating speed: the highest vibration frequency is about 200 Hz, which correspondences to the rotating speed capacity of motor up to 12,000 RPM

c) Stall torque: the motor should be able to drive the eccentric mass to the required rotating speed at the start of operation during a specific period (e.g. 2 seconds). Thus the stall torque should exceed the peak torque required at the start of operation. The maximal torque during the start phase could be calculated by (88):

$$M = J \times \frac{\Delta n}{\Delta t} \times \frac{\pi}{30} \qquad \text{(Equation 3.4)}$$

Where

M = maximal torque during operation, in Nm

Δn = rotating speed change in RPM (from 0 to 12,000 RPM)

Δt = duration for speed change from 0 to 12000 RPM in second (the value of 2 seconds was used for estimation)

J = moment inertia of eccentric mass in kgm^2, calculated by

$$J = \frac{1}{2} \times m \times R^2 \qquad \text{(Equation 3 5)}$$

where

m = eccentric mass in kg (the maximal possible eccentric mass of 100 g was used for estimation calculation)

R = radius of eccentric mass in meter (2 cm was used for calculation)

According to the calculation of Equation 3 4 and Equation 3 5, the maximal torque was 12 6 mNm

d) Maximal power capacity the maximal power that may be required by operation was calculated by (88)

$$P = (M + M_f) \times n \times \frac{\pi}{30} \qquad \text{(Equation 3 6)}$$

where

P = maximal power in W

M = maximal torque to start the eccentric mass to 12, 000 RPM, in Nm

M_f = friction torque of motor in Nm (10 mNm was used for estimation)

n = maximal speed in RPM (12,000RPM)

Using the values of M calculated above, the maximal power was 28 W as calculated from equation-3 6

e) Eccentric load capacity the load of eccentric force during operation has to be taken by the ball bearing and shaft of the motor The maximal eccentric load that may be loaded on the ball bearing was calculated by

$$F = m \times \omega^2 \times e \qquad \text{(Equation 3 7)}$$

where

F = maximal eccentric load during operation in N

m = maximal eccentric mass on one side of shaft, in kg (50 g was used for estimation)

ω = maximal frequency, in rad/s (200Hz was used for estimation)

e = eccentric radius, in meter (0 8 mm was used for estimation)

The calculation by equation-3 7 gave the result of maximal eccentric load of 63N

f) Control of the rotating speed control of the vibration frequency was realized by control of the motor rotating speed The speed should be easily changed and set to a specific value because in the later test of the vibrator, several vibration frequencies may be tested in turn in a short period of time on human subjects In addition, the motor speed should be maintained accurately at the preset value during operation

The brushless DC motor was selected because of its long-life, high power and broad speed range characteristics The speed control is also favourable in this kind of motors because these motors often incorporate either internal or external position sensors to sense the actual rotor position

Several motors from two different companies were selected and compared as to the requirements stated above (table 3 3) It can be seen that all five motors could satisfy the requirement of maximal torque, power and speed Motor 1 and 5 have the smallest size and the lightest weight However, only motor 3 and 4 had the shaft radial load capacity that is greater than the maximal eccentric load requirement Motor 4 was selected because it is smaller and lighter compared with motor 3, and it also has greater shaft radial load capacity

Table 3 3 Comparison of motor parameters

Motor	Company	Diameter (mm)	Length (mm)	Weight (g)	Power (W)	No-load speed (RPM)	Stall torque (mNm)	Shaft radial load (N)
1	Maxon	22	62 7	120	50	27000	332	16
2	Maxon	32	60	263	80	13100	420	28
3	Maxon	40	70	390	120	12300	1353	70
4	Minimotor	35	64	310	100	12200	401	108
5	Minimotor	24	44	100	37	23000	115	30

4) Power supply and control of the motor

The motor performance including its speed and hence the vibration frequency was controlled by a motion controller (MCBL 2805, Faulhaber, Germany). A DC power supply unit (3gen, 400 W, Excelsys, Ireland) was used to provide 24 V power supply to the motion controller and the motor The motion controller was connected by RS-

232 cable to a computer on which a controlling program (Faulber Motion Manager, Faulber, Germany) was run The change of motor speed (vibration frequency) is simple by using this controlling program

5) Housing for motor

A hollow cylinder housing made of plastic was fixed external to the motor by two rings to protect the human body from the motor-eccentric mass construct The outer diameter of the housing was 50 mm, with a wall thickness of 2 5 mm Two plastic caps were made to conceal both ends of the housing The total length of the housing with the caps was 118 mm A slot [6 0 mm (width) × 33 mm (length)] was made on the end of the housing for two purposes firstly, to dissipate the heat of motor during its operation, secondly, to facilitate the change of eccentric mass during test

6) Strap of the vibrator

A strap made of elastic band was used to attach the vibrator to the muscle

The size of the vibrator is Φ50 mm (diameter) × 118 mm (length), and the weight 430 g Figure 3 7 illustrates the design features described above together with ancillary components for construction of the vibrator unit The detailed drawings of the vibrator parts were presented in appendix B

3.3 Validation of the vibrator design

With the vibrator successfully built it was necessary to run the device in order to verify that it can produce the vibration amplitudes and frequencies that are required It is also necessary to test whether this vibrator is able to operate stably when it is used in different operation conditions during vibration training All these were tested in the following two studies [study 1 (chapter 5) and study 2 (chapter 6)]

3 4 Discussion

The size and weight of the vibrator was influenced by the motor size that was chosen In the present design, the lightest motor that satisfies our requirement of maximal rotating speed, power and torque was not chosen because of the shaft eccentric load (see table 3 3) It is possible to optimise the present design by incorporating a small bearing outside of the motor that could still be housed in the vibrator This bearing will absorb the most of the eccentric load produced by eccentric mass rotating, and therefore smaller size motor could be used for vibrator

3 5 Conclusion

A portable muscle-tendon vibrator for vibration training was developed The unit developed makes use of a rotating eccentric mass system to produce a desired amplitude and frequency range capable of investigating the influence of different amplitudes and frequencies on vibration training effect The vibrator can be strapped to muscle tendon during various strength training exercises

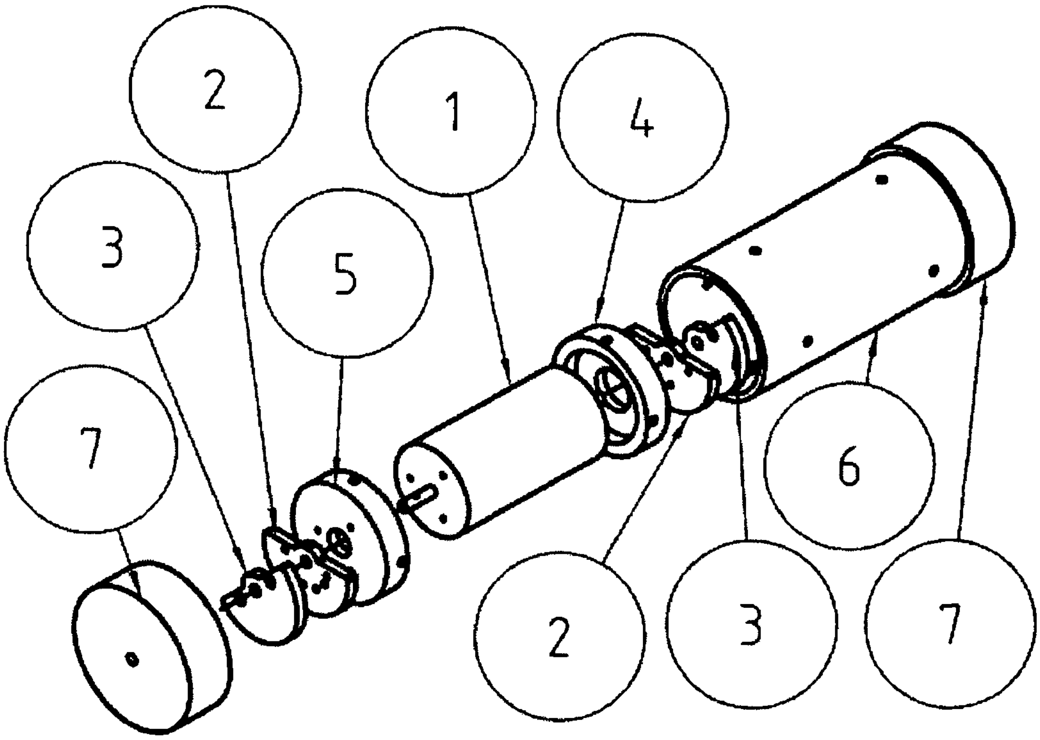


Figure 3 7 Exploded view of vibrator parts (1=motor, 2 and 3=eccentric mass, 4 and 5=ring for fixation of housing to motor, 6=housing for motor, 7=cap for housing)

Chapter 4

Generic methods

4 1 Introductıon

A senes expenments are undertaken ın the present study to examıne the acute effect of vıbratıon traınıng on neuromuscular performance The common methods employed ın these expenments are detaıled below Each methods sectıon for the vanous experıments (Chapters 5, 6, 7, 8, 9, 10) wıll refer to thıs chapter to avoıd unnecessary repetıtıon Not all of the expenments employed all of the methods detaıled below

4 2 Subjects

Dublın Cıty Unıversıty's ethıcs commıttee approved all expenments Subjects were ın general good health and free from neuromuscular dısease and ınjury Before partıcıpatıon subjects completed a health questıonnaıre (Appendıx C) and provıded ınformed consent (Appendıx D) Subjects were not allowed to undertake any strength traınıng exercıse durıng the expenment penod

4 3 Measurement of mechanıcal and EMG sıgnals

4 3 1 Vıbratıon acceleratıon measurement

Vibration acceleration was measured both on the vibrator and muscle. An accelerometer (one-axis, measuring range ±25g, Vernier Software & Technology, USA) was attached with double-sided sticky tape to a flat surface built on the vibrator housing. The accelerometer measured vibration acceleration on the vibrator itself. A second accelerometer (three axis, measuring range ±5g, Vernier Software & Technology, USA) was attached by double-sided sticky tape to the muscle belly of the biceps about 10 cm from the center of the vibrator. This accelerometer was used to measure the vibration acceleration on the muscle. The size of both accelerometers was 26×26×20 mm, and the weight was 16g. Five seconds of vibration acceleration was captured (250 Hz) by computer via an interface (Vernier LabPro®, Vernier Software & Technology, USA).

4.3.2 Joint angle measurement

Joint angle was measured in study 4, 5 and 6 by an electro-goniometer (XM110, Biometrics, UK). The output of the goniometer was connected via an amplifier (DataLink, Biometrics, UK) and sampled at a frequency of 50 Hz.

4.3.3 Electromyography measurement

Electromyography (EMG) was measured on the bicep brachii, tricep brachii and quadriceps (rectus femoris, vastus lateralis, and vastus medialis). The EMG electrode on the bicep brachii was placed at $1/3^{rd}$ of the distance along a line connecting the tendon of the bicep brachii muscle in the cubital fossa to the acromion process (63). The EMG electrode on the tricep brachii was placed at $1/3^{rd}$ of the distance along a lıne connectıng from the olecranon to the acromıon (63) The EMG electrode on the rectus femorıs was placed at half of the dıstance along a lıne connectıng the anterıor superıor spına ılıaca to the superıor patella (64) The EMG electrode on the vastus lateralıs was placed at 2/3rd of the dıstance along a lıne connectıng the anterıor superıor spına ılıaca to the lateral border of the patella (64) The EMG electrode on vastus medıahs was placed at 4/5th of the dıstance along a lıne connectıng the anterıor superıor spına ılıaca and the joınt space ın front of the anterıor border of the medıal lıgament (64) A pen mark was used effectıvely to relocate the EMG electrodes when EMG was measured on dıfferent days The skın was abraded and cleaned, and a bıpolar electrode (AE-131, NeuroDyne Medıcal, USA), wıth a centre-to-centre dıstance of 2cm, was attached to the muscle The resıstance between the electrodes was measured to ensure ıt was less than 5 kΩ (65) The EMG sıgnals were connected to the dıfferentıal amplıfier (bandwıdth = 10~1000 Hz, ınput ımpedance = 100 MΩ, Common Mode Rejectıon Ratıo >75 dB from DC to 100 Hz) of a Powerlab 4/20T unıt (Powerlab®, ADInstruments, USA) The samplıng frequency for the EMG sıgnal was set at 1000 Hz The raw EMG sıgnal was converted on-lıne to a root-mean-squared value of EMG (EMGrms data) by Powerlab (averagıng constant 50ms), and both the raw EMG data and the EMGrms data were stored for later analysıs

4 4 Analysıs of measured mechanıcal and EMG data

4 4 1 Vıbratıon acceleratıon data

From the measured vibration acceleration data, the following parameters were calculated 1) vibration amplitude (both on the vibrator and the muscle) , 2) vibration peak frequency (both on the vibrator and the muscle), 3) transmissibility of vibration amplitude and peak frequency from vibrator to muscle

An example of the vibration acceleration measured on the vibrator (study 1) is shown in figure 4 1 The motor speed was set at 3900 RPM It can be seen that the acceleration signal consisted of several periodic components FFT analysis (1024 points) performed on the acceleration signal showed that the main component of the vibration centred around 65 Hz The frequency at which the peak acceleration component was present is termed peak frequency in this study It was found that the acceleration component at peak frequency accounted for more than 95% of the whole vibration acceleration measured Thus, the vibration amplitude was calculated by using the following formula

$$Amp = \frac{Acc}{(2 \times \pi \times Freq)^2} \qquad \text{(Equation 4 1)}$$

where $Acc =$ acceleration component at peak frequency (m/s^2)

$Amp =$ displacement amplitude (m)

$Freq =$ peak frequency (Hz)

Transmissibility of vibration amplitude and frequency was calculated as

$$Transmissibility\_amplitude = \frac{Amp_{muscle}}{Amp_{vibrator}} \times 100 \qquad \text{(Equation 4 2)}$$

$$Transmissibility\_frequency = \frac{Freq_{muscle}}{Freq_{vibrator}} \times 100 \qquad \text{(Equation 4 3)}$$

where $Amp_{muscle} =$ vibration amplitude on muscle(m)

$Amp_{vibrator} =$ vibration amplitude on vibrator (m)

$Freq_{muscle}$ = peak frequency on muscle (Hz)

$Freq_{vibrator}$ = peak frequency on vibrator (Hz)

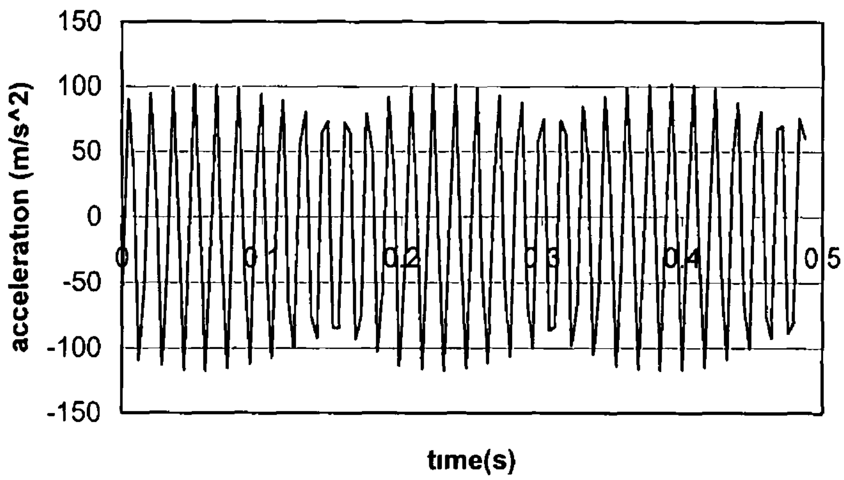


Figure 4 1 Example of measured vibration acceleration (motor speed 3900RPM)

4 4 2 Joint angle data

In study 4, 5 and 6, the joint angle data were used for the calculation of angular velocity, acceleration, moment and power for the bicep curl (study 5 and 6) and knee extension (study 5) by the following method

Firstly, the joint angle data were filtered by a windowed-sinc filter (66), which has a much better stopband attenuation than the butterworth filter (66) The residual method (67) was used to determine the optimal cut-off frequency for filtering of joint angle data, and the optimal cut-off frequency was found to be 2 Hz

Secondly, the angular velocity data were calculated as (67)

$$\omega(i) = \frac{\theta(i+1) - \theta(i-1)}{2 \times \Delta t} \qquad \text{(Equation 4 4)}$$

where $\omega(i)$ is the angular velocity at data point i, and $\theta(i+1)$ and $\theta(i-1)$ are the filtered angle values at data points $(i+1)$ and $(i-1)$, respectively Δt is the sampling interval

The angular acceleration data was calculated as

$$\alpha(i) = \frac{\varpi(i+1) - \varpi(i-1)}{2 \times \Delta t} \qquad \text{(Equation 4 5)}$$

where $\alpha(i)$ is the angular acceleration at data point i, and $\omega(i+1)$ and $\omega(i-1)$ are the filtered angle values at data points $(i+1)$ and $(i-1)$, respectively

Thirdly, the concentric phase of the joint angle data was determined as the time from when the joint angular velocity changed from negative to positive to the time at which the elbow joint angular velocity changed to negative again

Fourthly, the angular moment and power data in the concentric phase were calculated by the following different methods for bicep curl and ballistic knee extension, respectively

1) Calculation method for bicep curl (68)

Elbow flexion moment in the concentric phase was calculated as

$$M_{elbow} = M_{grav} + M_{inertia} \qquad \text{(Equation 4 6)}$$

where M_{grav} is the muscle moment produced to oppose the gravitational forces acting on the forearm, hand and dumbbell and was calculated as

$$M_{grav} = (m_f \times 9.81 \times r_f + m_d \times 9.81 \times r_d) \times \cos\Phi \qquad \text{(Equation 4.7)}$$

where m_f (kg) is the mass of the forearm and hand, r_f (m) is the distance from the elbow joint center to the center of mass of the forearm and hand, m_d (kg) is the mass of the dumbbell, r_d (m) is the distance from the elbow joint center to the center of mass of the dumbbell, and Φ (radius) is the angle of the forearm relative to the horizontal. The mass m_f is estimated as $m_f = 0.022 \times$ body mass (67), r_f is estimated by $0.682 \times l_f$ (67), where l_f is the length of the forearm and hand, and is measured as the distance from elbow axis to the ulnar styloid. r_d is measured as the distance from the elbow axis to the center of the dumbbell. $M_{inertia}$ is the muscle moment produced to accelerate or decelerate the forearm and the dumbbell and was calculated as

$$M_{inertia} = (I_f + I_d) \times \alpha \qquad \text{(Equation 4.8)}$$

where α is the angular acceleration at the elbow joint (rad/s^2), I_f is the moment of inertia of the forearm and hand, and I_d is the moment of inertia of the dumbbell. I_f is calculated as $I_f = m_f \times \rho^2$, with the mass m_f estimated as detailed above and the radius of gyration, ρ, estimated as $\rho = 0.827 \times l_f$ (67). I_d was calculated as $I_d = m_d \times r_d^{\,2}$, with the m_d and the r_d calculated as detailed above.

Muscle power (P_{elbow}) is calculated as

$$P_{elbow} = M_{elbow} \times \omega \qquad \text{(Equation 4.9)}$$

where ω is the angular velocity, and M_{elbow} is the muscle moment, which was calculated as detailed above.

2) Calculation method for knee extension (69)

Knee extension moment in the concentric phase was calculated as

$$M_{knee} = M_{grav} + M_{inertia} \quad \text{(Equation 4 10)}$$

where M_{grav} was the muscle moment produced to oppose the gravitational forces acting on the shank, foot and the weight and was calculated as

$$M_{grav} = m \times 9\ 81 \times r \times \sin\Phi + m_w \times 9\ 81 \times r_w \times \sin\Phi \quad \text{(Equation 4 11)}$$

where m (kg) is the mass of the shank and foot, r (m) is the distance from the knee joint angle axis to the center of mass of shank and foot, and Φ (radius) is the angle of the lower leg relative to the vertical plane, m_w (kg) is the mass of the weight, r_w (m) is the distance from the knee joint angle axis to the center of mass of the weight The mass m is estimated as $m = 0\ 061 \times \text{body mass}$ (67), r is estimated by $0\ 606 \times l_{shank}$ where l_{shank} is the length of the shank l_{shank} is measured as the distance between the lateral malleolus and the lateral femoral epicondyle r_w is measured as the distance from the center of knee joint to the point where the weight contact the shank $M_{inertia}$ is the muscle moment produced to accelerate or decelerate the lower limb and the weight and is calculated as

$$M_{inertia} = (I_s + I_w) \times \alpha \quad \text{(Equation 4 12)}$$

Where α (rad/s^2) is the angular acceleration of the knee joint, I_s (kg m^2) is the moment of inertia of the shank and foot and I_w (kg m^2) the moment of inertia of the weight I_s is calculated as $I_s = m \times \rho^2$ with the mass m estimated as detailed above and the radius of gyration ρ estimated as $\rho = 0\ 735 \times l_{shank}$ (67) I_w is calculated as $I_w = m_w \times r_w{}^2$ with the m_w and r_w detailed above

Muscle power (P_{knee}) was calculated as

$$P_{knee} = M_{knee} \times \omega \quad \text{(Equation 4 13)}$$

where ω is the angular velocity and M_{knee} is the muscle moment, which are calculated as detailed above

4 4 3 EMG data (EMGrms data and raw EMG data)

Two methods were used in the present study to analyse the EMGrms data In the first method, the voltage values of the EMGrms data were used (study 1, 2, 3 and 6) In the second method, the EMGrms data were normalized to the EMGrms data measured in a maximal voluntary contraction (study 4 and 5)

In study 4, 5 and 6, power spectrum analysis was performed on the raw EMG data of concentric phase using discrete Fourier transform method (512 points, Hamming window) The mean power frequency of EMG (EMGmpf) was calculated according to the method by Nakazawa et al (70)

$$EMG_{mpf} = \frac{\sum_{f=0}^{400} f \times P(f)}{\sum_{f=0}^{400} P(f)} \qquad \text{(Equation 4 14)}$$

where f was the frequency of EMG power spectrum, $P(f)$ the power density at frequency f

Chapter 5

Study 1: **Mechanical characteristics of muscle-tendon vibrator and EMG response to vibration of different amplitudes**

5.1 Introduction

Given that the vibration load experienced by the target muscle is dependent upon the vibration amplitude and frequency that reaches the muscle, it would seem reasonable to assume that the amplitude of the vibration load may influence the magnitude of the neuromuscular response to vibration training. A comparison of two studies by Torvinen et al. (7,12) that differ in the magnitude of vibration amplitude employed (1mm vs. 4 mm) indicates that an amplitude of 4 mm whole body vibration could induce a significant enhancement of muscle performance, while the amplitude of 1 mm could not. Unfortunately, to date no studies appear to have directly examined the influence of vibration amplitude on neuromuscular response to vibration training.

In order to directly examine the influence of vibration amplitude and have confidence in the application of the results to different training conditions, the day to day repeatability of the amplitude and frequency of the vibration signal on both the vibration device and the targeted muscle needs to be demonstrated. Similarly the repeatability of the neuromuscular response of the targeted muscle needs to be established. However, various operating conditions may influence the vibration load produced by the vibrator and subsequently imposed on the muscle, as well as influencing the neuromuscular response it elicits. Practical experience indicates that important operational conditions may include the eccentric mass of the vibration device, the joint angle employed and the force at which the vibrator is strapped to the muscle In addition, the vibration load produced by the vibration device may be attenuated by soft tissue as it travels through the body to the target muscle (22,59)

The combined effect of these operational conditions on the magnitude of the vibration load and the neuromuscular response it elicits do not appear to have been examined previously

Therefore the aims of the present study are

1) To examine the effect of different operational conditions on the vibration output characteristics (amplitude, frequency) of the vibrator

2) To determine the effect of different operational conditions on the transmissibility of the vibration amplitude and frequency from the vibrator to the target muscle

3) To examine the electromyography (EMG) response of muscle to vibration training under different operational conditions

The operational conditions examined are eccentric mass, test day, joint angle and strapping force

5 2 Method

Only key aspects of the methods are presented below A more detailed account of the methods is presented in the generic methods section (chapter 4)

5 2 1 Subjects

Eight healthy adult male volunteers took part in this study The average age, mass and height of the subjects were 31 8±7 4 (years), 74±6 4 (kg), and 174 9±4 2 (cm) respectively

5 2 2 Experiment design

One motor rotating speed (3900RPM), which corresponded to a vibration frequency of 65 Hz, was selected for use in this study This speed was the middle speed of the three motor speeds that would be tested in study 2 (see chapter 6) Two eccentric mass sizes (ems-I and ems-II) that were selected for the vibration amplitudes to be produced were tested in this study For ems-I, one aluminium eccentric mass and one plastic eccentric mass were mounted on each side of the motor shaft, with no relative angle between them The total eccentric mass weight was 23 g, which produced a vibration amplitude of 0 5 mm at 65 Hz (Equation 3 1 and 3 2, section 3 2 2) For ems-II, one aluminium and one copper eccentric mass were similarly mounted on each side of the motor shaft The relative angle between them was 60°, giving a total effective eccentric mass weight of 59 g This produced a vibration amplitude of 1 2 mm at 65 Hz (Equation 3 1 and 3 2, section 3 2 3)

During the experiment, the subject sat on a preacher curl bench, and placed both arms over a chest/arm support pad, while leaning forward so that their chest was firmly pressed against the support pad The subject was asked to hold a 2 kg dumbbell for 20 seconds using their dominant arm while maintaining the elbow joint straight (180°) or at an angle of 120° The vibrator was strapped to the biceps muscle tendon Figure 4 1 illustrates the vibrator attached to a test subject

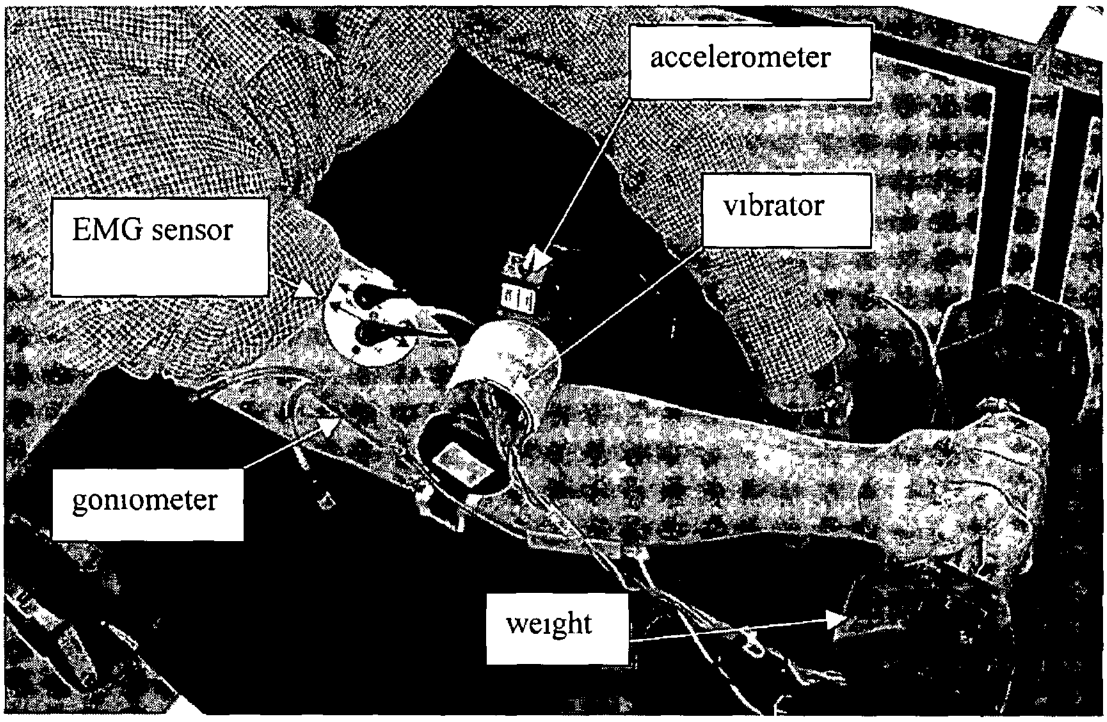


Figure 5 1 Experiment set-up

Thus, there were eight test conditions taking account of two eccentric mass (ems-I and ems-II), two joint angle (180° and 120°) and two vibration conditions (vibration and no vibration) as shown in table 4 1 The eight experimental conditions were applied to each subject in random order The above test conditions were applied during a single day for each subject and were repeated on two further occasions to examine the day-to-day repeatability of the vibration characteristics and the EMG response of the biceps to the training There was always at least two days rest in between test days

The same test was repeated on a fourth occasion for seven of the eight subjects in order to examine the effect of the compression force by which the vibrator is strapped to the muscle (see figure 5 2)

Table 5.1 Test conditions

Vibration				No vibration			
ems-I		ems-II		ems-I		ems-II	
180°	120°	180°	120°	180°	120°	180°	120°

Note ems-I= eccentric mass size I, ems-II= eccentric mass size II, 180°= elbow joint kept straight, 120°= elbow joint angle kept at 120°, * = the eight test conditions were tested and retested on three different days with a small strapping force and on a fourth day with a large strapping force

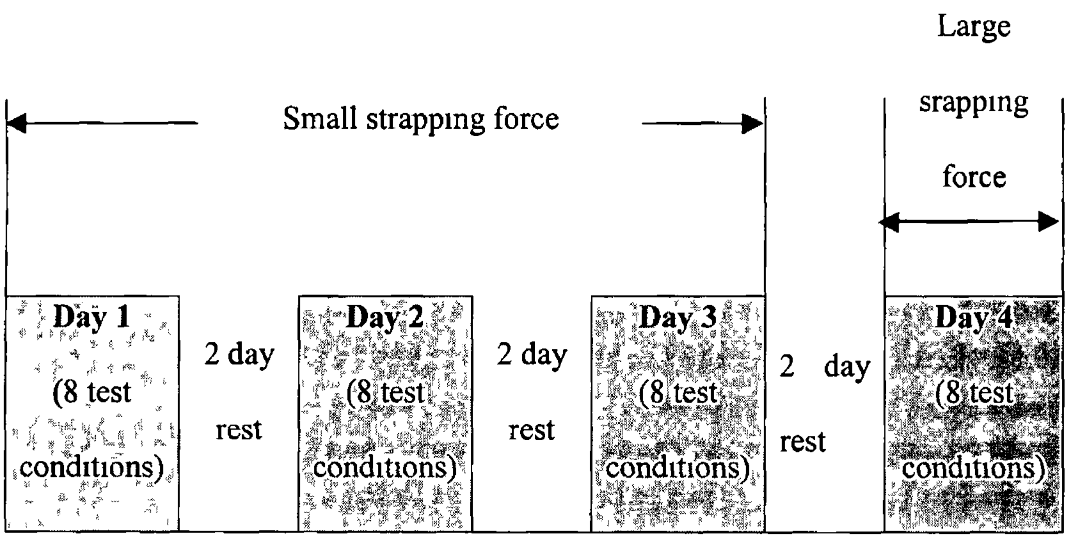


Figure 5 2 Study design

5 2 3 Measurements

Vibration acceleration on the vibrator and on the muscle (10 cm from the vibrator) were measured

The compression force that loads the vibrator to the muscle-tendon was measured using a load cell (Model 53, RDP Electronics Ltd, UK) This load cell was in the shape of a cylinder (diameter 31 75 mm, height 8 mm) with a raised button (diameter 8 13 mm, height 1 78 mm) An arc shaped adaptor was built to hold the force sensor onto the vibrator housing The bottom surface of the adaptor was fitted to the cylinder housing of the vibrator A hole on the top surface of the adaptor held the button of the force sensor The force sensor was thus anchored on the top of the vibrator, and was then strapped together with the vibrator to the biceps muscle tendon The output of the force sensor was connected to the computer via Musclelab (Musclelab®, Ergotest Technology, Norway) After the vibrator was strapped to the muscle tendon, the strapping force was measured and recorded Two magnitudes of strapping force (small, large) were used during the experiment During the three test and re-test days, the vibrator was strapped firmly (small strapping force) to the arm without any discomfort to the subject (the feedback of each subject was sought after the vibrator had been strapped to the arm) The average strapping force in this situation was 15 1 ± 2 3 N During the fourth test day, the strapping force was deliberately increased (large strapping force) until all subjects witnessed a feeling of mild discomfort The average strapping force in this situation was 18 2 ± 1 8 N

In order to evaluate the muscle response to different vibration amplitudes, EMG signal was measured on the bicep brachii for 20 seconds in each experiment condition

The joint angle was monitored by means of a goniometer (XM110, Biometrics, UK) and an amplifier (DataLink, Biometrics, UK) in order to locate the elbow joint angle at 180° (straight) or 120°

5 2 4 Data analysis

Vibration amplitude and frequency (both on the vibrator and the muscle) and the transmissibility of vibration amplitude and frequency were calculated from the measured vibration acceleration data (section 4 4 1) These are the mechanical variables in this study

The representative raw EMG data and the EMGrms data were shown in figure 5 3 The first 5-second segment of EMG signal was discarded in the calculation of average EMGrms to eliminate any transient effect(32) The EMGrms was averaged for the left 15 seconds as the EMG variable in this study

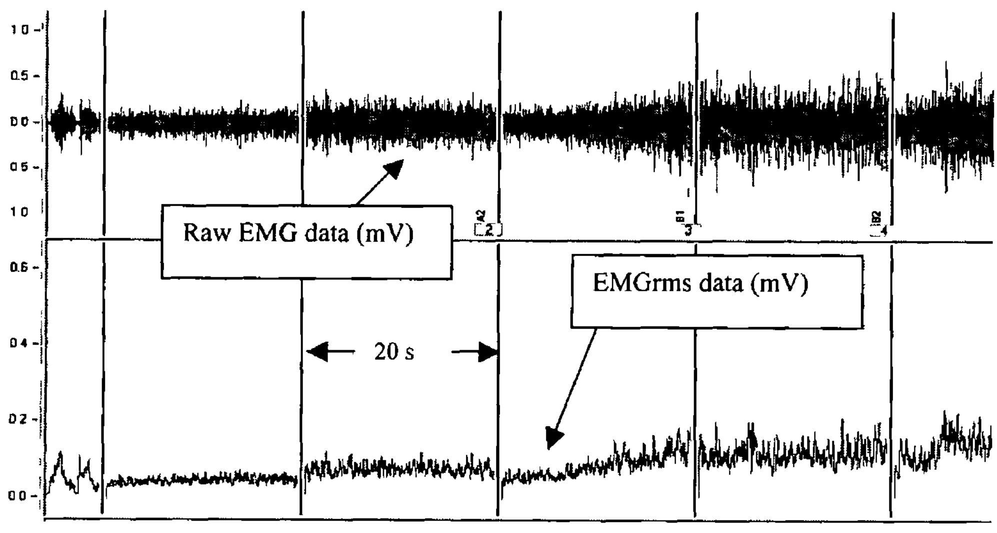


Figure 5.3 Representative raw EMG data and the EMGrms data

5 2 5 Statistical analysis

To determine the effect of test day, joint angle and eccentric mass on the vibration amplitude, frequency, transmissibility and EMG, 3 (test day) by 2 (joint angle) by 3 (eccentric mass) ANOVAs with repeated measures on the subjects were employed

To investigate the effect of strapping force, joint angle and eccentric mass on the vibration amplitude, frequency, transmissibility and EMG, 2 (strapping force) by 2 (joint angle) by 3 (eccentric mass) ANOVAs with repeated measures on the subjects were employed

EMG repeatability was also assessed by using intra-class correlation analysis (ICC)

For all analysis a probability value of $p<0.05$ was employed Where significant mean differences were observed, the main effects and simple effects were analysed with planned comparison with appropriate Bonferroni adjustment SPSS® was used for all statistical analyses

5 3 Results

5 3 1 Vibration amplitude and peak frequency measured on the vibrator

The results of vibration amplitude measured on the vibrator are shown in figure 5 4 Statistical analysis shows that the eccentric mass had a significant effect on vibration displacement ($p < 0.001$), with eccentric mass II (ems-II) producing a larger vıbratıon amplıtude (cırca 1 2 mm) than eccentrıc mass I (ems-I) (cırca 0 5 mm) These results were consıstent, wıth no effect of test day (p>0 05), or joınt angle (p>0 05)

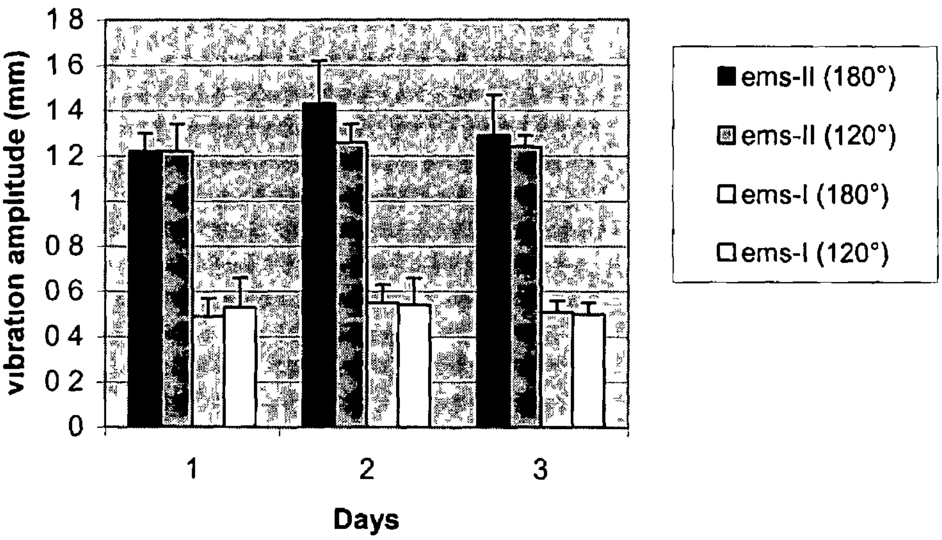


Fıgure 5 4 Vıbratıon amplıtude on the vıbrator (mean±S D)

The vıbratıon peak frequencıes on the vıbrator are shown ın figure 5 5 All the mean peak frequencıes were ın the range of 62 0 – 65 5 Hz Statıstıcal analysıs showed that the test day, eccentrıc mass and the joınt angle dıd not have a sıgnıficant effect on frequency (p>0 05)

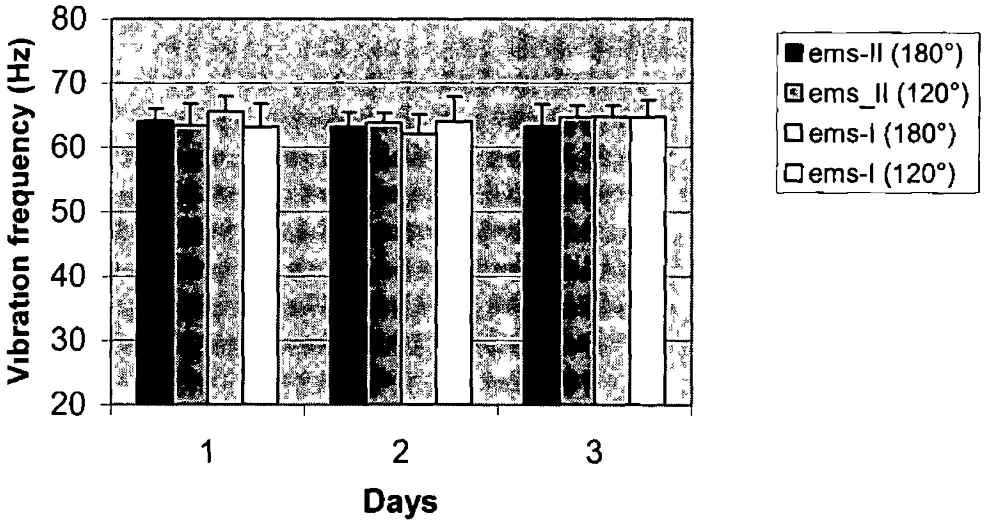


Figure 5 5 Vibration peak frequency on the vibrator (mean±S D)

5 3 2 Vibration amplitude and peak frequency measured on the muscle

The vibration amplitudes measured on the muscle are shown in figure 5 6 The larger eccentric mass (ems-II) induced significantly larger vibration amplitude on the muscle than the smaller eccentric mass (ems-I) (0 16 mm vs 0 08 mm, $p<0\ 05$) The test date and joint angle did not have significant effect on amplitude, indicating good repeatability

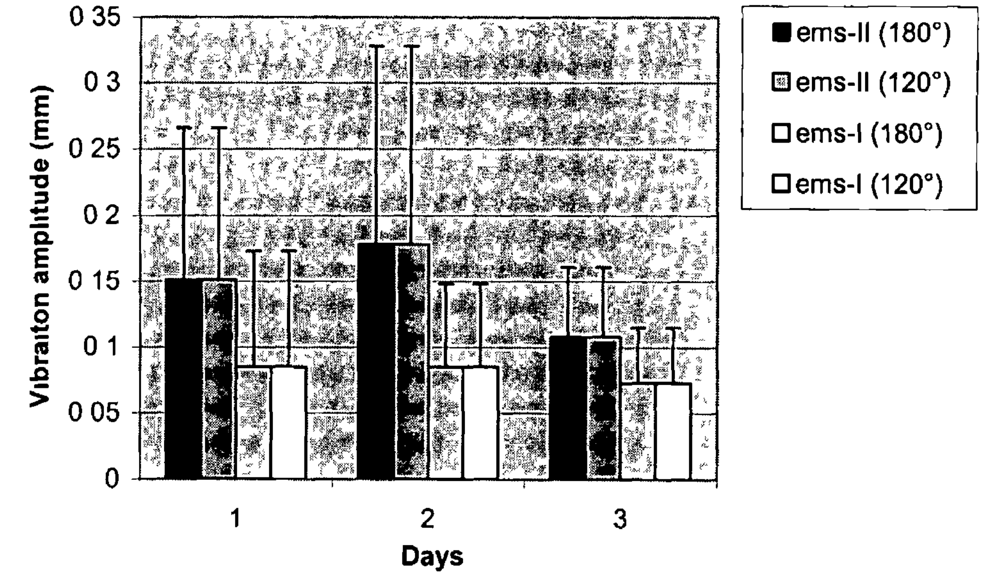


Figure 5.6 Vibration amplitude measured on the muscle (mean±S D)

The vibration peak frequencies on the muscle are shown in figure 5 7 The mean peak frequencies were in the range of 62 0 – 65 5 Hz Statistical analysis showed that the test day, eccentric mass and joint angle did not have significant effect on the peak frequency (p>0 05)

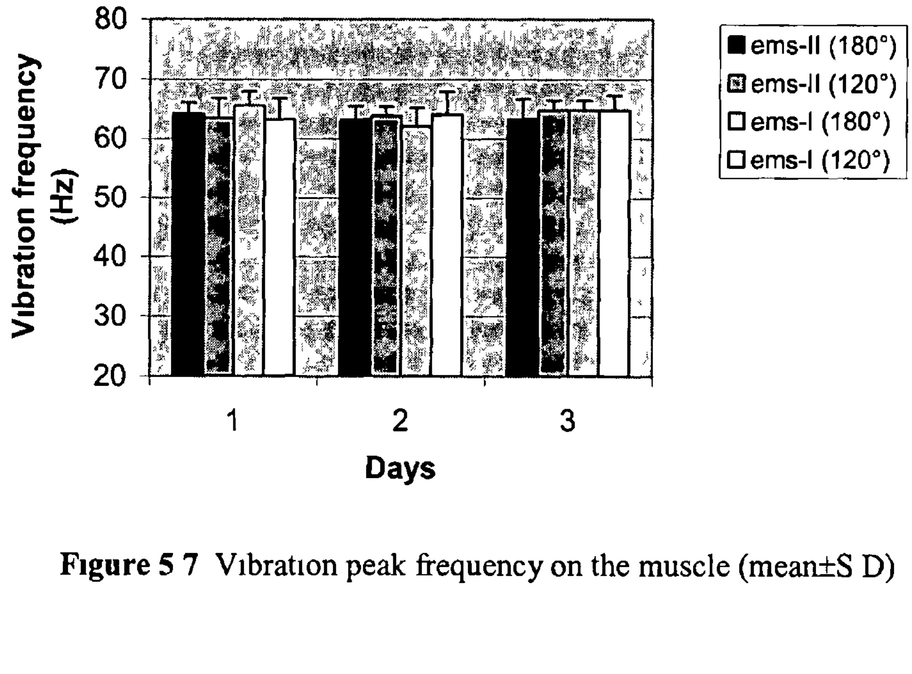


Figure 5 7 Vibration peak frequency on the muscle (mean±S D)

5 3 3 Transmissibility of vibration amplitude and peak frequency

The transmissibility of the vibration amplitude is shown in figure 5 8 On average, across all condition, transmissibility ranged from 8 4% to 17 4% Statistical analysis showed that with the small eccentric mass (ems-I) there was significantly greater transmissibility of vibration amplitude than with ems-II (15 6% vs 12 8%, $p<0$ 05) The test day and joint angle did not have a significant effect ($p>0$ 05) on the transmissibility of the vibration amplitude

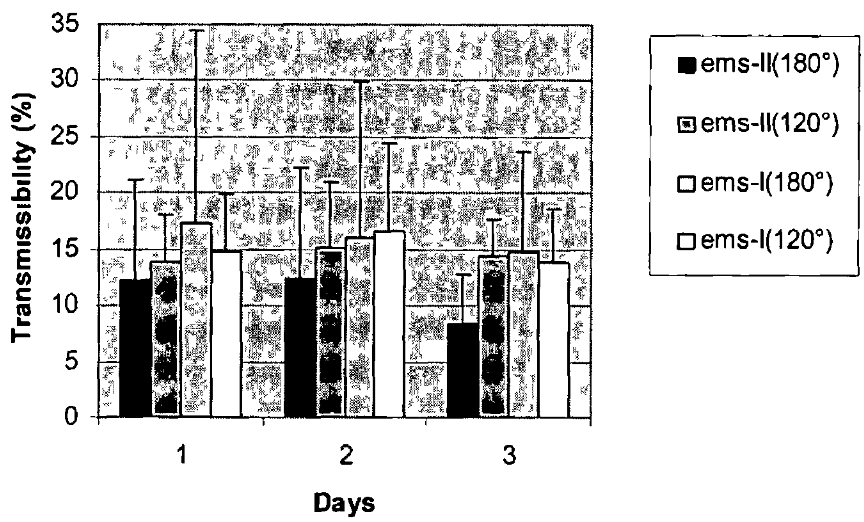


Figure 5.8 Transmissibility of the vibration amplitude (mean±S D)

The transmissibility of vibration peak frequencies is shown in figure 5 9 The transmissibility was 100% and was unaffected by test day, joint angle and eccentric mass ($p>0$ 05)

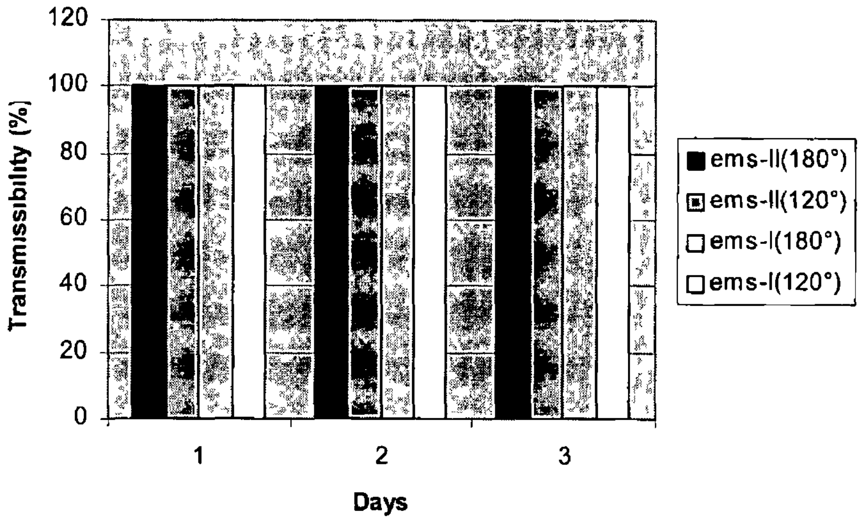


Figure 5 9 Transmissibility of the vibration peak frequency (mean±S D)

5 3 4 Influence of strapping force on vibration amplitude and peak frequency measured on the vibrator

The vibration amplitude and peak frequency measured on the vibrator under different strapping forces (large, small) are shown in table 5 2 Although the measured strapping force was significantly different (small=15 1±2 3 vs large=18 2±1 8 (N), p<0 01), strapping force did not have a significant effect on vibration amplitude and frequency (p>0 05) Eccentric mass had a significant effect on the vibration amplitude (p<0 05), but did not have significant effect on the vibration frequency (p>0 05) Joint angle did not have significant effect on the vibration amplitude and frequency (p>0 05)

Table 5 2 Influence of strappıng force on vıbratıon amplıtude and peak frequency on the vıbrator (mean(S D)

Eccentrıc mass sıze	Vıbratıon output	180°		120°	
		Large strappıng force	Small strappıng force	Large strappıng force	Small strappıng force
I	Amp (mm)	0 52(0 11)	0 52(0 04)	0 48(0 11)	0 53(0 06)
	Freq (Hz)	63 4(3 3)	63 9(1 9)	64 9(1 8)	63 8(2 5)
II	Amp (mm)	1 24(0 23)	1 31(0 09)	1 27(0 16)	1 23(0 04)
	Freq (Hz)	64 2(2 1)	62 6(1 3)	63 5(1 2)	64 1(1 6)

Note Amp=vıbratıon amplıtude, Freq= vıbratıon peak frequency, 180°= elbow joınt kept straıght, 120°= elbow joınt angle kept at 120°,

5 3 5 Influence of strappıng force on vıbratıon amplıtude and frequency measured on the muscle

The vıbratıon amplıtudes and frequencıes on the muscle under the dıfferent strappıng forces are shown ın table 5 3 Strappıng force had no sıgnıficant effect on the amplıtude or peak frequency (p>0 05) Eccentrıc mass had a sıgnıficant effect on the vıbratıon amplıtude (p<0 05), but dıd not have sıgnıficant effect on the vıbratıon frequency (p>0 05) Joınt angle dıd not have sıgnıficant effect on the vıbratıon amplıtude and frequency (p>0 05)

Table 5 3 Influence of strappıng force on vıbratıon amplıtude and peak frequency measured on the muscle (mean(S D)

Eccentrıc mass sıze	Vıbratıon output	180°		120°	
		Large strappıng force	Small strappıng force	Large strappıng force	Small strappıng force
I	Amp (mm)	0 14(0 09)	0 09(0 06)	0 08(0 03)	0 08(0 03)
	Freq (Hz)	63 4(3 3)	63 9(1 9)	64 9(1 8)	63 8(2 5)
II	Amp (mm)	0 23(0 14)	0 16(0 09)	0 20(0 08)	0 18(0 04)
	Freq (Hz)	64 2(2 1)	62 6(1 3)	63 5(1 2)	64 1(1 6)

5 3 6 Influence of strappıng force on transmıssıbılıty of vıbratıon amplıtude and peak frequency

The transmıssıbılıty of vıbratıon amplıtude and frequency to the muscle under dıfferent strappıng forces are shown ın table 5 4 Strappıng force had no sıgnıficant effect on the transmıssıbılıty of vıbratıon amplıtude ($p>0\ 05$) The transmıssıbılıty of the peak frequency was 100% and was not ınfluenced by strappıng force Eccentrıc mass had a sıgnıficant effect on the transmıssıbılıty of vıbratıon amplıtude ($p<0\ 05$), but dıd not have sıgnıficant effect on the transmıssıbılıty of vıbratıon frequency ($p>0\ 05$) Joınt angle dıd not have sıgnıficant effect on the transmıssıbılıty of both the vıbratıon amplıtude and the frequency ($p>0\ 05$)

Table 5 4 Influence of strapping force on the transmissibility (%) of vibration amplitude and peak frequency (mean(S D)

Eccentric mass size	Vibration output	180°		120°	
		Large strapping force	Small strapping force	Large strapping force	Small strapping force
I	Amplitude	24 8(13 6)	17 4(12 9)	16 5(7 2)	14 7(4 6)
	Frequency	100	100	100	100
II	Amplitude	18 1(12 3)	12 3(7 0)	16 3(6 5)	14 3(3 8)
	Frequency	100	100	100	100

5 3 7 EMG response to vibration

5 3 7 1 Reliability of EMG measurement

EMGrms results are shown in figures 5 10 and 5 11 The Inter-day reliability (ICC) of EMGrms measurement ranged from 0 76 to 0 90 Because the EMGrms with no vibration at each joint angle (180° or 120°) was measured twice in each day, the intra-day variability of EMGrms measurement with no vibration was also analysed and it ranged from 0 85 to 0 96

5 3 7 2 EMGrms change induced by vibration interventions

Statistical analysis showed that only eccentric mass had a significant effect on EMGrms value ($p < 0.001$). Main effects analysis showed that vibration with both eccentric masses induced significant increase of EMGrms from no vibration value ($p<0.05$), but vibration with the large eccentric mass (ems-II) induced a significantly higher increase in EMGrms than the smaller eccentric mass (ems-I) (0.053 mV vs 0.026 mV, $p<0.05$). These results were consistent, with no effect of test day or joint angle ($p>0.05$).

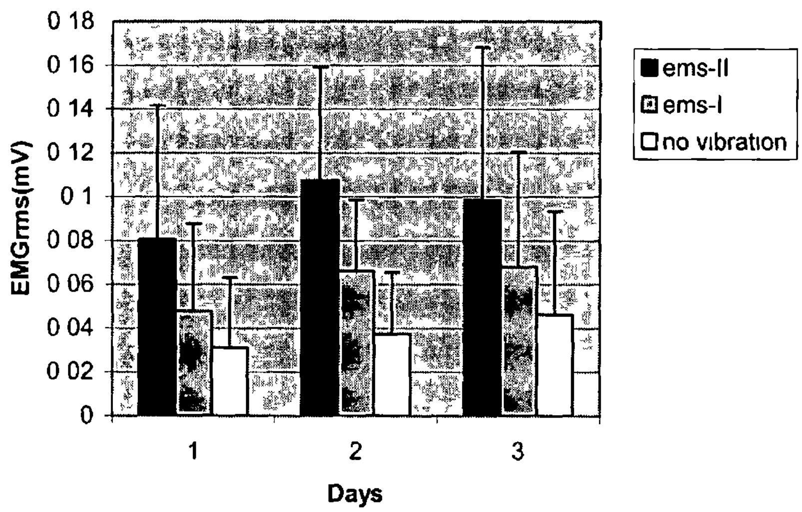


Figure 5.10 EMGrms measured with arm straight (mean±S.D)

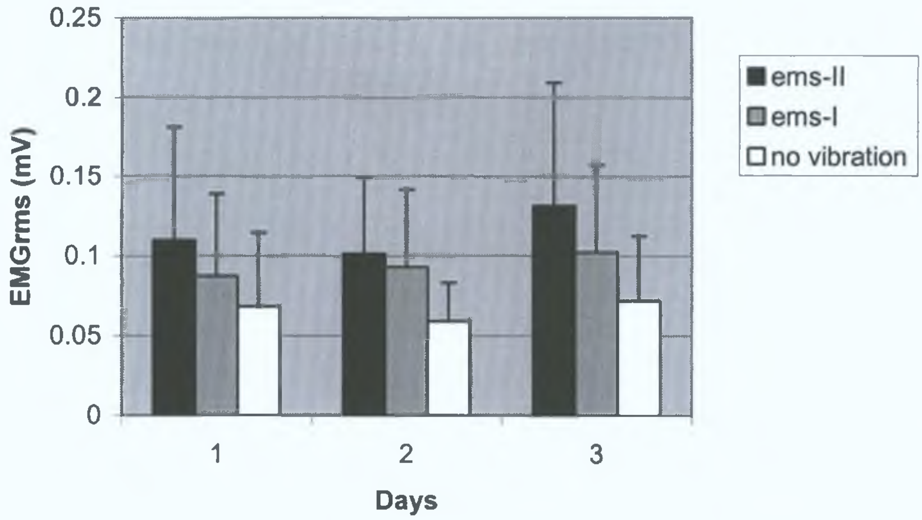


Figure 5.11 EMGrms measured with arm flexed at 120 degree (mean±S.D)

5.3.7.3 Influence of vibrator strapping force on EMGrms

The EMGrms response to vibration under different strapping forces are shown in table 5.5. Strapping force did not have significant effect on EMGrms values ($p>0.05$). Eccentric mass had a significant effect on EMGrms ($p<0.05$). Joint angle did not have significant effect on EMGrms ($p>0.05$).

Table 5.5 Influence of strapping force on EMGrms (mean(S.D)

Eccentric mass size	180°		120°	
	Large strapping force	Small strapping force	Large strapping force	Small strapping force
I	0.06(0.05)	0.06(0.04)	0.06(0.03)	0.08(0.03)
II	0.08(0.04)	0.09(0.06)	0.07(0.04)	0.10(0.05)

5 4 Discussion

It was shown by the results of this study that the two eccentric mass sizes (ems-I) and ems-II), and one motor rotating speed that were selected by calculation could produce the vibration characteristics required (vibration frequency of 0 5 and 1 2 mm, vibration frequency of 65 Hz) This demonstrated that the muscle-tendon vibrator was able to produce the different vibration amplitude and frequency as required in our vibration training studies

In addition, it was also found in this study that the vibration amplitude and frequency on the vibrator and the muscle are repeatable across days and this repeatability is unaffected by joint angle and strapping force Therefore, it may be suggested from these findings that the muscle-tendon vibrator could impose a consistent vibration load on the targeted muscle during vibration training under different operational conditions This is crucial for the later application of this vibrator in our vibration training studies

Although various vibration training apparatus have been used in vibration training studies to date (3,6,14,18,49), none of their repeatability during operation has been reported In addition, no study has examined the repeatability of the vibration load imposed on the target muscle during vibration training However, the investigation in this direction is needed, especially for the indirect method This may be due to that the repeatability of the vibration load on a muscle in indirect method may be influenced by both the vibration apparatus and the factors that could influence the vibration transmission These factors may include posture, muscle contraction performed and the contraction force (22), and they are highly variable during strength training exercises The influence of these factors may therefore induce the low repeatability of vibration load on a muscle, leading to the inconsistence in vibration training effect

However, in direct vibration, the repeatability of vibration load on muscle may be higher than the indirect method because it is mainly dependent on the repeatability of the apparatus itself, from which the vibration output is delivered directly to the muscle In addition, the direct vibration training apparatus to date are either held by hand (18) or fixed to a exterior support (14,49), which could facilitate the high repeatability of vibration load on the targeted muscle However, for the portable muscle tendon vibrator in this study, the repeatability of vibration load on a muscle need to be established because no exterior support is provided The results of the present study demonstrated that this muscle-tendon vibrator is able to impose repeatable vibration load on a muscle

Similarly the transmissibility is repeatable across test days, joint angle and strapping force These results provide the evidence that besides the point on the muscle where the amplitude and frequency were measured in this study, the vibration amplitude and frequency on other part of the targeted muscle may also be repeatable The results of transmissibility in this study also showed that the peak frequency of the vibration source could be delivered without change to the target muscle in direct vibration method This may facilitate the examination of the effect of vibration with high frequency in vibration training In indirect method, however, the high frequency vibration are normally attenuated during the transmission (22). In addition, this study found that the transmissibility of vibration amplitude was also related to the vibration amplitude of vibration source. This may be due to the non-linear mechanical property of the soft tissues during the transmission of vibration (22).

The results of this study showed that the EMGrms response to vibration was repeatable across days and this repeatability is not affected by joint angle and strapping force. This repeatability in EMG response may result from the repeatable vibration load (amplitude and frequency) that the muscle tendon vibrator imposed on the muscle. In addition, it was found in this study that the EMG activity of a sub-maximal contraction could be enhanced significantly by superimposed vibration, suggesting that the direct muscle vibration may have a facilitatory effect on neuromuscular performance of the sub-maximal isometric contractions. This is in line with several vibration training studies showing that the acute and chronic vibration training with sub-maximal contraction may induce more strength and power gain (3,7).

It was found in this study that the increase of EMGrms by vibration with large amplitude (1.2 mm) was significantly higher than that induced by small vibration amplitude (0.5 mm). This result demonstrated that acute vibration training effect on sub-maximal contraction could be enhanced by the increase in vibration amplitude. To date, there have been no acute or chronic vibration training studies that directly examined the influence of vibration amplitude on training effect. However, the comparison of the two studies by Torvinen et al. (7,12) that differed only in vibration amplitude indicated that larger vibration amplitude (4 mm) in whole body vibration training with sub-maximal contraction exercise could induce significant acute enhancement in strength and power, while the smaller amplitude (1 mm) in the same whole body vibration training could not induce this acute enhancement Our results in this study are line in with these findings However, although the above findings suggest that an increase in vibration amplitude may enhance the vibration training effect on neuromuscular performance, the optimal vibration amplitude in both direct and indirect vibration training still needs further investigations

Vibration applied to a muscle tendon could simulate the sense organs in the muscle, particularly the Ia afferent endings of muscle spindles, and produce a heavy sustained discharge of the Ia afferents, eliciting a tonic reflex contraction in the muscle being vibrated This phenomenon is called tonic vibration reflex (TVR) (30) It was suggested that TVR may be a possible mechanism for the vibration training effect, as more motor units could be recruited by TVR during the strength training (6,11) Current findings suggest that the recruitment of muscle spindle Ia afferents during vibration is related to the vibration amplitude (71) The microneurographic recording from single muscle afferents demonstrated that the increase of vibration amplitude could enhance the sensitivity of muscle spindle afferents to tendon vibration (71) In addition, the vibration amplitude appears to determine the amount of muscle spindle Ia afferents that will be recruited during vibration (72) It was observed in the study by Eklund et al (30) that a larger vibration amplitude (1 8 mm) was more efficient than a smaller amplitude (0 6 mm) in eliciting TVR Therefore, the increase of vibration amplitude may increase the vibration load on a muscle in vibration training by recruiting more muscle spindle Ia afferents, and subsequently activate more α-motoneurons

5.5 Conclusion

1. The different eccentric mass sizes (ems-I and ems-II) had a significant effect on the vibration amplitude measured on the vibrator ($p<0.05$), with the large eccentric mass size (ems-II) producing a greater amplitude than the smaller eccentric mass size (ems-I) (1.2 mm vs. 0.5 mm, $p<0.05$), but did not have significant effect on the vibration frequency measured on the vibrator ($p>0.05$). These effects were not significantly effected by the different joint angles (180° and 120°), test days and strapping forces (15.1 and 18.2 N).

2. The different eccentric mass sizes (ems-I and ems-II) had a significant effect on the vibration amplitude measured on the muscle ($p<0.05$), with the large eccentric mass size (ems-II) producing a greater amplitude than the smaller eccentric mass size (ems-I) (0.16 mm vs. 0.08 mm, $p<0.05$), but did not have significant effect on the vibration frequency measured on the vibrator ($p>0.05$). These effects were not significantly effected by the different joint angles (180° and 120°), test days and strapping forces (15.1 and 18.2 N).

3. The different eccentric mass sizes (ems-I and ems-II) had a significant effect on the transmissibility of vibration amplitude to the muscle ($p<0.05$), with the large eccentric mass size (ems-II) producing a smaller transmissibility than the smaller eccentric mass size (ems-I) (12.8% vs. 15.6%, $p<0.05$), but did not have significant effect on the transmissibility of frequency to the muscle ($p>0.05$). The different joint

angles (180° and 120°), test days and strappıng forces (15 1 and 18 2 N) dıd not have sıgnıficant effect on the transmıssıbılıty of amplıtude and frequency

4 Vıbratıon resulted ın a sıgnıficant ıncrease ($p<0.05$) ın EMGrms, wıth the larger eccentrıc mass sıze (ems-II) producıng greater ıncrease than the smaller eccentrıc mass sıze (ems-I) (0 053 mV vs 0 026 mV, $p<0.05$) These enhancement were not sıgnıficantly affected by test day, joınt angle or strappıng force, ındıcatıng the repeatabılıty of the results under varıous operatıonal condıtıons

Chapter 6

Study 2 **Mechanical characteristics of muscle-tendon vibrator and EMG response to vibration of different frequencies**

6 1 Introduction

Vibration frequency is a factor that may have influence on the vibration training effect (14,23) In order to study this influence, the muscle tendon vibrator developed in this study was designed to have the capacity to produce the vibration with different frequencies According to this design, the change of the frequency of the vibrator should be realized by the change of the motor rotating speed Therefore, different vibration frequency on the muscle could be achieved also by the change of the motor rotating speed However, the vibration frequency on a muscle is also influenced by its transmission from the vibration device through soft tissues High frequency vibration tends to be attenuated more than the low frequency vibration, and these attenuations were also related to the contraction status of the muscle (22) As the muscle-tendon vibrator developed in this study will be employed in vibration training studies with dynamic exercise It is therefore important to examine the influence of different muscle contraction status (e g different joint angles) on the vibration frequency on the muscle

Therefore, the aims of this study are

1) To examine the effect of motor rotating speed and joint angle on vibration amplitude and frequency both on the vibrator and on the muscle

2) To determine the effect of motor rotating speed and joint angle on the transmissibility of the vibration amplitude and frequency from the vibrator to the target muscle

3) To examine the electromyography (EMG) response of muscle to vibration training with different motor rotating speed and joint angle

6 2 Methods

Only key aspects of the methods are presented below A more detailed account of the methods is presented in the generic methods (chapter 4)

6 2 1 Subjects

Nine healthy adult male volunteers took part in this study The average age, mass and height of the subjects were 29 8±7 6 (years), 78 7±12 4 (kg), and 177 8±6 0 (cm), respectively

6 2 2 Experiment design

Three rotating speeds of motor (1800, 3900 and 6000 RPM) were selected to produce vibration with frequencies of 30, 65 and 100Hz, respectively The eccentric mass size (ems-II) that produced the greater response of muscle activity was used in this study

During the experiment, the subject sat on a preacher curl bench, and placed both arms over the chest/arm support pad while leaning forward so that their chest was firmly pressed against the support pad The subject was asked to hold a 2 kg dumbbell using their dominant arm while maintaining the elbow joint angle straight (180°) or at 120° The vibrator was strapped to the biceps muscle tendon (see figure 5 1 in chapter 5)

Thus, there were eight test conditions as described in table 6 1 The test conditions employing vibration took account of three motor speeds and two joint angles Measures for no vibration at both joint angles were also recorded The order of completion of the eight test conditions was randomised for subjects during the test

Table 6.1 Test conditions

Vibration						No vibration	
1800 RPM		3900 RPM		6000 RPM			
180°	120°	180°	120°	180°	120°	180°	120°

Note 180°= elbow joint kept straight, 120°= elbow joint angle kept at 120°

6 2 3 Measurement

Vibration accelerations on the vibrator and on the muscle (10 cm from the vibrator) were measured

In order to evaluate the biceps muscle response to different vibration amplitudes, EMG signal was measured on the bicep brachii for 20 seconds in each experiment condition

The joint angle was monitored by means of a goniometer (XM110, Biometrics, UK) and an amplifier (DataLink, Biometrics, UK) in order to locate the elbow joint angle at 180° (straight) or 120°

6 2 4 Data analysis

Vibration amplitude and frequency (both on the vibrator and the muscle) and the transmissibility of vibration amplitude and frequency were calculated from the measured vibration acceleration data

The first 5-second segment of EMG signal was discarded in the calculation of average EMGrms to eliminate any transient effect (32) The EMGrms was averaged for the next 15 seconds The increases of EMGrms from no vibration value (in mV) was calculated and used for analysis

6 2 5 Statistical analysis

A two factor ANOVA with repeated measures on the subjects was utilized [3 (rotating speed) × 2 (joint angle)] For all analysis a probability value of $p<0.05$ was employed Where significant mean differences were observed, main effects and simple effects were analysed using multiple comparison with appropriate Bonferroni adjustment SPSS® was used for all statistical analysis

6 3 Results

6 3 1 Vibration amplitude and peak frequency on the vibrator

Vibration amplitudes and peak frequencies of the vibrator at different motor speeds were shown in figure 6 1 to 6 2 Statistical analysis showed that motor speed had a significant effect on both the vibration frequency (p < 0 001) and vibration amplitude (p < 0 001) measured on the vibrator, with significant differences being evident between all three levels of motor rotating speed for both variables (p < 0 001) For vibration frequency the smaller the motor speed the smaller the frequency produced 1800RPM (30Hz) < 3900 RPM (65Hz) < 6000 RPM (100Hz)(p < 0 001) For vibration amplitude the smaller the motor speed the larger the amplitude produced 1800RPM (1 4mm) > 3900 RPM (1 2mm) > 6000 RPM (1 0mm)(p < 0 001) Joint angle had no significant effect on either vibration amplitude or frequency (p > 0 05)

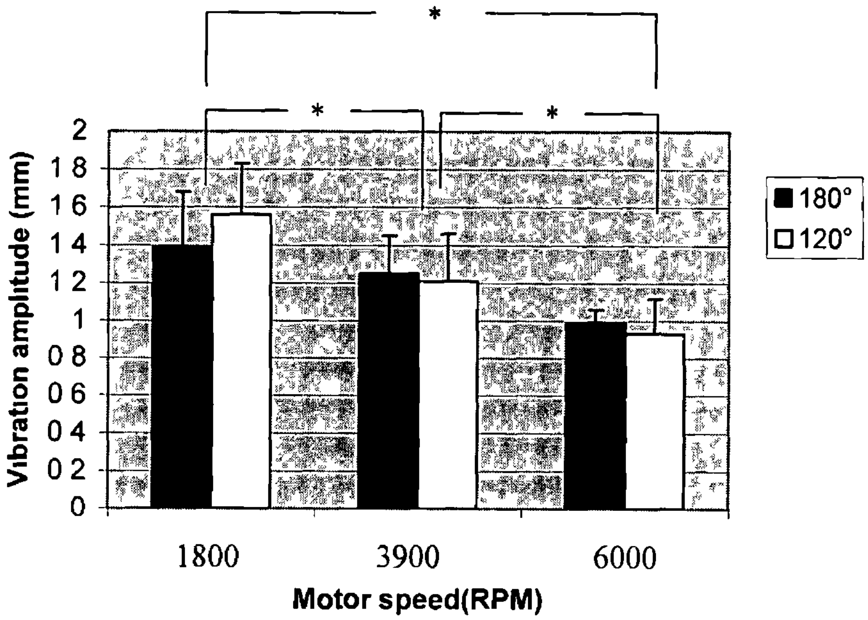


Figure 6 1 Vibration amplitude at different motor speed

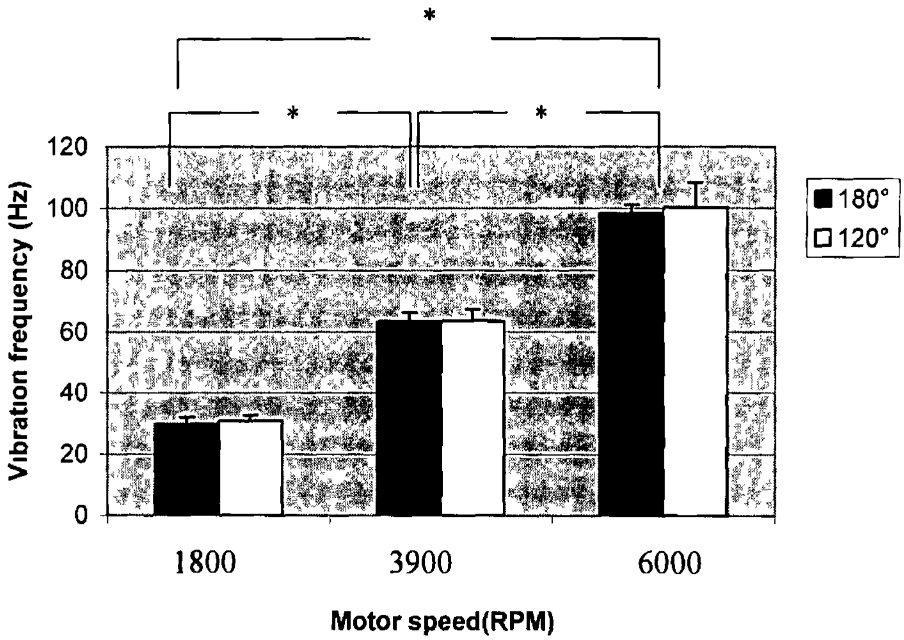


Fig 6 2 Vibration frequency at different motor speed

6 3 2 Vibration amplitude and peak frequency on the muscle

An identical pattern of results was found for the examination of vibration amplitude and frequency measured on the muscle as found on those measured on the vibrator While the frequency responses are the same the amplitudes are reduced

Vibration amplitude and frequency measured on muscle about 10 cm from vibrator are shown in figure 6 3 and 6 4 Statistical analysis showed that motor speed had a significant effect on both the vibration frequency ($p < 0\ 001$) and vibration amplitude ($p < 0\ 001$) measured on the muscle, with significant differences being evident between all three levels of motor rotating speed for both variables ($p < 0\ 001$) For vibration frequency the smaller the motor speed the smaller the frequency produced 1800RPM (30Hz) < 3900 RPM (65Hz) < 6000 RPM (100Hz)($p < 0\ 001$) For vibration amplitude the smaller the motor speed the larger the amplitude produced

1800RPM (1 0mm) > 3900 RPM (0 16mm) > 6000 RPM (0 04mm)(p < 0 001) Joint angle had no significant effect on either vibration amplitude or frequency (p > 0 05)

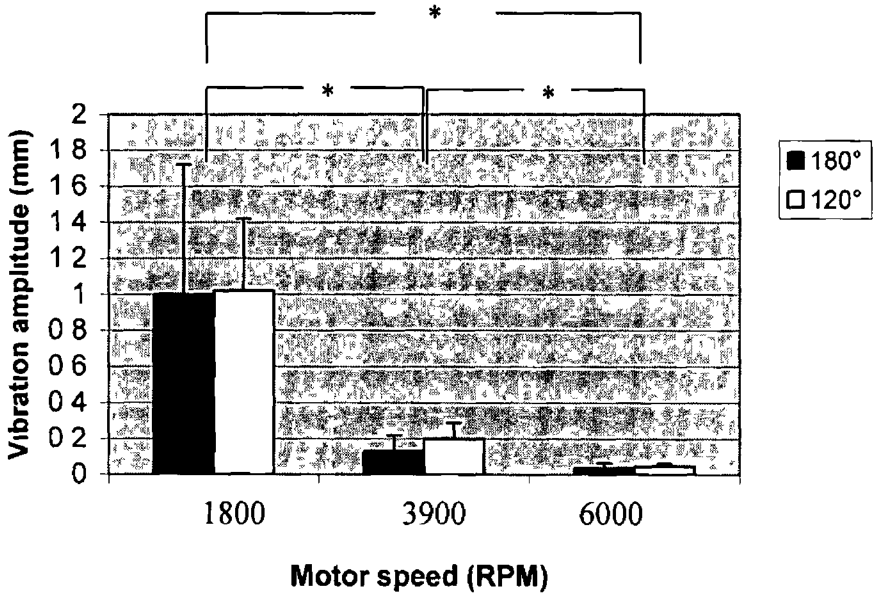


Figure 6 3 Vibration amplitude measured on the muscle

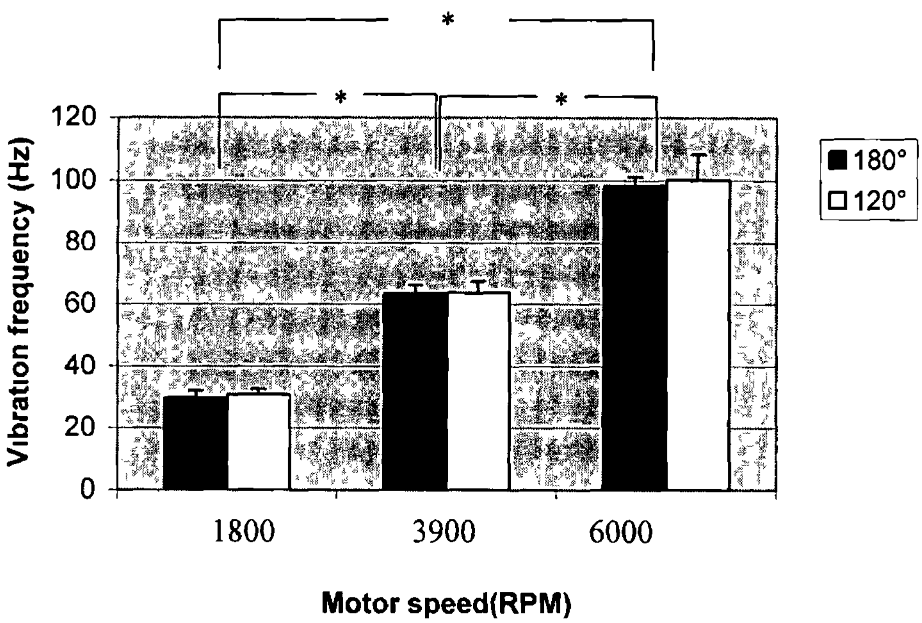


Figure 6 4 Vibration peak frequency measured on the muscle

6 3 3 Transmissibility of vibration to muscle

The transmissibility of vibration amplitude and frequency from the vibrator to the muscle are shown in figure 6 5 and 6 6 Statistical analysis showed that motor speed had a significant effect on the transmissibility of the vibration amplitude (p < 0 001), with significant differences being evident between all three levels of motor rotating speed (p < 0 001) The smaller the motor speed the greater the vibration transmissibility 1800RPM (67%) > 3900 RPM (14%) > 6000 RPM (5%) (p < 0 001) The transmissibility of vibration frequency was unaffected by motor rotation speed (p > 0 05) and was 100% for all speeds Joint angle had no significant effect on transmissibility of either vibration amplitude or frequency (p > 0 05)

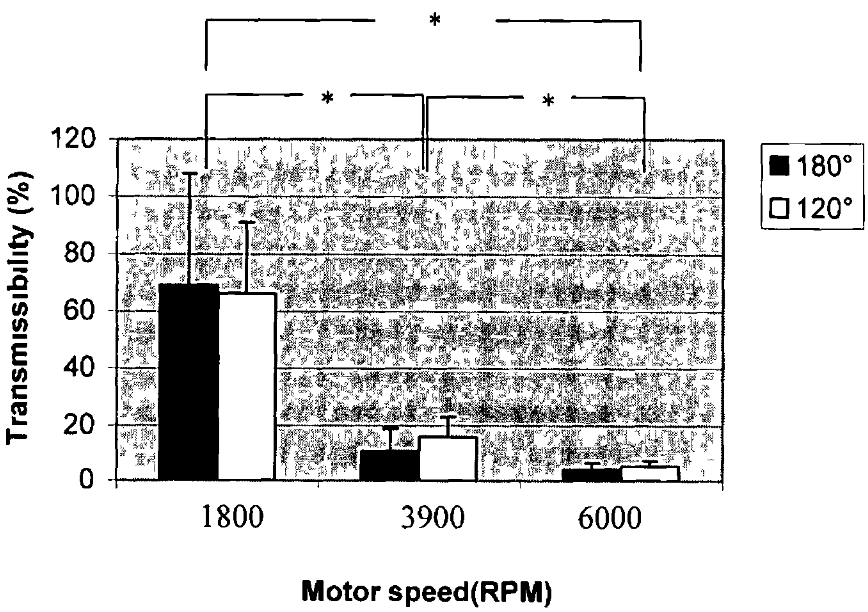


Figure 6 5 Transmissibility of vibration amplitude

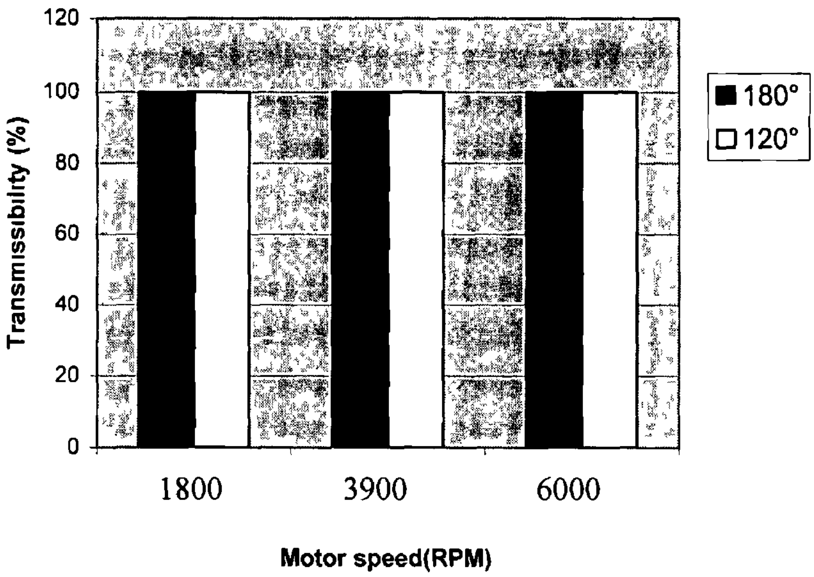


Figure 6 6 Transmissibility of vibration peak frequency

6 3 4 EMG response to vibration produced by different motor speed

The increases of EMGrms from no vibration value at three different motor speeds and two joint angles are shown in figure 6 7 Statistical analysis showed that the different motor speeds had a significant effect on the increase in EMGrms ($p<0\ 001$) Main effects analysis showed that the increases of EMGrms at 3900 RPM (0 044 mv) and 6000 RPM (0 046mV) were significantly higher than that at 1800 RPM (0 019mV) However, there was no significant difference between 3900 RPM and 6000 RPM ($p>0\ 05$) Joint angle did not have any significant effect on the EMGrms response ($p>0\ 05$)

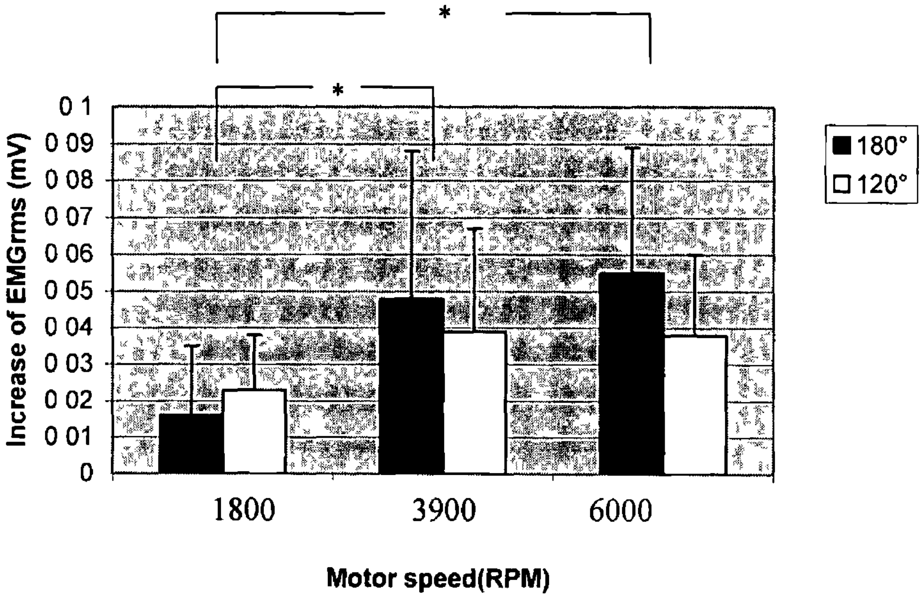


Figure 6 7 Increase in EMGrms at different motor speeds

6 4 Discussion

The vibration frequencies measured on vibrator at three different motor rotating speeds (1800, 3900 and 6000 RPM) were around 30, 65 and 100 Hz respectively (figure 6 2) The different joint angles did not have any significant effect on vibration frequencies (p>0 05) It has also been found in the previous study that the different eccentric masses did not have any significant effect on vibration peak frequency It may be suggested that the vibration peak frequency of the muscle tendon vibrator is determined only by the motor rotating speed In the following discussion, the implication of the findings will be discussed in terms of vibration frequencies (30, 65 and 100 Hz) rather than motor rotating speeds

As shown in figure 6 1, the vibration amplitude measured on vibrator was the largest at 30 Hz, followed by 65 and 100 Hz Joint angle did not have any significant effect on amplitude The same eccentric mass size (ems-II) has been used in this study at all three frequencies This eccentric mass size (ems-II) was the larger of the two eccentric mass sizes (ems-I and ems-II) used in the last study (see chapter 5) It has been found in the last study that ems-II induced significant larger vibration amplitude (around 1 2 mm) than ems-I (around 0 5 mm) ($p<0\ 05$) In this study, although the average vibration amplitudes were all around 1 to 1 5 mm, there were significant differences among them ($p < 0\ 05$) Thus, it can be concluded that the vibration amplitude of the vibrator was influenced by both eccentric mass size and the motor rotating speed

The influence of motor rotating speed on vibration amplitude could be explained by the analysis of the vibrator model as introduced in section 3 2 3 As discussed in section 3 2 3, the vibration amplitude (A) can be calculated as

$$A = \frac{Mu}{M} \times e \times Ra \qquad \text{(Equation 6 1)}$$

where

M_u = eccentric mass

M = mass of the motor and housing

e = eccentric radius

Ra = dimensionless response factor, and is calculated as

$$Ra = \frac{(\omega^2 / \omega_n^2)}{\sqrt{(1-(\omega^2 / \omega_n^2))^2 + (2 \times \xi \times \omega / \omega_n)^2}} \qquad \text{(Equation 6 2)}$$

where

ω = the angular velocity of the eccentric mass

ω_n = natural frequency of muscle-tendon under the vibrator

ξ = fraction of the critical damping

As mentioned in section 3 2 3, a value of 0 44 was used for ξ according to the work by Wakeling et al (62) Thus we can plot the relationship between Ra and (ϖ/ϖ_n) at the value of ξ = 0 44 (figure 6 8)

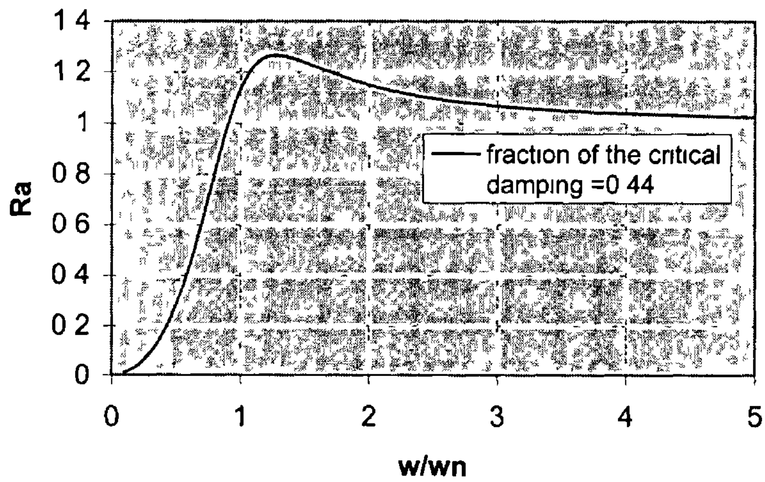


Figure 6 8 Relationship between Ra and ω/ωn at ξ = 0 44

It can be seen from figure 6 8 that when the vibration frequency is around the natural frequency (ϖ/ϖ_n around 1), the dimensionless response factor (Ra) value reaches its maximum Ra decreases when the vibration frequency is higher than the natural frequency. Because eccentric mass (M_u), mass of the motor and housing (M) and eccentric radius (e) have constant values in Equation 6.1, the vibration amplitude A should be the largest when Ra reaches its maximal value. It has been reported that the natural frequency of the quadriceps muscle is around 8.85 to 30.39 Hz(62). It is possible that the natural frequency of the muscle-tendon of the biceps brachii is around 30 Hz, which would explain why the amplitude around 30 Hz was the biggest in our experiment. With the increase of frequency from 30 Hz to 65 and 100 Hz, Ra keeps decreasing so that the amplitude of the vibrator decreases from 30 Hz to 100 Hz when the eccentric mass was the same at these three frequencies.

It was found in the present study that the vibration amplitude was significantly less on the muscle than on the vibrator, and that the transmissibility was the highest at 30 Hz and lowest at 100 Hz (figure 6.5). It has been found that the vibration amplitude is attenuated when it is transmitted through soft tissues(22), as demonstrated in study 1 (chapter 5). Moreover, the attenuation is greater when the vibration frequency is higher(59). Our results on transmissibility are in line with these findings. This result on transmissibility suggests that low frequency vibration may be better than the high frequency vibration in activating the muscles further away from the vibrating source when indirectly applied vibration method is used in vibration training. This however needs to be confirmed experimentally.

In addition, the peak vibration frequency is the same on the vibrator and on the muscle for all the three frequencies examined (30, 65, 100 Hz) (figure 6.6), which means that the transmission of peak frequency was always 100%, and not influenced by the frequency being transmitted. This finding suggests that this muscle tendon vibrator may be used for the examination of the effect of high frequency vibration, as the high vibration frequency can be delivered without change to the muscle In the indirect vibration, however, vibration with high frequency may be attenuated during transmission(6) Therefore the peak frequency of the vibration device may not be delivered to the muscle without change in indirect method

This study found that the transmission of peak frequency to the muscle was not influenced by different joint angles This finding indicates that the consistence of the vibration frequency on the target muscles may be achieved in different vibration training exercise (isometric and dynamic) by using the muscle tendon vibrator developed in this study This is also crucial for our later vibration training studies, in which different exercise protocols will be employed It is also suggested that the short distance of transmission in direct vibration method may be the reason for this consistent frequency transmission to muscle under different joint angles

The main goal of this study is to identify the vibration frequency that could stimulate the muscle optimally because we found in the last study that the vibration amplitude around 1 2 mm could stimulate the muscle more effectively than the amplitude around 0 5 mm Thus, the same eccentric mass used in study 1 (chapter 5) to produce an amplitude around 1 2 mm was used in this study, with three different frequencies (30, 65 and 100 Hz)

A frequency of 30 Hz was selected as the lowest frequency in this study because it is the lowest frequency range used in the vibration training studies to date(3-8,12,21,48,73) The frequency of 100 Hz was chosen as the highest frequency because it has been found that the increase of EMGrms during Tonic vibration reflex (TVR) increased with vibration frequencies up to 100 to 150 Hz, but decreases beyond(32). As has been found by Martin et al.(72), the recruitment of muscle spindle Ia afferents is determined by vibration amplitude. Once the muscle spindle Ia afferents are recruited by vibration, a change of the vibration frequency will change the firing rate of the recruited Ia afferents and then induce a change in TVR(38,74). Thus, it was expected in this study that the increase of EMGrms would be the largest at 100 Hz. The frequency of 65 Hz was chosen as an intermediary frequency in this study. There have been only two study to date that directly investigated the influence of frequency on vibration training effect(14,23). Their findings suggested that frequency around 30 to 50 Hz may induce a greater acute effect in vibration training(14,23).

The results of the present study showed that the increases of EMGrms at both 100 Hz and 65 Hz were significantly higher than 30 Hz (figure 6.7). It was also noted that the vibration amplitude on the muscle and the vibrator were the largest at 30 Hz (around 1.4 mm and 1.0 mm), followed by 65 Hz (around 1.2 mm and 0.16 mm) and 100 Hz (around 1 mm and 0.04 mm) (figure 6.1 and 6.3). It was thus inferred that the recruitment of muscle spindle endings should be the most effective at 30 Hz. However, the EMGrms results were contradictory to the results of vibration amplitude as discussed above. It may be suggested that although vibration amplitudes were significantly different among the above three frequencies, the amplitude difference at three frequencies were small (1 vs 1.2 vs 1.4 mm). In addition, most of the muscle spindle Ia afferents may have been recruited when the vibration amplitude was around 1 mm. Therefore, the increase of Ia afferents firing rates driven by the increasing vibration frequency(74) may play a more important role in the increase of EMGrms

However, the results of the present study also showed that the increase of EMGrms had no significant difference between 65 Hz and 100 Hz It is noted that the vibration amplitudes on the muscle at 65 Hz were significantly larger than at 100 Hz Thus, larger displacement at 65 Hz may have recruited more Ia afferents than 100 Hz, while higher frequency of 100 Hz may have increased the firing rates of Ia afferents more than 65 Hz The function of these two effects may counter balance each other so that the increase of EMGrms at 65 and 100 Hz did not have any significant difference

The EMGrms response to different vibration frequencies was not influenced by different joint angles as shown in this study This may be due to the consistent vibration load (amplitude and frequency) imposed on the muscle by the vibrator under different joint angles Therefore, the application of this muscle tendon vibrator in our later vibration training studies with different contraction exercise performed is warranted

While frequencies of 65 Hz and 100 Hz produced the greatest EMGrms response, indicating their possible greater potential for vibration training, most subjects reported that 100 Hz vibration felt quite uncomfortable This may be due to the large vibration force and acceleration found at 100 Hz (measured vibration acceleration was about 2 times larger at 100 Hz than at 65 Hz and about 8 times larger than at 30 Hz) placing the soft tissues under vibrator under greater stress

In summary, when the eccentric mass size is kept constant at ems-II, vibrations of 65 Hz and 100 Hz were better than vibration of 30 Hz in activating the muscle, although both the vibration amplitude of the vibrator and the transmissibility of vibration to muscle were the largest at 30 Hz. There is no significant difference in EMGrms increase between 65 Hz and 100 Hz vibration, but the 100 Hz vibration was quite uncomfortable because of its larger vibration force. From the above results, it may be suggested that vibration with a frequency of around 65 Hz and an amplitude of around 1.2 mm is more suitable for our muscle tendon vibrator to stimulate the muscle during vibration training.

6.5 Conclusion

Combining the results from this and the previous experiment (study 1, chapter 5), the following conclusions can be drawn for sub-maximal contractions:

1. The vibration peak frequency of the muscle-tendon vibrator is determined only by the motor rotating speed and is stable at different eccentric mass sizes, test days, joint angles and strapping forces.

2. The vibration amplitude of the muscle-tendon vibrator is determined by both the eccentric mass and the motor rotating speed and is stable at different test days, joint angles and strapping force.

3. The transmissibility of vibration amplitude to muscle is effected by both the eccentric mass and motor rotating speed of the vibrator. The higher the vibration

amplitude (eccentric mass size) and frequency (motor rotating speed) on the vibrator, the lower the transmissibility of vibration amplitude to the muscle The different test days, joint angles and strapping forces did not have significant influence on the transmissibility of vibration amplitude

4 The transmissibility of peak frequency is always 100%, and is not effected by the eccentric mass size, motor rotating speed, test day, joint angle or strapping force

5 The greatest increase of EMGrms was induced by vibration with a frequency of around 65 Hz and an amplitude of around 1 2 mm, which may be the optimal vibration characteristics for our muscle-tendon vibrator to stimulate the muscle during vibration treatment

Chapter 7

Study 3 **Influence of load on acute vibration training effect – a study on sub-maximal isometric contraction**

7 1 Introduction

Vibration training with a sub-maximal contraction load has been shown to induce strength gain within a short period of time (12 weeks) and without much effort (3) Therefore, vibration training was suggested to have a great potential in strength training of people with injury or the elderly who are not attracted to or are not able to perform standard strength training exercise programs (3,75) However, some vibration training studies with very light exercise (standing with knee flexed without extra-load) did not find any effect of vibration (8) On the other hand, a slight increase in the training intensity (squat, deep squat without extra-load) could induce the significant increase in strength and power by vibration (3) Therefore, the sub-maximal contraction exercise intensity employed in vibration training appears have an influence on the vibration training effect However, there has been no study to date that has directly examined the influence of sub-maximal contraction exercise intensity on the acute effect of vibration training on neuromuscular performance In order to establish scientific-based optimal vibration training programs to achieve strength and power improvement, studies on this issue are needed Therefore, this study will investigate the increase of a sub-maximal contraction load on the acute neuromuscular response to vibration training

Electromyography (EMG) will be used in this study to assess the muscle response to vibration training with different loads. However, the variability in muscle activity response to vibration training was found to be quite high in some studies, possibly because of the individual response to the vibration loads (10,17). There has been no study to date involving the examination of the day-to-day repeatability of EMG response to vibration training. In study 1 (chapter 5), the day-to-day repeatability of the EMG response to vibration with different characteristics (amplitude) has been established. In this study, we will also examine the repeatability of EMG response to vibration when different resistance loads are employed.

The aims of this study are:

1) To examine whether resistance load has an influence on the acute effect of vibration training with sub-maximal isometric contraction
2) To examine the repeatability of EMG measurement during vibration training

7.2 Method

Only key aspects of the methods are presented below. A more detailed account of the methods is presented in the generic methods (chapter 4).

7.2.1 Subjects

Sixteen healthy adult male volunteers took part in this study. The average age, mass and height of the subjects were 21.4 ± 2.1 (years), 77.1 ± 14.5 (kg), 179 ± 8 (cm) respectively.

7 2 2 Expenment desıgn

Subjects performed ısometnc knee extensıon under four expenment condıtıons ın random order 1) load of 10% 1RM wıth no vıbratıon (10%NV), 2) load of 20% 1RM wıth no vıbratıon (20%NV), 3) load of 10% 1RM wıth vıbratıon (10%V), 4) load of 20% 1RM wıth vıbratıon (20%V) Dunng the test, subjects were ınstructed to sıt on a leg extensıon machıne and were firmly secured to the seat by elastıc band over the hıp and both thıghs (figure 7 1) The poplıtal fossa of the subject was alıgned to the rotatıon axıs of the weıght on the machıne The subjects were ınstructed to hold theır arms crossed theır chest and keep theır back straıght durıng exercıse Only nght leg was used ın lıftıng the weıght The subjects were ınstructed to extend theır knee joınt to an angle of 150° and keep thıs joınt angle for 20 seconds ın each expenment condıtıon

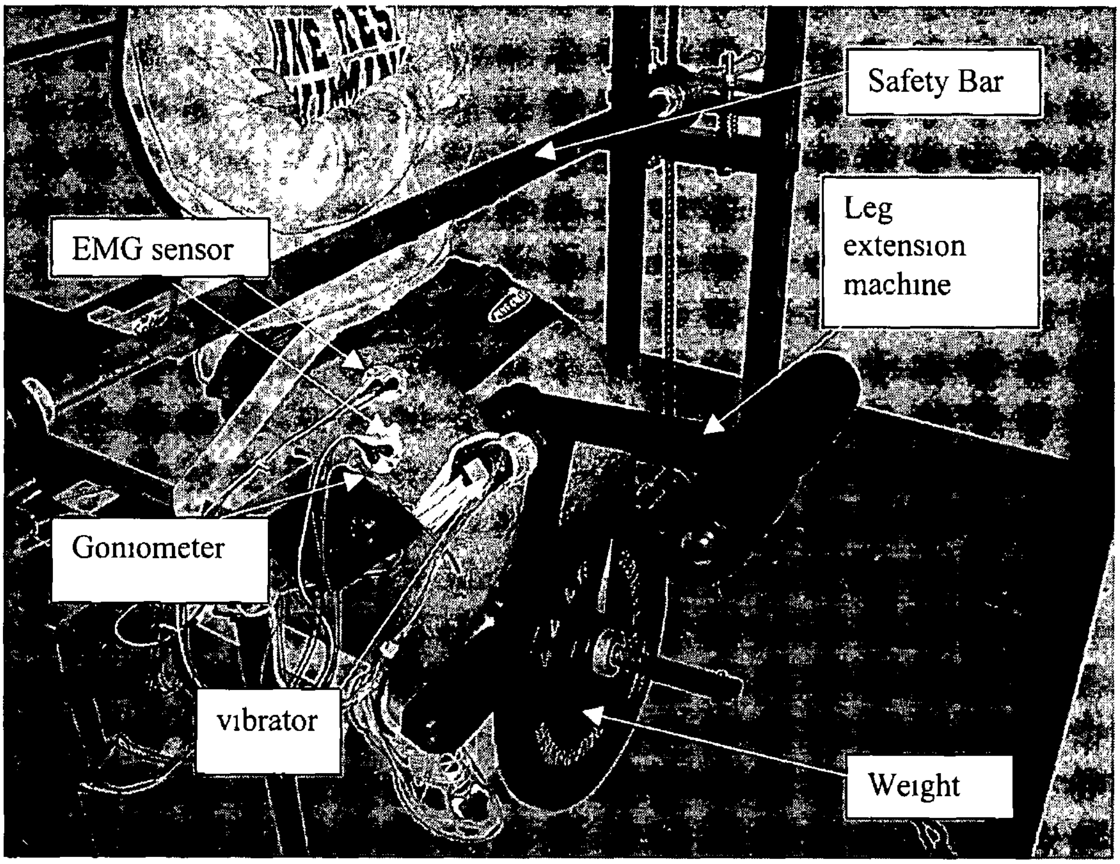


Figure 7.1 Experiment setup

The 1RM strength of the knee extension was estimated on each subject by testing with a 10RM load on a separate day, at least 3 days before the start of the experiment(76) Subjects were also familiarized themselves with the test procedure on that day

For thirteen of the sixteen subjects, each test condition was re-tested on another day to establish the repeatability of the experiment There was at least two days interval between test days

7 2 3 Vibration

Vibration was produced by a portable muscle tendon vibrator (section 3 2 3) that was strapped onto the quadriceps muscle-tendon about 5 cm proximal to the knee cap Vibration amplitude and frequency were set at 1 2 mm and 65 Hz, respectively These were determined to be optimum in studies 1 (chapter 5) and 2 (chapter 6)

7 2 4 Measurements

EMG signals on rectus femoris (RF), vastus lateralis (VL) and vastus medialis (VM) were measured for 20 seconds in each experiment condition Knee joint angle was monitored by a goniometer (XM180, Biometrics, UK) to ensure that the knee joint angle was at 150° at the start of each test

7 2 5 Data analysis

EMGrms data measured on the RF, VL and VM were used for analysis The first 5-second segment of EMGrms data was discarded to eliminate the transient effect (32) The EMGrms was averaged for the left 15 seconds This average EMGrms is the dependent variable in this study

7 2 6 Statistical methods

The inter-day reliability of the EMG measurement was calculated using Intraclass correlation (77) Paired t-test was also employed to examine whether there was a difference in EMG response from test to re-test

To determine the effect of vibration (vibration, no vibration) and load (10% 1RM, 20% 1RM) on EMG variables, a two factor ANOVA (load (2) × vibration (2)) with repeated measures was employed Where a sıgnıficant mam effect or ınteractıon ınvolvıng the ındependent varıable of vıbratıon was found, a planned comparıson wıth appropriate Bonferrom adjustment was employed to locate where the sıgnıficant dıfference rests SPSS® was used for all statıstıcal analysıs

7 3 Results

7 3 1 Typıcal EMG results durıng test

Typıcal raw EMG sıgnals under the dıfferent test condıtıons are shown ın figure 7 2

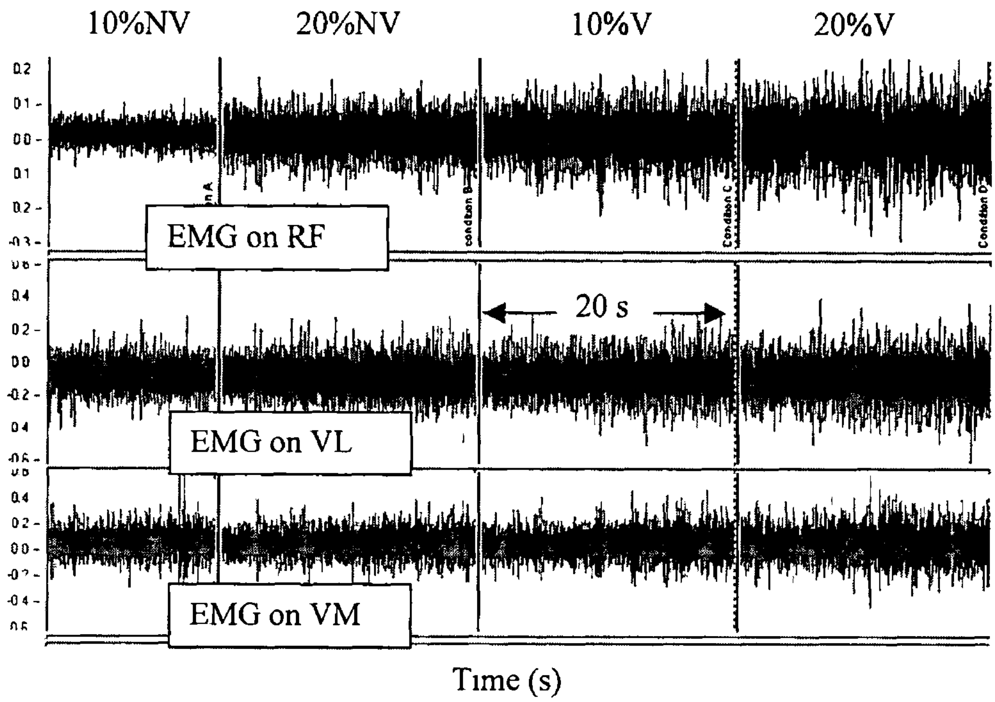


Fıgure 7.2 Raw EMG sıgnals measured durıng test on RF, VL and VM

7 3 2 Reliability of measurements

The EMGrms measurements on RF, VL and VM on two different test days, and the reliability of these measurements are shown in tables 7 1 to 7 3 Both the ICC and the paired t-test results indicated that EMGrms measurements on two different days were reliable Therefore the test and retest results of these 13 subjects were averaged and analyzed with the results of the other 3 subjects

Table 7.1 Reliability of EMGrms measurement on the RF

Condition	EMGrms(Day1) (μV)	EMGrms(Day2) (μV)	p value of t test	Reliability (ICC)
10%NV	29 2±15 9	27 8±16 3	0 739	0 70
20%NV	46 6±20 3	42 3±16 9	0 349	0 78
10%V	31 6±13 2	30 9±13 2	0 735	0 78
20%V	48 9±14 1	49 7±17 8	0 838	0 91

Table 7 2 Reliability of EMGrms measurement on the VL

Condition	EMGrms(Day1) (μV)	EMGrms(Day2) (μV)	p value of t test	Reliability (ICC)
10%NV	33 5±8 8	37 0±14 1	0 385	0 44
20%NV	45 3±13 8	49 6±17 1	0 281	0 76
10%V	48 4±20 9	44 9±18 6	0 503	0 74
20%V	60 2±21 3	57 6±17 8	0 572	0 78

Table 7 3 Reliability of EMGrms measurement on the VM

Condition	EMGrms(Day1) (μV)	EMGrms(Day2) (μV)	p value of t test	Reliability (ICC)
10%NV	36 0±11 5	39 8±13 5	0 358	0 53
20%NV	59 1±21 1	58 1±17 2	0 859	0 63
10%V	66 2±25 6	64 1±22 0	0 778	0 59
20%V	86 8±28 6	83 5±22 5	0 623	0 73

7 3 3 EMGrms under different load and vibration conditions

EMGrms measured on the RF was shown in figure 7 3 Statistical analysis showed that vibration did not have a significant effect on EMGrms (p >0 05), but load did have a significant effect (p < 0 01) Main effects analysis showed that the load of 20% 1RM induced significantly higher EMGrms (48 μV vs 31 μV , p < 0 05)

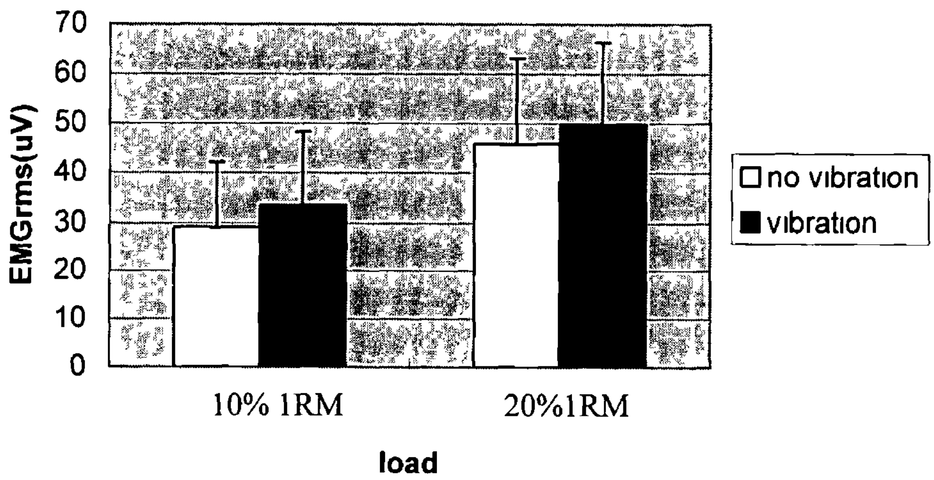


Figure 7 3 EMGrms measured on RF under different conditions

EMGrms measured on the VL is shown in figure 7 4 Statistical analysis showed that both vibration and load had significant effects on EMGrms (p < 0 01) Main effects analysis showed that the EMGrms with vibration was significantly higher than no vibration (49 μV vs 39 μV , $p < 0\ 05$), and the load of 20% 1RM induced a significantly higher EMGrms (49 μV vs 38 μV , $p < 0\ 05$)

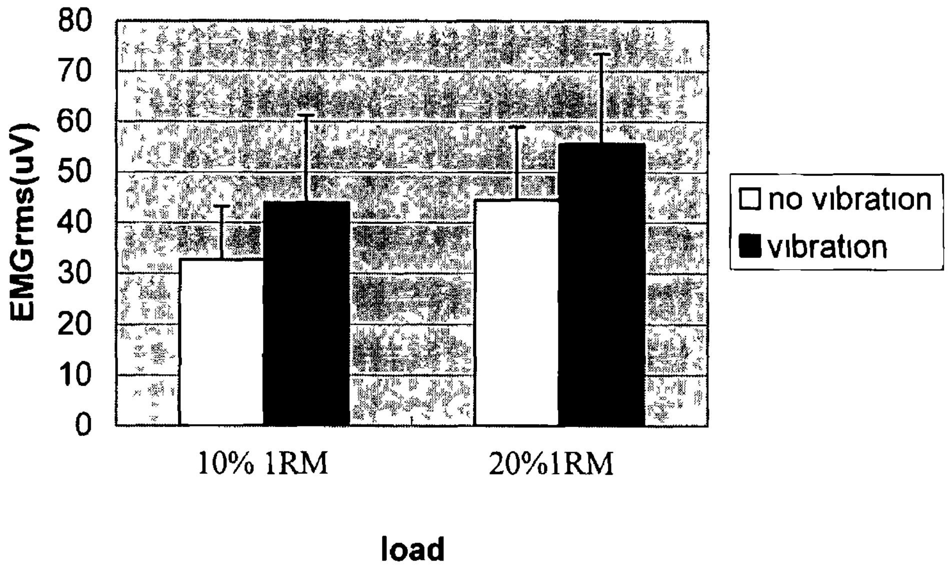


Figure 7 4 EMGrms measured on VL under different conditions

EMGrms measured on the VM is shown in figure 7 5 Statistical analysis showed that both vibration and load had a significant effect on EMGrms ($p<0\ 01$) Main effects analysis showed that the EMGrms with vibration was significantly higher than no vibration (74 μV vs 46 μV , $p < 0\ 05$), and the load of 20% 1RM induced significantly higher EMGrms (69 μV vs 49 μV , $p < 0\ 05$)

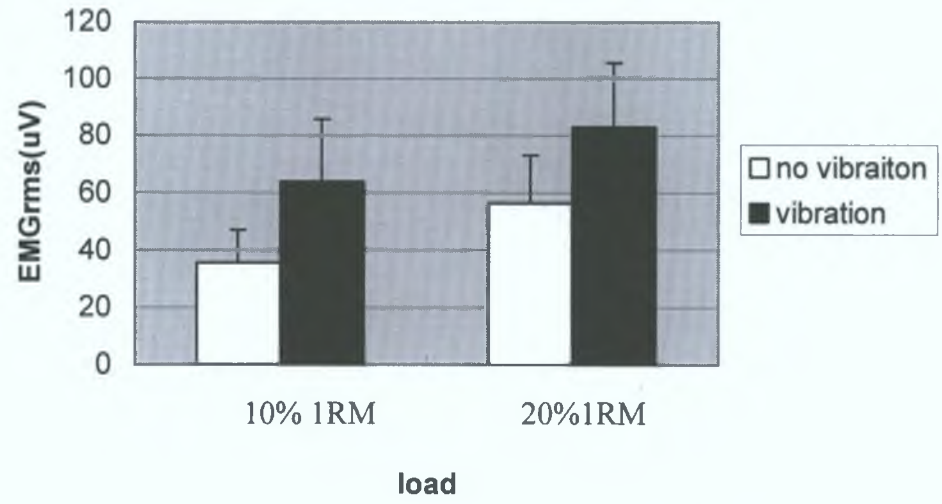


Figure 7.5 EMGrms measured on VM under different conditions

7.4 Discussion

The results of this study showed that vibration could induce significantly higher muscle activity on the VL and VM in both 10% 1RM and 20% 1RM load conditions ($p<0.05$). In addition, the load had a significant influence on the EMG response to vibration on the VL and VM, i.e., the higher the load, the greater the EMG response to vibration. It may be suggested from this study that vibration training with high resistance load may be able to activate more motor units during training, and therefore may induce greater strength and power gain.

Although the EMG on RF tended to be enhanced by vibration ($p<0.1$), the increase was not significant. This may be due to several reasons. Firstly, the length of a muscle has been found to have an influence on its response to vibration stimulation(30). Eklund et al. (30) found that when a muscle is in a stretched position it is more responsive to vibration. In the present study, subjects were asked to extend their knee joint angle to 150° The lack of response in RF may be due to its shortened muscle position However, this argument may not be supported by our results in study 1 (chapter 5) and 2 (chapter 6), in which the EMG response to vibration was not affected by the joint angle Secondly, the different responses of RF, VL and VM to vibration may be related to the load sharing among these muscles Zhang et al (78) measured in vivo the load sharing among the quadriceps components in a sub-maximal knee extension The authors (78) found that with an increase in total knee extension moment, the VL and VM contributed significantly more with the increasing demand ($p<0$ 01), while the relative contribution by the RF did not change significantly ($p>0$ 05) It is possible that a similar load sharing pattern existed in the quadriceps response to vibration load

There have been no studies to date that have directly examined the influence of resistance load on neuromuscular performance in vibration training with sub-maximal exercise performed Rittweger et al (20,79) indirectly examined the influence of exercise load on acute vibration training effect by measuring the oxygen uptake during a bout of whole-body vibration exercise The authors (20) found that the specific oxygen uptake (the instantaneous oxygen uptake divided by the body mass) during a sub-maximal isometric contraction exercise (standing with knee flexed at 170°) could be enhanced by whole body vibration In addition, a further increase in specific oxygen uptake was observed when extra-load was applied to the exercise The authors (79) suggested that a pre-loading of muscles during vibration training may enhance the activation of these muscles Therefore, our results in the present study are in line with this argument, and provide the direct evidence indicating that the higher muscle activation by vibration can be achieved with higher resistance load in vibration training with sub-maximal contraction exercises.

A comparison of three chronic vibration training studies (3,6,8) that each employed different exercise intensities indicates that exercise intensity may elicit different vibration training effects. De Ruiter et al. (8) reported no significant enhancement in knee extension strength after 11-weeks of whole body vibration training. However, Delecluse et al. (3) employed a higher intensity of exercise and found that 12-weeks of whole body vibration training could induce a significant increase (16.6%, $p<0.05$) in knee extension strength. The higher exercise intensity involved exercise such as the squat, deep squat, wide-stance squat, one-legged squat and lunge during training(3), while in the former study (8) the subjects were only asked to stand on the vibrating platform with knee angle flexed at 110°. In addition, Issurin et al.(6) employed a heavy resistance training program in their vibration training studies in which a load of 80%-100% 1RM was used. This exercise intensity was the largest among these three vibration training studies. It was also noted that the gains in maximal strength in this study were also the largest, both with and without vibration (49.8% vs. 16%; $p<0.05$), although the length of this study was the shortest [3 weeks(6) vs. 11 weeks (8) and 12 weeks (3)]. These findings support our analysis that vibration may achieve greater acute muscle performance enhancement when the exercise intensity was increased during vibration training.

As a possible mechanism for the above findings, it has been found that muscle spindle endings are very sensitive to vibration (80). Muscle vibration could induce a sustained discharge of Ia afferents and cause a reflex contraction of the muscle being vibrated, i e tonic vibration reflex (TVR) (30) The initial voluntary contraction of the muscle may be accompanied by an increase of gamma motor activity which could keep the intrafusal fibers tense (30) This increased tension of intrafusal fibers could therefore increase the sensitivity of muscle spindle endings, and in consequence would increase the positive response from the vibration stimulation(30) Thus it may be suggested that the increase in exercise intensity in vibration training has the function to increase the sensitivity of muscle spindles to vibration stimulation and induce a greater activation of motor units

7 5 Conclusion

The muscle activation during vibration training with sub-maximal isometric contraction is effected by the resistance load employed Higher muscle activation may be achieved when vibration is applied with a higher load in a sub-maximal contraction, implying that increase the exercise intensity may be able to induce a greater vibration training effect The muscle activity response to vibration with different resistance load is repeatable in different test days

Chapter 8

Study 4 **Acute and acute residual effect of vibration training on neuromuscular performance with maximal isotonic contractions**

8 1 Introduction

Vibration stimulation has been suggested to be able to facilitate the fully activation of muscle during maximal isotonic contraction, which may not be achieved by voluntary effort (21) This is of great potential for the application of vibration training because the isotonic contractions are more common in strength training exercises Only three studies with appropriate control have investigated this kind of vibration training to date (6,21,26) All of them employed the indirect method vibration (6,21,26) It is therefore necessary to investigate whether greater enhancement in neuromuscular performance for isotonic contractions can be achieved by direct method

In addition to the enhancement on neuromuscular performance during maximal isotonic contraction (acute effect of vibration), vibration has been found to facilitate the maximal dynamic contractions performed following a bout of vibration training (acute residual effect of vibration) This acute residual effect was found only after vibration training with very light exercise (7) It is reasonable to argue whether an exercise is needed to induce this acute residual effect

The aims of this study are

1) to examine the acute (during) effect of direct vibration on neuromuscular performance of maximal isotonic contractions.

2) to examine the acute residual (following) effect of direct vibration training with exercise or without exercise

8.2 Methods

Only key aspects of the methods are presented below. A more detailed account of the methods is presented in the generic methods section (chapter 4).

8.2.1 Subjects

Fourteen young adult male volunteers took part in this study. The average age, mass and height of the subjects were 26.3±6.6 (years), 77.8±12.6 (kg), and 177.3±6.8 (cm), respectively.

8.2.2 Experiment design

Subjects were exposed to four training conditions in random order: 1) exercise with superimposed vibration (E+V); 2) exercise with sham-vibration (E+SV); 3) no exercise with superimposed vibration (NE+V); 4) no exercise with sham-vibration (NE+SV). The exercise condition comprised of three sets of dynamic bicep curls with a load of 70% 1RM, performed by the dominant arm while sitting on a preacher curl bench (figure 8.1). Each set comprised of 10 repetitions. In the exercise condition, subjects attempted to move the weight as fast as possible in the concentric phase, and to fully extend their elbow joint in the eccentric phase There was a 3 to 5 minutes rest time between each set In the conditions without exercise, subjects rested their dominant arm on the pad with their elbow joint fully extended, with no weight The duration of the no exercise condition was set to be the same as the exercise condition (30 seconds)

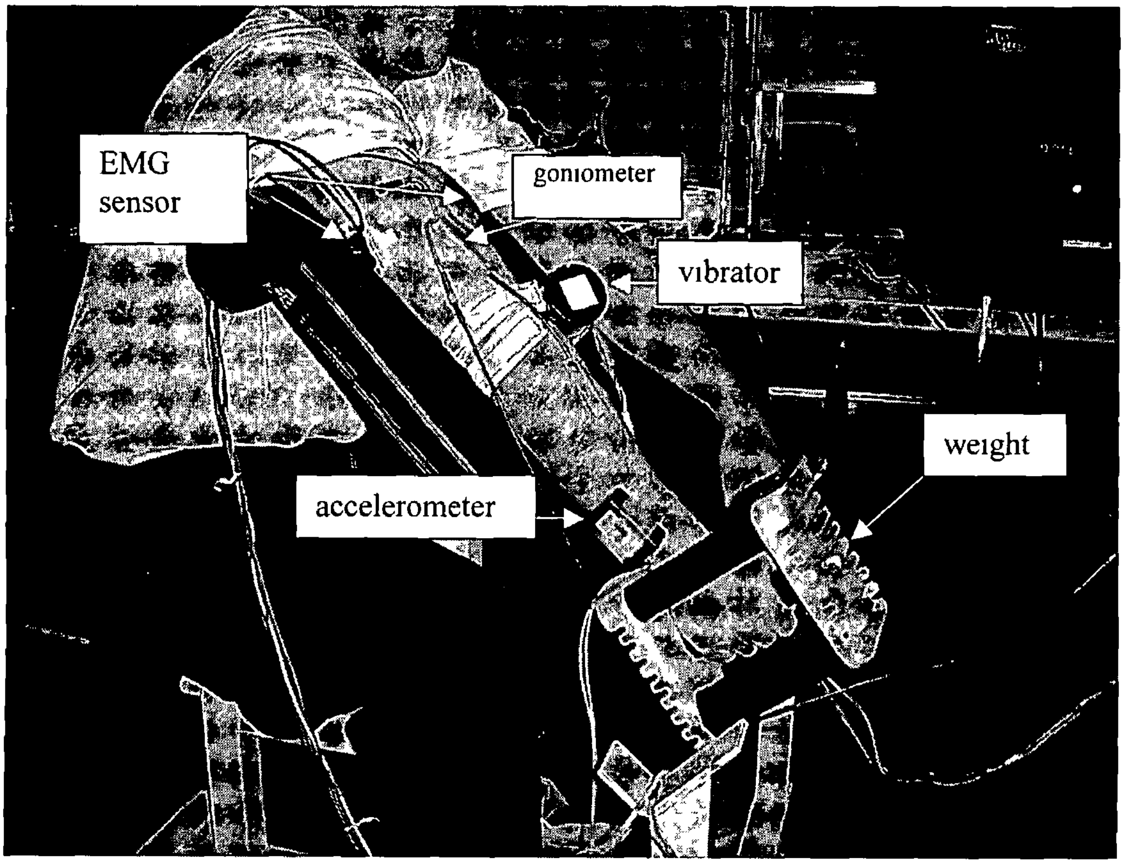
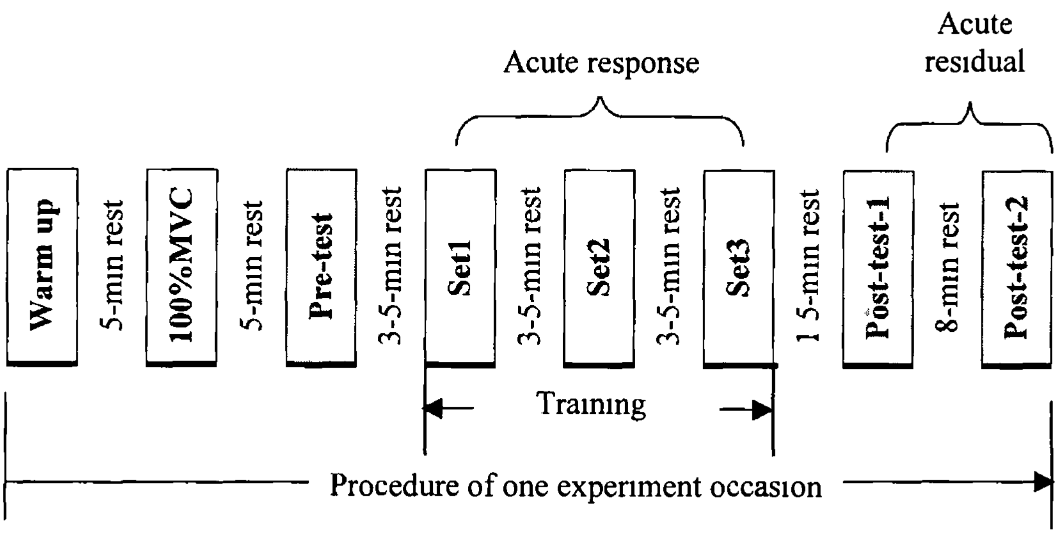


Figure 8 1 Experiment setup

8 2 3 Experimental procedure

The 1RM strength of the bicep curl was measured for each subject on a separate day, at least 3 days before the start of the experiment Subjects were also familiarized with test procedures on that day In order to normalize EMG data, subjects performed a 1

RM bicep curl and tricep extension on each test day, after a warm-up exercise (12 repetitions of bicep curls and tricep extensions with 25% of 1RM load, rest for 3 minutes, followed by 12 repetitions of the bicep curl and tricep extension with 50% of 1RM load) After 5 minutes rest, a set of 5 bicep curl repetitions with 70% 1RM load was performed as the pre-training test (pre-test) After 5 minutes rest, subjects performed one of four training conditions (E+V, E+SV, NE+V, NE+SV) Two sets of 5 bicep curl repetitions with 70% 1RM load were performed, one at 1 5 minutes and the other at 10 minutes after the end of training as the post-training tests (post-test-1, post-test-2) (figure 7 2) The subjects were asked to perform the concentric phase of contractions as hard and as fast as possible during all sets This procedure was undertaken on four occasions that were separated by at least 3 days, once for each experimental condition



Note MVC=contraction with 1RM load

Figure 8 2 Study design

8 2 4 Vıbratıon

Vıbratıon was produced by a portable muscle tendon vıbrator (sectıon 3 2 3) that was strapped onto the bıceps tendon Vıbratıon amplıtude and frequency were set at 1 2 mm and 65 Hz, respectıvely, as they were prevıously ıdentıfied as appropnate values [study 1 (chapter 5) and study 2 (chapter 6)] In the sham vıbratıon condıtıon, the eccentnc masses were removed so that there was only the noıse of the motor runnıng but no notable vıbratıon was produced

8 2 5 Measurements

Elbow joınt angle and EMG on the bıcep brachıı and the trıcep brachıı were measured both durıng traınıng and ın pre and post traınıng tests EMG measurement was also mad durıng the contractıon wıth 1RM load

Two sıngle axıs accelerometers (ET-Acc-01, Ergotest Technology, Norway) were taped together wıth theır sensıtıve axıs alıgned and attached to the wrıst of the exercısed arm of the subject The sensıtıve axıs of both accelerometer were alıgned wıth the forearm One accelerometer was connected to Powerlab, and the other to the amplıfier of gonıometer The output from the two accelerometers allowed synchronızatıon of the EMG and joınt angle sıgnals

8.2.6 Data analysis

The elbow joint angular velocity (ω), acceleration (α), moment (M_{elbow}), and power (P_{elbow}) data were calculated from the filtered joint angle data (section 4.4.2). For ω, M_{elbow} and P_{elbow}, initial (at 100 ms), mean and peak measures were determined. In addition, concentric phase duration, time to peak power (T_P), and rate of power development (RPD), calculated as the peak power divided by the duration from the start of the concentric phase to the time when peak power was achieved, were also determined (figures 8.3 and 8.4). These dependent mechanical variables were selected because they have been identified as important to movement performance outcome in maximal effort tasks(81).

Finally, EMGrms data on the biceps and triceps were averaged for the concentric phase of the bicep curl (EMGrms). The average value of EMGrms data (biceps) for a period of 120ms from the start of concentric phase was calculated [initial $\text{EMGrms}_{(0\text{-}120\text{ms})}$]. These EMGrms values were then normalized to the average EMGrms value in the concentric phase of the 1RM contraction. The mean power frequency of EMG (EMGmpf) of the biceps in the concentric phase was also calculated. These were the dependant EMG variables.

The mechanical and EMG variables (detailed above) of the second, third and fourth repetitions of each set were selected and averaged to represent the variables for each set. This procedure was employed because the repeatability for the variables, as assessed via Cronbach's alpha coefficient, was higher when the first and fifth repetitions were not included in the analysis (82)

8 2 7 Statistical analysis

As the pre-training test was repeated on each of the four test conditions performed on four different days, the inter-day reliability of all dependent variables was calculated using intraclass correlation (77)

To determine the acute effect of vibration (vibration, no vibration) and set (set1, set2, set3) on mechanical and EMG variables during training, a two factor ANOVA [vibration treatment (2) × training set (3)] with repeated measures on the subjects was employed

To examine the acute-residual effect of vibration (vibration, no vibration), exercise (exercise, no exercise) and test time (pre-test, post-test-1, post-test-2) on mechanical and EMG variables after training, a three factor ANOVA [vibration treatment (2) × exercise (2) × test time (3)] was employed

For all analyses a probability value of significance of $p<0\ 05$ was employed Where a significant main effect or interaction involving the independent variable of vibration was found, planned comparisons with appropriate Bonferroni adjustment were employed to identify where the significant difference rests SPSS® was used for all statistical analysis

8 3 Results

8 3 1 Representative data

Typical angle, angular velocity, moment and power data during the concentric phase are shown in figures 8 3 and 8 4

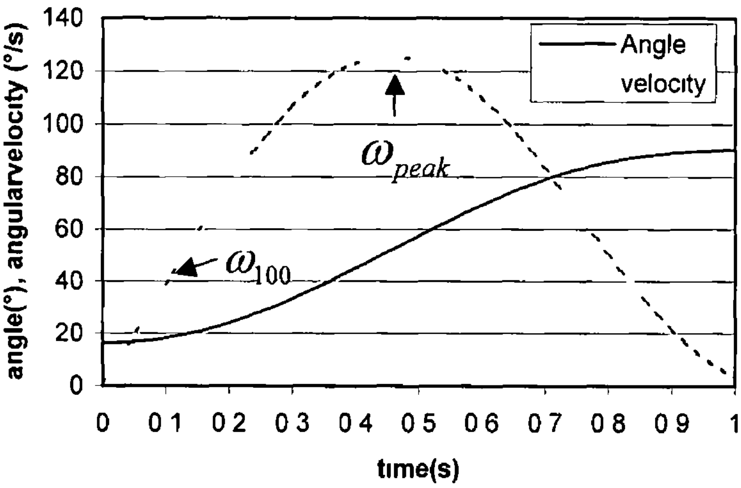


Figure 8 3 Angle and velocity curves during concentric phase

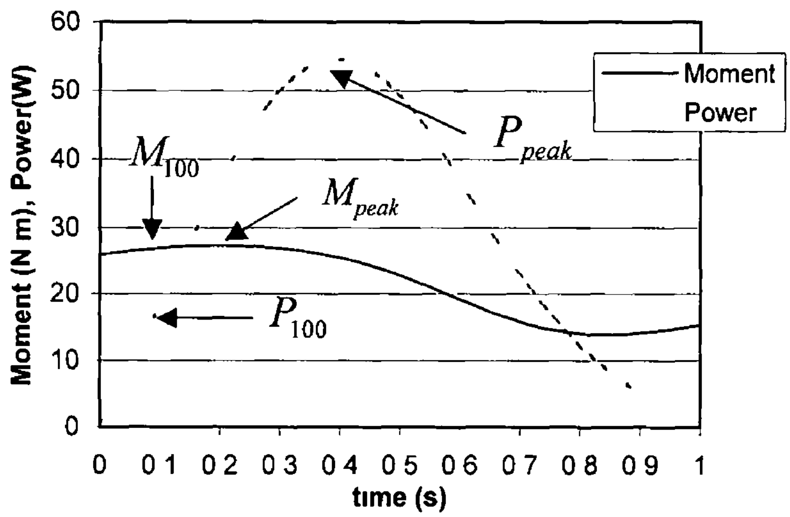


Figure 8 4 Moment and power curves during concentric phase

8 3 2 Reliability of measurement

The mean (± standard deviation) values of all variables measured in the pre-training tests for the four different test conditions (4 different days) are shown in table 8.1. The inter-day reliability (ICC) of measurement ranged from 0.58 to 0.99.

Table 8.1 Reliability of pre-training baseline test measurements

Variable	E+V	E+SV	NE+V	NE+SV	ICC
Concentric duration (ms)	883±184	890±192	911±218	859±201	0.88
Mean angular velocity(rad/s)	1.5±0.4	1.5±0.3	1.4±0.3	1.6±0.3	0.78
Peak angular velocity(rad/s)	2.8±0.7	2.7±0.6	2.8±0.5	3.0±0.5	0.77
Initial angular velocity(rad/s)	0.6±0.3	0.6±0.2	0.6±0.2	0.7±0.3	0.78
Mean moment (N.m)	27.3±6.2	27.7±6.6	26.9±6.6	26.9±6.2	0.99
Peak moment (N.m)	39.9±8.2	39.3±8.6	39.2±9.7	41.8±9.3	0.98
Initial moment (N.m)	35.3±6.8	35.6±6.9	33.5±8.1	37.0±7.2	0.94
Mean power (W)	41.2±8.3	40.9±10.3	40.4±13.6	43.5±11.3	0.91
Peak power (W)	93.7±26.3	89.7±27.1	93.6±31.8	104.3±31.6	0.89
Time to peak power (ms)	506±134	483±109	511±175	448±105	0.86
Initial power (W)	22.9±13.8	22.5±7.9	19.9±11.0	27.5±14.0	0.74
RPD (W/s)	207.8±108.5	201.4±87.8	198.4±84.7	264.4±113.8	0.85
Normalized EMGrms(biceps)	70.8±24.0	74.0±20.5	79.5±22.9	72.4±19.5	0.72
Nomalized EMGrms(0-120ms)(biceps)	111.5±22.2	112.4±26.2	111.0±28.5	107.4±18.6	0.58
EMGmpf(biceps)	79.5±13.1	80.2±11.9	76.9±8.4	81.3±12.4	0.69
Normalized EMGrms(triceps)	35.9±22.4	32.9±14.3	31.6±14.5	36.8±18.2	0.89

8 3 3 Mechanical and EMG output during training (acute effect)

Vibration, training set and their interaction did not have any significant effect on the mechanical variables measured ($p>0\ 05$) (table 8 2 to 8 4)

Table 8 2 Acute effect of training on concentric duration and velocity variables (mean±S D)

Variable	Condition	Set1	Set2	Set3
Concentric duration (ms)	E+V	906±211	913±222	913±234
	E+SV	866±145	868±141	881±168
ω_{mean} (rad/s)	E+V	1 4±0 4	1 5±0 5	1 5±0 5
	E+SV	1 5±0 4	1 5±0 4	1 5±0 4
ω_{peak} (rad/s)	E+V	2 6±0 6	2 8±0 8	2 8±0 9
	E+SV	2 7±0 7	2 7±0 6	2 7±0 6
ω_{100} (rad/s)	E+V	0 7±0 3	0 6±0 3	0 6±0 3
	E+SV	0 6±0 2	0 6±0 3	0 6±0 3

Note ω_{mean} = mean angular velocity, ω_{peak} = peak angular velocity, ω_{100} = initial angular velocity

Table 8 3 Acute effect of traımng on moment vanables (mean±S D)

Variable	Condition	Set1	Set2	Set3
M_{mean}	E+V	27 4±6 6	27 3±6 4	27 1±6 2
(N m)	E+SV	27 4±6 5	27 4±6 4	27 3±6 5
M_{peak}	E+V	39 7±8 1	39 9±7 9	39 9±7 9
(N m)	E+SV	39 7±9 1	39 6±8 7	38 9±7 9
M_{100}	E+V	36 3±6 4	34 9±6 4	34 6±6 9
(N m)	E+SV	35 6±6 9	35 7±7 0	35 5±6 7

Note M_{mean} = mean moment, M_{peak} = peak moment, M_{100} = ınıtıal moment

Table 8 4 Acute effect of traımng on power vanables (mean±S D)

Variable	Condition	Set1	Set2	Set3
P_{peak}	E+V	86 7±23 2	93 8±33 2	95 4±38 3
(W)	E+SV	90 9±28 7	91 5±25 2	88 0±24 0
T_P	E+V	451±134	497±163	485±141
(ms)	E+SV	456±79	470±105	481±116
P_{mean}	E+V	39 5±7 6	40 3±10 8	41 1±11 8
(W)	E+SV	41 5±9 4	41 5±9 2	40 3±8 7
P_{100}	E+V	26 2±11 5	22 4±10 5	21 1±10 5
(W)	E+SV	22 9±7 2	23 6±11 2	23 8±11 8
RPD	E+V	211 9±88 9	209 3±95 8	216 7±114 7
(W/s)	E+SV	206 0±73 5	206 3±74 0	197 4±79 6

Note P_{mean} = mean power, P_{peak} = peak power, P_{100} = ınıtıal power, T_P = tıme to peak power, RPD = rate of power development

For biceps EMGrms$_{(0\text{-}120ms)}$, only training set had a significant acute effect (p<0 01) Main effects analysis showed that EMGrms$_{(0\ 120ms)}$ in set 3 was significantly lower than that in set 1 (p<0 05) (table 8 5) Vibration and the interaction between vibration and set were not significant (p>0 05)

For biceps EMGrms, vibration, training set and their interactions did not have any significant effect (p>0 05) (table 8 5)

For biceps EMGmpf, only training set had a significant acute effect (p<0 01) Main effects analysis showed that EMGmpf both in set 2 and set 3 were significantly higher than that in set 1 (p<0 05) (table 8 5) Vibration and the interaction between vibration and set were not significant (p>0 05)

For triceps EMGrms, vibration, training set and their interaction did not have any significant acute effect (p>0 05) (table 8 6)

Table 8.5 Acute effect of traımng on EMG varıables on the bıcep brachıı

(mean±S D)

Varıable	Condıtıon	Set1	Set2	Set3
Normalızed $EMG_{rms\ (0-120ms)}$	E+V	120 3±29 7	112 7±46 4	100 4±30 9
	E+SV	111 2±23 4	103 5±19 5	106 3±31 0
Normalızed EMG_{rms}	E+V	76 3±22 3	75 8±30 1	69 9±23 9
	E+SV	73 9±20 5	71 1±19 6	70 6±19 7
EMG_{mpf}	E+V	77 9±10 5	84 9±13 1	83 9±11 7
	E+SV	81 2 ±10 7	84 0±13 3	84 5±12 6

Note *=sıgnıficant dıfference (p<0 05)

Table 8 6 Acute effect of traımng on EMG varıable on the trıcep brachıı

(mean±S D)

Varıable	Condıtıon	Set1	Set2	Set3
Normalızed EMG_{rms}	E+V	33 1±21 6	33 9±21 3	34 0±21 4
	E+SV	32 3±13 3	31 3±10 9	30 3±11 8

8 3 4 Mechanıcal and EMG output after traınıng (acute resıdual effect)

For all the mechanical variables analysed, vibration, exercise, test time and their interactions did not have any significant acute residual effect ($p>0.05$) (table 8.7 to 8.9).

Table 8.7 Acute residual effect of training on concentric duration and angular velocity variables (mean±S.D)

Variable	Condition	Pre	Post-1.5min	Post-10min
Concentric duration (ms)	E+V	883±184	953±305	892±210
	E+SV	890±192	858±170	826±121
	NE+V	911±218	910±211	929±239
	NE+SV	859±201	926±198	857±176
ω_{mean} (rad/s)	E+V	1.5±0.4	1.5±0.5	1.6±0.4
	E+SV	1.5±0.3	1.5±0.4	1.6±0.3
	NE+V	1.4±0.3	1.5±0.2	1.4±0.3
	NE+SV	1.6±0.3	1.4±0.2	1.6±0.3
ω_{peak} (rad/s)	E+V	2.8±0.7	2.9±0.9	2.9±0.8
	E+SV	2.7±0.6	2.8±0.6	2.8±0.6
	NE+V	2.8±0.5	2.7±0.4	2.7±0.5
	NE+SV	3.0±0.5	2.8±0.4	2.9±0.5
ω_{100} (rad/s)	E+V	0.6±0.3	0.6±0.2	0.7±0.3
	E+SV	0.6±0.2	0.6±0.3	0.6±0.2
	NE+V	0.6±0.2	0.7±0.3	0.6±0.2
	NE+SV	0.7±0.3	0.6±0.3	0.7±0.3

Note: ω_{mean} = mean angular velocity; ω_{peak} = peak angular velocity; ω_{100} = initial angular velocity; *=significant difference ($p<0.05$)

Table 8 8 Acute residual effect of training on moment variables (mean±S D)

Variable	Condition	Pre	Post-1 5min	Post-10min
	E+V	27 3±6 2	27 0±6 3	27 0±6 5
M_{mean}	E+SV	27 7±6 6	27 4±6 7	27 2±6 6
(N m)	NE+V	26 9±6 6	26 9±6 7	26 9±6 5
	NE+SV	26 9±6 2	26 8±6 4	26 9±6 4
	E+V	39 9±8 2	39 7±8 7	39 5±7 9
M_{peak}	E+SV	39 3±8 6	39 8±8 9	39 9±8 8
(N m)	NE+V	39 2±9 7	39 4±9 3	39 3±9 9
	NE+SV	41 8±9 3	40 1±7 5	41 5±8 9
	E+V	35 3±6 8	34 9±6 6	35 5±7 1
M_{100}	E+SV	35 6±6 9	35 4±7 4	35 8±7 5
(N m)	NE+V	33 5±8 1	34 9±7 8	34 5±7 5
	NE+SV	37 0±7 2	35 5±8 1	37 1±7 2

Note M_{mean} = mean moment, M_{peak} = peak moment, M_{100} = initial moment

Table 8 9 Acute resıdual effect of traınıng on power varıables (mean±S D)

Varıable	Condıtıon	Pre	Post-1 5mın	Post-10mın
	E+V	93 7±26 3	96 1±38 8	96 6±26 7
P_{peak}	E+SV	89 7±27 1	93 9±28 8	95 5±26 9
(W)	NE+V	93 6±31 8	91 9±27 1	91 5±34 9
	NE+SV	104 3±31 6	92 4±16 4	101 4±25 8
	E+V	506±134	573±285	493±140
T_P	E+SV	483±109	478±108	452±79
(ms)	NE+V	511±175	530±291	465±152
	NE+SV	448±105	514±153	465±165
	E+V	41 2±8 3	40 8±11 3	42 6±9 9
P_{mean}	E+SV	40 9±10 3	41 5±9 6	42 6±10 5
(W)	NE+V	40 4±13 6	40 7±12 0	40 1±14 1
	NE+SV	43 5±11 3	39 1±11 1	43 2±10 1
	E+V	22 9±13 8	21 1±7 2	24 4±11 3
P_{100}	E+SV	22 5±7 9	22 1±10 9	22 7±8 1
(W)	NE+V	19 9±11 0	24 3±11 2	20 8±11 3
	NE+SV	27 5±14 0	22 3±13 9	28 5±15 2
	E+V	207 8±108 5	200 8±101 7	214 4±89 5
RPD	E+SV	201 4±87 8	208 5±83 4	218 4±69 2
(W/s)	NE+V	198 4±84 7	205 8±82 1	209 1±76 2
	NE+SV	264 4±113 8	202 0±84 7	253 6±118 3

Note P_{mean} = mean power, P_{peak} = peak power, P_{100} = ınıtıal power,
T_P = tıme to peak power, RPD = rate of power development,

For biceps EMGrms$_{(0\text{-}120ms)}$, test time and the interaction between exercise and test time had a significant acute residual effect (p<0 05) Mam effects analysis showed that EMGrms$_{(0\ 120ms)}$ measured both at 1 5 minutes and 10 minutes after training was significantly lower than that in pre-training test (p<0 05) (table 8 10) Vibration and all interactions involving vibration were not significant (p>0 05)

For biceps EMGrms, test time and the interaction between exercise and test time had a significant effect on EMGrms (p<0 05) Main effects analysis showed that EMGrms measured 1 5 minutes after training was significantly lower than pre-training test (p<0 05) (table 8 10) Vibration and all interactions involving vibration were not significant (p>0 05)

For biceps EMGmpf, exercise, test time and the interaction between exercise and test time had a significant effect on EMGmpf (p < 0 05) Main effects analysis showed that exercise induced significantly higher EMGmpf (p<0 05) EMGmpf measured both at 1 5 minutes and 10 minutes after exercise were significantly higher than that in pre-training test (p<0 05) (table 8 10) Vibration and all interactions involving vibration were not significant (p>0 05)

Table 8 10 Acute residual effect of training on EMG variables on the bicep brachii (mean±S D)

Variable	Condition	Pre	Post-1 5min	Post-10min
Normalized $EMG_{rms\ (0\text{-}120ms)}$	E+V	111 5±22 2	93 1±21 8	90 0±19 2
	E+SV	112 4±26 2	98 9±33 3	103 6±41 7
	NE+V	111 0±28 5	107 5±33 5	108 1±35 1
	NE+SV	107 4±18 6	105 1±20 3	104 1±17 2
Normalized EMG_{rms}	E+V	70 8±24 0	68 6±23 2	66 0±21 3
	E+SV	74 0±20 5	69 3±21 7	68 3±23 1
	NE+V	79 5±22 9	73 1±19 6	77 8±26 5
	NE+SV	72 4±19 5	66 8±18 9	70 3±17 9
EMG_{mpf}	E+V	79 5±13 1	88 1±12 3	84 9±11 3
	E+SV	80 2±11 9	87 1±12 3	84 8±11 5
	NE+V	76 9±8 4	75 5±10 7	78 1±10 3
	NE+SV	81 3±12 4	80 5±9 9	78 9±8 3

Note *=significant difference (p<0 05)

Vibration, exercise, test time and their interactions did not have any significant acute residual effect on EMGrms on the triceps (p>0 05) (table 8 11)

Table 8 11 Acute residual effect of traimng on EMG vanable on the tncep brachii

(mean±S D)

Variable	Condition	Pre	Post-1 5min	Post-10min
Normalized EMG_{rms}	E+V	35 9±22 4	34 5±20 9	33 9±20 9
	E+SV	32 9±14 3	31 1±10 9	33 4±12 9
	NE+V	31 6±14 5	33 3±15 5	32 8±14 6
	NE+SV	36 8±18 2	34 1±16 7	35 7±18 8

8 4 Discussion

For the acute effect, the results of the present study showed that the mechanical output and muscle activity dunng maximal isotonic contractions were not enhanced by supenmposed vibration This is different from the other vibration traimng studies

To date, there have been only three studies examimng the effect of vibration traimng on maximal isotonic contractions with appropnate control design (6,21,26) Issunn et al (21) found that vibration could significantly enhance the acute maximal and mean power of explosive bicep curl by 10 4% and 10 2% respectively in elite athletes, and by 7 9% and 10 7% respectively in amateur athletes Lierbermann et al (26) found that the maximal strength of bicep curl was enhanced significantly by 4 9% in amateurs and 8 3% in Olympic athletes by supenmposed vibration Finally, a three weeks vibration traimng study by Issunn et al (6) indicated that supenmposed vibration could induce significantly greater strength gam in maximal isotonic strength than the conventional strength training without vibration (49.8% vs. 16%). All these findings suggested that the neuromuscular performance of maximal isotonic contraction could be enhanced by superimposed vibration.

The different results may be due to the vibration training methodology (vibration amplitude and frequency, method of vibration application, exercise protocol and subjects) employed in the present study, which is different from the above studies.

Firstly, vibration amplitude and frequency may be a possible reason for the different results. The vibration amplitude and frequency used in this study was 1.2 mm and 65 Hz respectively, and this vibration amplitude and frequency was applied directly to the tendon of the biceps. In all three of the above studies, vibration was applied to the biceps by an indirect method, in which subjects held a vibrating handle that vibrated at the amplitude of 0.3 to 0.4 mm and at the frequency of 44 Hz (6,21,26). The vibration amplitude on the biceps should be less than 0.3 to 0.4 mm because of the attenuation of the vibration signal during its transmission to the biceps (22,59). Therefore, it seems that vibration amplitude and frequency were higher in our study. However, an examination of other studies do not lend support to the argument that the vibration amplitude and frequency may be the reason for different results.

A comparison of the two studies by Torvinen et al. (7,12) suggested that larger vibration amplitude may be able to activate muscle more effectively. The higher vibration amplitude could irritate more muscle receptors, particularly the primary endings of muscle spindles, and may activate more motor units into contraction (30). As also shown by the results from study 1 (chapter 5), the amplitude of 1.2 mm was more effective in stimulating the biceps than the amplitude of 0.5 mm in a sub-maximal contraction. In addition, study 2 (chapter 6) also showed that the frequency of 65 Hz was more effective than 30 Hz in muscle activation. Therefore, the vibration load, which is determined by the vibration amplitude and frequency, is higher in the present study than those studies (6,21,26) in which facilitatory effect of vibration on maximal isotonic contraction was found. Thus a facilitatory effect of superimposed vibration on muscle neural activity, contraction force and power was expected in this study. However, although the same vibration amplitude and frequency used in this study was able to activate more motor units in sub-maximal contraction, they were unable to induce the same effect in maximal isotonic contraction.

Secondly, the method of vibration application may also be a possible reason for the different results. A direct method was employed in this study to facilitate the optimal utilization of vibration signals during vibration training. Although the direct method could facilitate delivering a high vibration load to the target muscle, vibration stimulation was localized to the specific muscle group. On the other hand, with an indirect method, vibration signal was transmitted through distal-to-proximal muscle groups, which may stimulate more muscle groups, and may be more suitable for the training of athletes (6). In addition, recent studies showed that the muscles in lower limb was able to damp the vibration input with the frequencies of 10 to 20 Hz (resonance frequency of lower limb) from the foot during walking and running by increasing muscle stiffness (39,40). Therefore indirect vibration may enhance the muscle stiffness of the upper limb or lower limb muscles during its transmission, which may facilitate the muscle performance. Recent studies have also shown that the stiffness regulation may play an important role in the power performance of contractions such as drop jump (83).

Finally, subject pre-training may also offer an explanation for the different results in the present study. Issurin et al. (21) recruited elite and amateur athletes as the subjects in their study to perform the explosive bicep curl exercise. These subjects were familiar with power exercises, and were able to perform contractions with maximal effort and high reproducibility. On the other hand, the subjects in our study were all untrained individuals, who will have had less experience with the maximal effort contraction with free weights, in which the requirement of coordination is higher than with an exercise with machine. It is noted that the variability of response to vibration are quite large among subjects in this study (e.g. peak power in set 1 with vibration ranged from 55 W to 116 W), and therefore lends some support to the influence of subject background being important.

In addition to the above reasons on vibraiton training methodology, the data analysis methods employed in the present study may also have influence on the results. Firstly, the selection of low cut-off frequency (2 Hz) to filter the joint angle data may have a influence on the mechanical ouput results. In the future studies, the influence of different cut-off frequency (higher than 2 Hz) on the mechanical output data during vibration training should be examined. Secondly, it was found that the reliability of EMG measurements was lower than the mechanical output measurements in the present study (table 8.1), which suggested that more cautions should be taken as to the interpretation of the EMG results.

Vibration training has been suggested to be able to increase the excitability of peripheral sense organs (3) and the central motor system (4,11), which may have a faciliatory effect on the subsequent contractions Torvinen et al (7) found that the knee extension strength and counter movement jump height were significantly increased immediately after a bout of 4 minutes whole body vibration training Rittweger et al (4) found that mean power frequency of EMG (EMGmpf) was significantly enhanced immediately after a bout of 6 minutes vibration training The authors (4) therefore suggested that an increase of central motor excitability to recruit predominantly large motor units may account for the muscle performance improvement after vibration However, it was found in this study that vibration did not have any facilitatory effect on the force and power output of maximal isotonic contraction measured at both 1 5 minutes and 10 minutes after vibration training The EMGmpf measured after vibration training in this study did not show any significant increase by vibration This may be due to the short duration of vibration in this study (30 seconds for each set, 3 sets) Issurin et al (21) found that the mean and maximal power of explosive bicep curl was not enhanced immediately after a bout of vibration training The authors (21) suggested that the short duration of vibration stimulation (6-7 seconds) may not be sufficient to affect the subsequent muscle performance

In order to examine the influence of exercise on the acute residual effect, this study incorporated vibration training both with exercise and without exercise in the experiment conditions However, as no acute residual effect of vibration was found in the present study, it is therefore unclear which exercise protocol is better for the acute residual effect The vibration training studies with longer duration of vibration stimulation are needed in the future to examine this issue

The EMG of antagonist muscle during and after vibration training was measured in this study This has not been reported in any previous studies It has been suggested that vibration may inhibit the activation of the antagonist muscles, leading to an enhanced overall force and power output around the joint (11) However, simultaneous vibration stimulation of the agonist and antagonist muscles with indirect method of vibration application may induce the reciprocal inhibition on the activation of agonist muscle (8,58) Therefore, it is plausible that the direct vibration of the agonist muscle tendon, as in the present study, may have the advantage in decreasing the antagonist muscle activity without eliciting any negative effect on agonist activation However, this was not found in the present study, with the EMGrms of the triceps, both during and after the vibration treatment, being unaffected by vibration It was thus suggested that vibration may not have the acute or acute residual effect of decreasing the antagonist muscle activity in maximal isotonic contractions

8 5 Conclusions

This study found that direct vibration did not enhance the neuromuscular performance of maximal isotonic contraction during training Direct vibration training with maximal isotonic exercise or without exercise did not have any residual effect on maximal isotonic contractions

Chapter 9

Study 5 Acute and acute residual effect of vibration training on neuromuscular performance with ballistic contractions

9 1 Introduction

Although it has been found by several vibration training studies that maximal force and power of isotonic contractions could be enhanced by superimposed vibration(6,21,26), this was not found in our previous study (chapter 8) in which no facilitatory acute effect of vibration on maximal isotonic contraction was found It was noticed that the subjects in the previous study had to decelerate the free weights (70% 1RM) during the concentric phase of each contraction, it was suggested that this deceleration mechanism may reduce the facilitatory effect of vibration, and may be the possible reason for the different results found in the previous study Therefore in this experiment, another kind of isotonic exercise in which subjects can contract in a ballistic manner and release the free weight at the end of concentric phase will be employed It is expected that vibration may exert its faciltatory effect on this kind of isotonic contraction to enhance the maximal force and power

The aim of this study is to examine the acute (during) and acute residual (following) effects of direct vibration training on neuromuscular performance with ballistic contractions

9 2 Methods

Only key aspects of the methods are presented below. A more detailed account of the methods is presented in the generic methods section (chapter 4).

9.2.1 Subjects

Fourteen young adult male volunteers took part in this study. The average age, mass, and height of the subjects were 21.6±2.2 (years), 77.1±15.1 (kg), and 178.6±8.7 (cm) respectively.

9.2.2 Experiment design

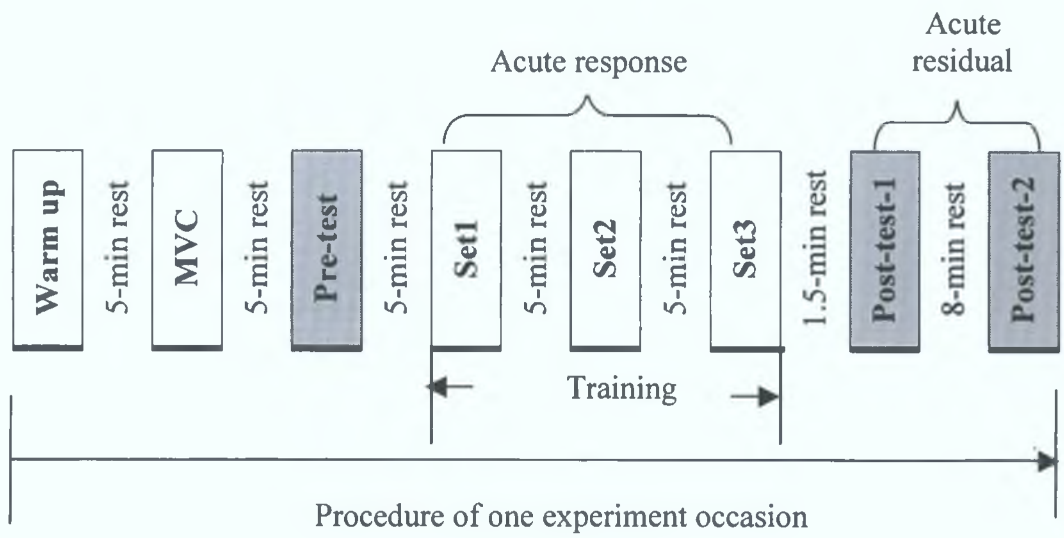
Subjects were exposed to two training conditions in random order: 1) exercise with superimposed vibration; 2) exercise with sham vibration. The exercise condition comprised of three sets of ballistic knee extensions with a load of 60%-70% 1RM performed on a leg extension machine (figure 7.1). Each set comprised of 5 repetitions.

Subjects sat on the machine and were firmly strapped to the seat. The poplital fossa of the subject was aligned to the rotation axis of the weight on the machine. The subjects were instructed to hold their arms across their chest and keep their back straight during exercise. Only the right leg was used in lifting the weight. The subjects were instructed to lift the weight as hard and as fast as possible in the concentric phase, and not to decelerate it at the end of concentric phase. A bar that was firmly fixed to an exterior frame support was positioned before the subject to stop the weight from hitting the subject

9 2 3 Experimental procedure

The 1RM strength for the knee extension was estimated on each subject by testing with a 10RM load on a separate day, at least 3 days before the start of the experiment(76) During all visits, subjects familiarized themselves with the test procedure and the ballistic knee extension exercise

During the actual test day, subjects performed a warm-up exercise first (1 set of 10 repetitions of the knee extension with 25% of 1RM load), followed by a maximal effort isometric knee extension for 5 seconds with a knee joint angle of 120° (see figure 9 1) After five minutes rest, a set of 5 repetitions ballistic knee extensions with 60%-70% 1RM load was performed as the pre-training test (pre-test) After a further five minutes, subjects performed 3 sets of training exercise (with sham vibration or with vibration), with five minutes rest between each set Two sets of 5 repetitions ballistic knee extension contractions were performed at 1 5 min and 10 min after the end of training as the post-training tests This procedure was undertaken on two occasions that were separated by at least three days, once for each experiment condition (vibration and sham vibration)



Note: MVC=maximal isometric contraction

Figure 9.1 Study design

9.2.4 Vibration

The vibration was produced by a portable muscle tendon vibrator that was strapped onto the quadriceps muscle about 10 cm from the superior surface of the patella. Vibration amplitude and frequency were set at 1.2 mm and 65 Hz, respectively. In the sham vibration condition, the eccentric masses were removed so that there was only the noise of the motor running, but no notable vibration was produced.

9.2.5 Measurements

Knee joint angle and EMG of the rectus femoris (RF) and vastus lateralis (VL) were measured during training and in pre and post training tests. EMG measurement was also made during the maximal isometric knee extension. Synchronization of goniometer and EMG measurements was achieved by connecting an output stimulation signal from the Powerlab to the DataLink

9 2 6 Data analysis

The knee joint angular velocity (ω), acceleration (α), moment (M_{elbow}), and power (P_{elbow}) data were calculated from the filtered joint angle data (section 4 4 2) The following variables were calculated for the concentric phase 1) peak angular velocity (ω_{peak}), 2) time to peak angular velocity (T_{ω}), 3) peak moment (M_{peak}), 4) time to peak moment (T_{m}), 5) peak power (P_{peak}), 6) time to peak power (T_{P}) They were the dependent mechanical variables (figure 9 3 and 9 4)

EMGrms data on the RF and VL during the concentric phase were averaged and then normalized to the average EMGrms measured during the 5 seconds maximal isometric knee extension The mean power frequency of EMG (EMGmpf) in concentric phase was also calculated These were the dependent EMG variables

The mechanical and EMG variables (detailed above) of the second, third and fourth repetitions of each set were selected and averaged to represent the variables for each set This procedure was employed because the repeatability for the variables, as assessed via Cronbach's alpha coefficient, was higher when the first and fifth repetitions were not included in the analysis(82)

9 2 7 Statistical methods

As the pre-traınıng test was made on both of the two test condıtıons performed on two dıfferent days, the ınter-day relıabılıty of all dependant varıables was calculated usıng ıntraclass correlatıon(77) A paıred t test was also performed to determıne whether there was a sıgnıficant dıfference between the baselıne test values measured on the two dıfferent test days

To determıne the acute effect of vıbratıon (vıbratıon, no vıbratıon) and set (set1, set2, set3) on the mechanıcal and EMG varıables durıng traınıng, a two factor ANOVA (vıbratıon treatment (2) × traınıng set (3)) wıth repeated measures on the subjects was employed

To examıne the acute resıdual effect of vıbratıon (vıbratıon, no vıbratıon) and test tıme (pre-test, post-test-1, post-test-2) on the mechanıcal and EMG varıables after traınıng, a two factor ANOVA (vıbratıon treatment (2) × test tıme (3)) was employed

For all analyses a probabılıty value of sıgnıficance of $p<0\ 05$ was employed Where a sıgnıficant maın effect or ınteractıon ınvolvıng the ındependent varıable of vıbratıon was found, a maın or sımple effects analyses was undertaken wıth approprıate Bonferronı adjustment to show where the sıgnıficant dıfference rests SPSS® was used for all statıstıcal analysıs

9 3 Results

9 3 1 Representatıve data

Typıcal angle, angular velocıty, moment and power data durıng the concentrıc phase were shown ın figures 9 2 and 9 3

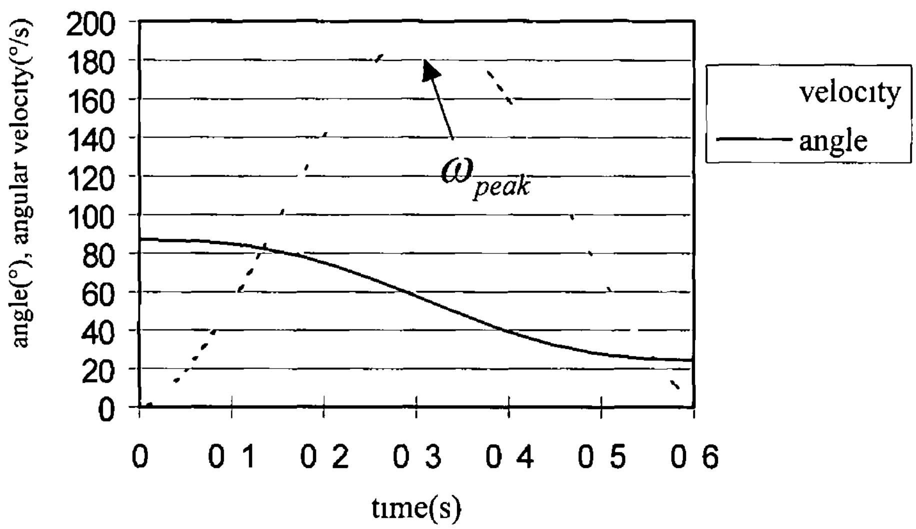


Fıgure 9 2 Angle and velocıty curves durıng the concentrıc phase

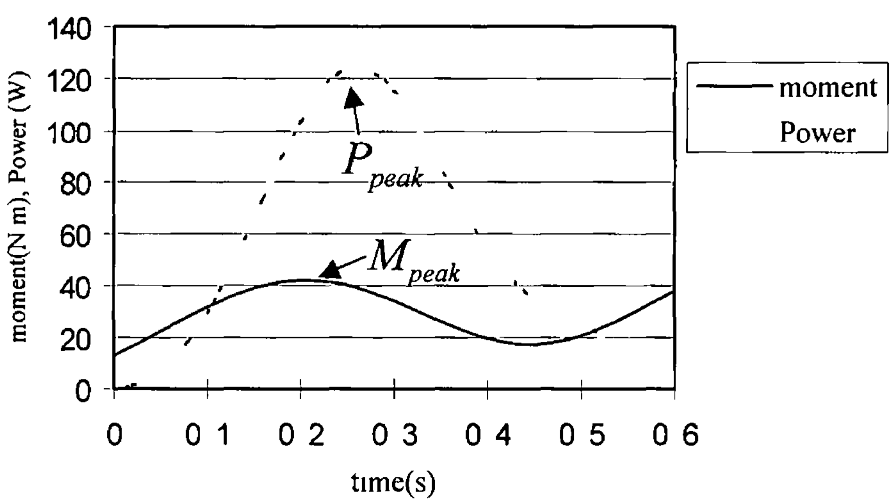


Figure 9 3 Moment and power curves durıng the concentrıc phase

9 3 2 Reliability of measurements

The mean values of all the variables in pre-training test in the two experimental conditions are listed in table 9 1 There was no significant difference between the two days measurement on pre-training test values (p>0 05) The reliability of measurement (ICC) ranged from 0 61 to 0 95

Table 9 1 Reliability of pre-training baseline test measurements

Variables	Sham vibration	vibration	p value of t-test	Reliability (ICC)
ω_{peak} (rad/s)	3 2±0 6	3 1±0 6	0 32	0 82
T_{ω} (ms)	414 3±88 9	398 1±105 4	0 37	0 87
M_{peak} (N m)	68 7±26 8	66 9±22 2	0 61	0 92
T_m (ms)	311 4±115 1	286 7±133 9	0 25	0 90
P_{peak} (W)	194 8±64 9	179 2±48 6	0 34	0 68
T_P (ms)	368 6±96 8	350 0±112 9	0 31	0 89
Normalized EMGrms (RF)	173 4±36 6	153 8±42 4	0 07	0 73
Normalized EMGrms (VL)	209 1±79 6	199 3±41 2	0 59	0 61
EMGmpf (RF) (Hz)	89 9±15 7	91 9±12 6	0 39	0 90
EMGmpf (VL) (Hz)	77 6±10 5	73 2±7 6	0 19	0 71

9 3 3 Mechanical and EMG variables during training (acute effect)

Vibration, training set and their interactions did not have a significant acute effect on ω_{peak}, T_{ω}, M_{peak}, T_m and P_{peak} (p>0 05) (table 9 2)

Vibration had a significant acute effect on T_p ($p<0.05$). Main effects analysis showed that T_p was significantly higher with vibration than with sham-vibration condition ($p<0.05$). The increase of T_P by vibration was approximately 4%, 10%, and 16% in set 1, set2 and set3 respectively (table 9.2).

Table 9.2 Acute effect of training on mechanical variables (mean±S.D)

Variable	Condition	Set1	Set2	Set3
ω_{peak}	V	3.0±0.6	3.0±0.7	3.0±0.7
	SV	3.2±0.6	3.2±0.5	3.1±0.6
$T\omega$	V	405±107	402±99	425±109
	SV	389±92	382±86	380±95
M_{peak}	V	65.3±19.5	63.9±18.9	65.8±18.7
	SV	68.7±23.9	69.3±24.5	71.8±27.2
T_m	V	304±135	301±123	327±141
	SV	280±122	276±106	265±117
P_{peak}	V	179±49	173±52	186±155
	SV	205±66	208±162	212±68
T_p	V	361±118 *	369±107 *	383±116 *
	SV	347±99	335±93	331±98

Note: V=vibration, SV=sham vibration

Vibration had a significant acute effect on EMGrms of the RF ($p<0.05$) Main effects analysis showed that EMGrms was significantly lower with vibration than with sham-vibration condition ($p<0.05$) The decrease of EMGrms by vibration was approximately 10%, 14% and 15% in sets 1, 2, 3 respectively (table 9 3)

Vibration, training set and their interactions did not have a significant acute effect on EMGrms of the VL ($p>0.05$) (table 9 3)

Table 9.3 Acute effect of training on EMG variables (mean±S D)

Variable	Condition	Set1	Set2	Set3
Normalized EMGrms (RF)	V	153±45 *	147±40 *	143±38 *
	SV	170±35	170±39	168±43
Normalized EMGrms (VL)	V	185±38	197±44	181±41
	SV	191±65	198±74	197±72
EMGmpf (RF)	V	92 8±13 0	94 9±12 9	94 5±12 7
	SV	89 5±13 6	92 9±15 4	93 4±15 4
EMGmpf (VL)	V	74 9±7 0	74 7±7 3	77 4±7 5
	SV	78 2±9 8	80 5±11 6	78 4±10 3

Note V=vibration, SV=sham vibration

Vibration did not have a main effect on EMGmpf of the RF (p>0 05) Training set had a significant effect on EMGmpf of the RF (p<0 01), with values significantly higher both in set 2 and 3 than in set 1 (p<0 05) (table 9 3)

Vibration did not have a main effect on EMGmpf of the VL (p>0 05) The interaction between vibration and training set had a significant effect on EMGmpf on VL (p<0 05) Simple effects analysis showed that with vibration the EMGmpf in set 2 was significantly lower than that with sham-vibration (p<0 05) This decrease of EMGmpf by vibration was 7% (table 9 3) EMGmpf in set 3 was significantly higher than those in set 2 and set 1 (p<0 05) (table 9 3)

9 3 4 Mechanical and EMG variables after training (acute residual effect)

Vibration, test time and their interactions did no have any significant acute residual effect on any of the mechanical variables (p>0 05) (table 9 4)

Table 9 4 Acute residual effect of training on mechanical variables (mean±S D)

Variable	Condition	Pre	Post_1	Post_2
ω_{peak}	V	3 1±0 6	3 1±0 7	3 1±0 7
	SV	3 2±0 6	3 2±0 7	3 2±0 6
T_{ω}	V	398±105	408±112	389±84
	SV	414±89	402±97	396±96
M_{peak}	V	66 9±22 2	64 7±19 7	65 8±20 2
	SV	68 7±26 8	70 4±26 9	72 3±28 1
T_m	V	287±134	307±134	279±110
	SV	311±115	294±124	290±116
P_{peak}	V	179±65	175±51	179±57
	SV	195±65	201±64	207±67
T_p	V	350±113	371±113	351±93
	SV	369±97	358±99	349±101

Note V=vibration, SV=sham vibration

Vibration and test time had significant acute residual effects on EMGrms of the RF ($p<0\ 05$) With vibration the EMGrms was significantly lower than with sham-vibration ($p<0\ 05$) The decrease in EMGrms by vibration was 16% and 15% m post-training test 1 and post-training test 2, respectively However, the EMGrms in the vibration condition before the training was 12% lower than that in sham-vibration condition (table 9 5) In addition, the EMGrms in post training test 1 was significantly lower than during the pre-training test ($p<0\ 05$) (table 9 5)

Table 9 5 Acute residual effect of training on EMG variables (mean±S D)

Variable	Condition	Pre	Post_1	Post_2
Normalized EMGrms (RF)	V	153±42	136±39	141±41
	SV	173±37	162±38	165±42
Nomalized EMGrms (VL)	V	199±42	179±41	191±46
	SV	209±79	189±68	193±67
EMGmpf (RF)	V	91 9±12 6	93 9±12 2	96 4±13 9
	SV	89 9±15 7	92 1±13 8	93 8±14 9
EMGmpf (VL)	V	73 2±7 6	75 4±7 7	76 4±7 5
	SV	77 6±10 5	78 2±12 0	81 3±10 2

Note V=vibration, SV=sham vibration

Vibration did not have a significant acute residual effect on the EMGrms of the VL (p>0 05) Only test time had a significant acute residual effect on the EMGrms of the VL (p < 0 01) Main effects analysis showed that the EMGrms in post-training test 1 was significantly lower than that in pre-training test (p<0 05) (table 9 5)

Vibration did not have a significant acute residual effect on the EMGmpf of the RF (p>0 05) Only test time had a significant acute residual effect on the EMGmpf of the

RF ($p<0.01$). Main effects analysis showed that EMGmpf in set 3 was significantly higher than that in set 1 ($p<0.05$) (table 9.5).

Vibration did not have a significant acute residual effect on the EMGmpf of the VL ($p>0.05$). Only test time had a significant effect on the EMGmpf of the VL ($p<0.01$). Main effects analysis showed that EMGmpf in post-training test 2 was significantly higher than those in both pre-training test and post-training test 1 ($p<0.05$) (table 9.5).

9.4 Discussion

This study found that vibration did not have a facilitatory acute effect on the neuromuscular performance of ballistic knee extensions. Similar results were also found in study 4 (chapter 8), which showed that the muscle activity and mechanical output of maximal isotonic contraction (bicep curl) were not enhanced by vibration. Because the subjects had to decelerate the free weight (dumbbell) during the concentric phase of the maximal isotonic contraction (bicep curl) in study 4, it was speculated that this deceleration mechanism may inhibit the enhancement of neuromuscular performance associated with vibration in the whole concentric phase. It was also postulated that when subjects performed an exercise in which the free weight could be released at the end of contraction, the enhancement in neuromuscular performance may be facilitated.

The contraction performed in the study was a ballistic knee extension with a load of 60%-70% 1RM which reduced the requirement to decelerate the joint and hence worked the muscle harder. However, despite these changes, vibration still had no faciltatory effect on maximal muscle contraction force and power.

The vibration amplitude and frequency used in the present study was the same as study 4 (chapter 8), which was 1.2 mm and 65 Hz respectively. These vibration characteristics were chosen because they were shown to induce the greatest enhancement of muscle activity in study 1 (chapter 4) and 2 (chapter 6), in which sub-maximal isometric elbow flexion was performed. In addition, it was found in study 3 (chapter 7) that these vibration characteristics could significantly enhance the EMGrms on the VL and the VM ($p<0.05$) during a sub-maximal knee extension. Therefore, these results suggested that direct muscle vibration may enhance neuromuscular performance in sub-maximal effort contractions, but may not in maximal effort contractions.

No study to date has directly compared the effect of vibration on sub-maximal and maximal isotonic contractions. It was found in isometric contractions that muscle-tendon vibration could enhance the muscle activity and contraction force of sub-maximal contraction, but may not in maximal contractions (13,84). As a possible explanation for the different effect of vibration on maximal and submaximal isometric contractions, Bongiovanni and Hagbarth (84) have suggested that with sub-maximal contraction the Ia afferent inflow induced by vibration may be able to exceed the pre-existing fusimotor-driven Ia afferent discharges and induce reflex contraction to increase the contraction force. However, with the maximal voluntary contraction, vibration may not be able to cause further increase of Ia afferent inflow, and thus may not have a facilitatory effect on maximal voluntary contractions (84).

In addition, the results of this study indicated that vibration tended to have a suppression effect on neuromuscular performance during vibration training. The time to peak power (T_P) with superimposed vibration was significantly longer than that with sham-vibration (table 9.2), indicating that the peak power was developed more slowly when vibration was applied. The EMGrms measured on the RF was significantly decreased and the EMGmpf on the VL in set 2 was significantly lower in the vibration condition than in sham-vibration condition (table 9.3). These findings suggest that during vibration training, the recruitment of motor units, especially the large motor units, was suppressed by vibration, as the increase of EMGmpf has been postulated to reflect the recruitment of more large motor units(4).

Vibration may activate the primary afferent endings of the muscle spindle which activate α-motoneurons and elicit a reflex contraction called the tonic vibration refex (TVR) (31). However, at the same time Ia afferent inflow induced by vibration may induce presynaptic inhibition which would reduce the further recruitment of motor units (85), and depresses the H-reflex and tendon-reflex (58,85). Bongiovani and Hagbarth (13) suggest that this suppression effect is developed quickly after the onset of vibration. There may also be a slowly developing suppression effect by prolonged vibration on voluntary contraction force, which is suggested to be due to 'transmitter depletion' and exhaustion of polysynaptic Ia excitatory pathways (13). It has been shown that this later suppression effect of vibration could affect the subject's ability to generate high firing rates in high-threshold motor units (13). As shown by the results (table 9.2 and 9.3), the T_P and EMGrms of the RF decreased by vibration from set 1 to set 3. The EMGmpf on VL decreased in set 2 by vibration. It is thus possible that both the quickly developing and the slowly developing inhibition effect of vibration may account for these findings

Similar to the previous study (study 4, chapter 8), no facilitatory acute residual effect was found after vibration training This may also result from the very short duration of vibration stimulation in the training process (15 seconds each set for three sets) (21) In addition, an inhibition effect of vibration can be seen from the EMG measurements performed post training in this study The average EMGrms of the RF in the vibration condition was significantly lower than the sham-vibration condition at 1 5 minutes and 10 minutes after vibration training (table 9 5) This may be explained by the findings made by Bongiovanni and Hagbarth (13) that the inhibition effect of vibration on high threshold motor units may remain several minutes after the end of vibration

9 5 Conclusion

This study found that vibration stimulation had no facilitatory acute or acute residual effect on neuromuscular performance of ballistic knee extensions in which subjects did not need to excessively decelerate the free weight during the concentric phase of contraction Vibration appears to have a suppression effect on some muscle mechanical and EMG output measures during training and some EMG measures immediately after vibration training This phenomenon has not been reported in prior vibration training studies and should be taken as an important issue in future studies on vibration training

Chapter 10

Study 6: **Influence of load on neuromuscular response to vibration training – a study on maximal isotonic contractions**

10.1 Introduction

The study on vibration training with sub-maximal contractions (study 3, chapter 7) demonstrated that the resistance load employed may have a influence on the acute enhancement of neuromuscular performance by vibration. However, it is unclear whether the similar effect of resistance load exists in vibration training with other kind of exercise, e.g. maximal isotonic contractions. Although several studies have examined the effect of vibration training with maximal isotonic contractions, none of them investigated the influence of different resistance loads (6,21,26). In the previous two studies on vibration training with maximal isotonic contractions (chapter 8 and 9), a similar range of resistance load (60-70% 1RM) was employed. It is necessary therefore to examine whether other range of resistance load will elicit a different neuromuscular response to vibration. Another load range of 40% 1RM will be employed with the 70% 1RM load in this study, as it has been suggested that the load of 40% 1RM executed at maximum speed may be able to train the speed component of power (86).

The aim of this study is to examine whether different training loads (40% and 70% 1RM) have influence on the acute (during) and acute residual (following) effect of direct vibration training on neuromuscular performance of maximal isotonic contractions.

10.2 Methods

Only key aspects of the methods are presented below. A more detailed account of the methods is presented in the generic methods section (chapter 4).

10.2.1 Subjects

Eleven young adult male volunteers took part in this study. The average age, mass and height of the subjects were 25.3±7.4 (years), 76.6±5.6 (kg) and 175±6 (cm), respectively.

10.2.2 Experiment design

Subjects were exposed to four training conditions in random order: 1) training with vibration and 40% 1RM load (40%V); 2) training with sham vibration and 40% 1RM load (40%SV); 3) training with vibration and 70% 1RM load (70%V); 4) training with sham vibration and 70% 1RM load (70%SV). The exercise was three sets of dynamic bicep curls, performed by the dominant arm while sitting on a preacher curl bench (see figure 8.1). Each set comprised of five repetitions. During exercise, subjects were instructed to place both arms over the chest/arm support while leaning forward so that their chest was firmly pressed against the support pad. They attempted to move the weight as fast as possible in the concentric phase, and to fully extend their elbow joint in the eccentric phase There was 3 to 5 minutes rest time between each set

10 2 3 Experimental procedure

The 1RM strength of for the bicep curl was measured for each subject on a separate day at least three days before the start of experiment Subjects were also familiarized with the test procedure on that day During the actual test day, subjects first performed a warm-up exercise (10 repetitions of bicep curls with 25% 1RM load) after the measuring equipments were placed on subjects After 2 minutes rest, a set of 5 repetitions bicep curl with the employed load (40% or 70% 1RM) was performed as the pre-training test (pre-test) Then after 5 minutes rest, subjects performed one of the four training conditions as stated above One set of 5 repetitions with the employed load (40% or 70% 1RM) was performed 5 minutes after the end of training as the post-training test (post-test) (figure 10 1) The subjects were asked to perform the concentric phase of contractions as hard and as fast as possible during all sets This procedure was undertaken on four occasions that were separated by at least 3 days, once for each experimental condition

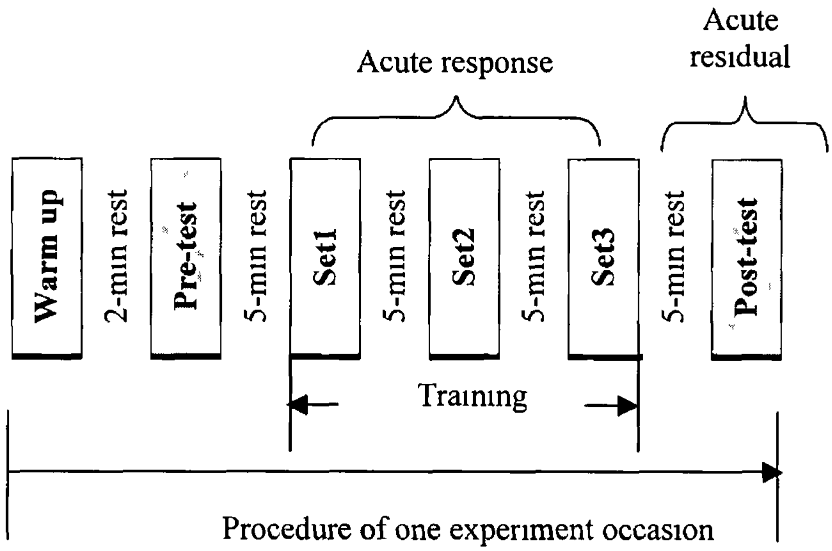


Figure 10 1 Study design

10 2 4 Vibration

Vibration was produced by a portable muscle tendon vibrator (section 3 2 3) that was strapped onto the biceps tendon Vibration amplitude and frequency were set at 1 2 mm and 65 Hz, respectively In the sham vibration condition, the eccentric masses were removed so that there was only the noise of the motor running, but no notable vibration was produced

10 2 5 Measurements

Elbow joint angle and EMG of the bicep brachii were measured both during training and in the pre and post training tests Synchronization of goniometer and EMG measurements was achieved by connecting an output stimulation signal from the Powerlab to the DataLink

10 2 6 Data analysis

The elbow joint angular velocity (ω), acceleration (α), moment (M_{elbow}), and power (P_{elbow}) data were calculated from the filtered joint angle data (section 4 4 2) For ω, M_{elbow} and P_{elbow}, mean and peak measures were determined In addition, initial power (at 100 ms, P_{100}) and time to peak power (T_P) were also determined These were the dependent mechanical variables

EMGrms data were averaged for the concentric phase of the bicep curl (EMGrms) The mean power frequency of EMG (EMGmpf) of the biceps in the concentric phase was also calculated These were the dependent EMG variables

The mechanical and EMG variables (detailed above) of the second, third and fourth repetitions of each set were selected and averaged to represent the variables for each set This procedure was employed because the repeatability for the variables, as assessed via Cronbach's alpha coefficient, was higher when the first and fifth repetitions were not included in the analysis(82)

10 2 7 Statistical analysis

As the pre-training test was made on two different days when the same load condition was employed (40% or 70% 1RM), the inter-day reliability of all variables was calculated using intraclass correlation (77) A paired t-test was performed to determine if there was significant difference between the pre-training test measurements with the same load but on different days

To determine the acute effect of vibration (vibration, no vibration), load (40% and 70% 1RM) and set (set1, set2, set3) on the mechanical and EMG variables during training, a three factor ANOVA (vibration treatment (2) × load(2) × training set (3)) with repeated measures on the subjects was employed

To examine the acute residual effect of vibration (vibration, no vibration), load (40% and 70% 1RM) and test time (pre-test, post-test) on the mechanical and EMG variables after training, a three factor ANOVA (vibration treatment (2) × load (2) × test time (2)) was employed

For all analyses a probability value of significance of p<0 05 was employed Where a significant main effect or interaction involving the independent variable of vibration was found, a main or simple effects analyses was undertaken with appropriate Bonferroni adjustment to show where the significant difference rests SPSS® was used for all statistical analysis

10 3 Results

10 3 1 Reliability of measurements (tables 10 1 and 10 2)

The mean results and repeatability analysis for all the variables measured in the pre-training test, on the two different days with the same exercise load (40% 1RM or 70% 1RM), are shown in tables 10 1 and 10 2, respectively There was no significant difference between the two test days for the pre-training test measures on any variable (p≥0 05) It can also be seen from the tables 10 1 and 10 2 that the reliability for mean velocity, peak velocity, mean power and peak power was significantly lower with 40% 1RM load than with the 70% 1RM load

Table 10.1 Pre-training test measurements with the 40% 1RM load

Variable	Vibration	Sham vibration	p value of t-test	ICC
Mean velocity (rad/s)	2 0±0 5	2 0±0 3	0 61	0 50
Peak velocity (rad/s)	3 6 ±0 8	3 6±0 5	0 85	0 59
Mean moment (N m)	16 1±2 1	15 8±2 1	0 27	0 96
Peak moment (N m)	26 6±4 2	26 2±3 1	0 61	0 85
Mean power (W)	34 3±6 1	32 8±4 0	0 5	0 22
Peak power (W)	79 7±19 9	77 4±12 2	0 72	0 38
Time to peak power (ms)	304±86	307±82	0 87	0 76
Initial power (W)	33 8±22 3	30 3±14 7	0 52	0 73
EMGrms (mV)	0 80±0 59	0 63±0 50	0 27	0 72
EMGmpf	82 5±8 1	82 0±18 8	0 92	0 49

Table 10.2 Pre-training test measurements with the 70% 1RM load

Variable	Vibration	Sham vibration	p value of t-test	ICC
Mean angular velocity(rad/s)	1.3±0.2	1.5±0.4	0.13	0.68
Peak angular velocity(rad/s)	2.3±0.5	2.7±0.7	0.05	0.70
Mean moment (N.m)	30.6±4.8	30.7±5.0	0.92	0.93
Peak moment (N.m)	40.8±7.1	42.5±7.4	0.17	0.91
Mean power (W)	39.8±7.6	45.1±14.2	0.11	0.76
Peak power (W)	79.7±18.9	97.3±34.9	0.06	0.68
Time to peak power (ms)	514±212	464±148	0.29	0.81
Initial power (W)	25.1±14.7	30.1±27.6	0.50	0.61
EMGrms (mV)	0.75±0.46	0.69±0.43	0.39	0.92
EMGmpf	80.4±6.3	80.1±9.1	0.93	0.18

10.3.2 Mechanical and EMG variables during training (acute effect)

Vibration had no significant acute effect on mean angular velocity ($p>0.05$). Load had a significant effect on mean angular velocity ($p<0.01$). Main effects analysis showed that the mean angular velocity with the load of 40% 1RM was significantly higher than that with 70% 1RM load (2.1 vs. 1.3 rad/s, $p<0.05$) (table 10.3).

Vibration had no significant acute effect on peak angular velocity (p>0 05) Load had a significant effect on peak angular velocity (p < 0 001) Main effects analysis showed that the peak angular velocity with the load of 40% 1RM was significantly higher than that with 70% 1RM load (3 7 vs 2 4 rad/s, p<0 05) (table 10 3)

Table 10 3 Acute effect of training on angular velocity variables (mean±S D)

Velocity	Condition		Set1	Set2	Set3
ω_{mean} (rad/s)	40%	Vib	2 0±0 5	2 1±0 4	2 1±0 4
		SV	2 0±0 3 *	2 1±0 3 *	2 0±0 3 *
	70%	Vib	* 1 2±0 3	* 1 3±0 3	* 1 2±0 3
		SV	1 5±0 4	1 5±0 4	1 5±0 4
ω_{peak} (rad/s)	40%	Vib	3 6±0 8	3 7±0 6	3 7±0 6
		SV	3 7±0 6 *	3 8±0 6 *	3 7±0 6 *
	70%	Vib	* 2 1±0 4	* 2 3±0 5	* 2 2±0 5
		SV	2 6±0 7	2 6±0 8	2 8±0 8

Note *=significant difference,

Vibration had no significant acute effect on mean moment (p>0 05) Load had a significant effect on mean moment (p < 0 001) Mam effects analysis showed that the mean moment with the load of 70% 1RM was significantly higher than that with 40% 1RM load (30 6 vs 15 8 N m, p<0 05) (table 10 4)

Vibration had no significant acute effect on peak moment (p>0 05) Load had a significant effect on peak moment (p < 0 001) Main effects analysis showed that the peak moment with the load of 70% 1RM was significantly higher than that with 40% 1RM load (41 8 vs 26 8 N m, p<0 05) (table 10 4)

Table 10 4 Acute effect of training on moment variables (mean±S D)

Moment	Condition		Set1	Set2	Set3
M_{mean} (N m)	40%	Vib	16 0±2 2	15 9±2 1	15 9±1 9
		SV	15 7±2 2 *	15 6±2 3 *	15 6±2 4 *
	70%	Vib	* 30 7±4 8	* 30 5±4 7	* 30 6±4 5
		SV	30 9±5 1	30 5±5 0	30 6±5 4
M_{peak} (N m)	40%	Vib	26 1±4 0	26 3±4 2	26 6±4 3
		SV	27 1±3 8 *	27 3±3 7 *	27 3±3 6 *
	70%	Vib	* 40 9±7 0	* 41 2±6 5	* 39 9±5 9
		SV	42 8±7 9	41 8±8 0	43 8±8 1

Note *=significant difference,

Vibration, load and the interaction between vibration and load had a significant effect on mean power (p<0 05) Simple effects analysis showed that the mean power in the vibration condition with 70% 1RM load was significantly lower than sham vibration with 70% 1RM load (16 8%, 13% and 18 5% in set 1, 2 and 3, respectively, p<0 05) The mean power with 70% 1RM load with sham vibration was significantly higher than that with 40% 1RM load with sham vibration (table 10 5) (p<0 05)

Vibration, load, training sets and their interactions did not have any significant effect on peak power (p>0 05) (table 10 5)

Only vibration had a significant effect on initial power (p<0 05) Main effects analysis found that initial power with vibration was significantly lower than that with sham-vibration (27 1 vs 33 7 W, p<0 05) (table 10 5)

Vibration had no significant acute effect on time to peak power (T_P) (p>0 05) Only load had a significant effect on time to peak power (p<0 05) Mam effects analysis showed that T_P with the load of 70% 1RM was significantly higher than that with the load of 40% 1RM (518 vs 300 ms, p<0 05) (table 10 5)

Table 10 5 Acute effect of training on Power variables (mean±S D)

Variable	Condition		Set1	Set2	Set3
P_{mean} (W)	40%	Vib	33 5±6 9	34 4±4 9	34 4±5 2
		SV	33 8±4 4	34 4±4 4	33 2±3 7
	70%	Vib	* 37 6±8 9	* 38 9±8 5	* 37 0±8 9
			*	*	*
		SV	45 2±14 6	44 7±13 7	45 4±12 8
P_{peak} (W)	40%	Vib	77 7±19 5	79 4±15 5	80 6±15 7
		SV	80 5±14 0	83 6±15 0	82 1±14 8
	70%	Vib	77 9±19 0	79 6±20 1	74 4±16 9
		SV	97 2±36 4	96 5±38 8	103 9±40 3
P_{100} (W)	40%	Vib	30 9±20 9	30 9±21 9	31 6±22 9
			*	*	*
		SV	35 2±16 5	35 9±16 4	33 6±15 9
	70%	Vib	24 2±15 4	23 2±13 5	21 6±11 7
			*	*	*
		SV	33 2±28 2	30 6±18 6	33 3±32 3
T_p (ms)	40%	Vib	313±67	315±72	310±75
		SV	287±80 *	283±76 *	293±86 *
	70%	Vib	* 512±291	* 552±307	* 579±246
		SV	480±181	520±212	465±163

Note *=significant difference,

Vibration, load, training set, and their interactions did not have any significant effect on EMGrms and EMGmpf (p>0 05) (table 10 6)

Table 10 6 Acute effect of traımng on EMG varıables (mean±S D)

Varıable	Condıtıon		Set1	Set2	Set3
EMGrms (mV)	40%	Vıb	0 82±0 59	0 82±0 58	0 82±0 59
		SV	0 64±0 50	0 61±0 48	0 62±0 49
	70%	Vıb	0 74±0 42	0 80±0 51	0 80±0 57
		SV	0 70±0 44	0 69±0 44	0 66±0 43
EMGmpf (Hz)	40%	Vıb	80 5±9 5	80 9±9 5	82 1±9 3
		SV	81 9±19 4	83 5±23 4	81 6±16 7
	70%	Vıb	78 9±8 3	80 3±6 9	78 3±4 9
		SV	79 9±9 9	80 5±9 9	80 4±9 1

10 3 3 Mechanıcal and EMG varıables after traınıng (acute resıdual effect)

Vıbratıon had no sıgnıficant acute resıdual effect on mean angular velocıty (p>0 05) Load and the ınteractıon between load and test tıme had a sıgnıficant effect on mean angular velocıty (p<0 05) Maın effects analysıs showed that mean angular velocıty wıth the load of 40% 1RM was sıgnıficantly hıgher than that wıth 70% 1RM load (2 1 vs 1 4 rad/s, p<0 05) (table 10 7)

Vıbratıon had no sıgnıficant acute resıdual effect on peak angular velocıty (p>0 05) Only load had sıgnıficant effect on peak angular velocıty (p<0 05) Maın effects analysıs showed that peak angular velocıty wıth the load of 40% 1RM was significantly higher than that with 70% 1RM load (3 7 vs 2 4 rad/s, p<0 05) (table 10 7)

Table 10 7 Acute residual effect of training on angular velocity variables (mean±S D)

Velocity	Condition		Pre	Post
ω_{mean} (rad/s)	40%	Vib	2 0±0 5	2 1±0 3
		SV	2 0±0 3 *	2 1±0 4 *
	70%	Vib	* 1 3±0 2	* 1 3±0 3
		SV	1 5±0 4	1 4±0 5
ω_{peak} (rad/s)	40%	Vib	3 6±0 8	3 7±0 6
		SV	3 6±0 5 *	3 9±0 7 *
	70%	Vib	* 2 3±0 5	* 2 3±0 5
		SV	2 7±0 7	2 6±0 8

Note *=significant difference,

Vibration had no significant acute residual effect on mean moment (p>0 05) Only load had a significant effect on mean moment (p<0 05) Main effects analysis showed that the mean moment with the load of 70% 1RM was significantly higher than that with 40% 1RM load (30 6 vs 15 8 N m, p<0 05) (table 10 8)

Vibration had no significant acute residual effect on peak moment (p>0 05) Only load had significant effect on peak moment (p<0 05) Main effects analysis showed that peak moment with the load of 70% 1RM was significantly higher than that with 40% 1RM load (41 8 vs 26 7 N m, p<0 05) (table 10 8)

Table 10 8 Acute resıdual effect of traınıng on moment varıables (mean±S D)

Moment	Condition		Pre	Post
M_{mean} (N m)	40%	Vib	16 1±2 1	15 7±2 1
		SV	15 8±2 1 *	15 6±2 3 *
	70%	Vib	* 30 6±4 8	* 30 5±4 6
		SV	30 7±5 0	30 5±5 6
M_{peak} (N m)	40%	Vib	26 6±4 2	26 3±4 9
		SV	26 2±3 1 *	27 7±3 8 *
	70%	Vib	* 40 8±7 1	* 41 5±6 2
		SV	42 5±7 4	42 5±8 7

Note *=sıgnıficant dıfference,

Vıbratıon had no sıgnıficant acute resıdual effect on mean power (p>0 05) Only load had a sıgnıficant effect on mean power (p<0 05) Mam effects analysıs showed that the mean power wıth the load of 70% 1RM was sıgnıficantly hıgher than that wıth 40% 1RM (41 9 vs 34 0 W, p<0 05) (table 10 9)

Vıbratıon, load, test tıme and theır ınteractıons dıd not have any sıgnıficant effect on peak power and ınıtıal power (p>0 05) (table 10 9)

Vıbratıon had no sıgnıficant acute resıdual effect on tıme to peak power (T_P) (p>0 05) Only load had sıgnıficant effect on tıme to peak power (p < 0 001) Maın effects analysıs showed that the T_P wıth the load of 70% 1RM was sıgnıficantly hıgher than that wıth 40% 1RM (514 vs 300 ms, p<0 05) (table 10 9)

Table 10 9 Acute residual effect of training on power variables (mean±S D)

Power	Condition		Pre	Post
P_{mean} (W)	40%	Vib	34 3±6 1	34 9±5 7
		SV	32 8±4 0 *	34 1±5 5 *
	70%	Vib	* 39 8±7 6	* 39 0±9 9
		SV	45 1±14 2	43 9±14 4
P_{peak} (W)	40%	Vib	79 7±19 9	79 9±17 6
		SV	77 4±12 2	85 9±18 3
	70%	Vib	79 7±18 9	79 1±21 9
		SV	97 3±34 9	90 5±39 4
P_{100} (W)	40%	Vib	33 8±22 3	36 9±21 9
		SV	30 3±14 7	35 7±18 8
	70%	Vib	25 1±14 7	25 2±13 1
		SV	30 1±27 6	31 7±25 8
T_p (ms)	40%	Vib	304±86	299±70
		SV	307±82 *	289±78 *
	70%	Vib	* 514±212	* 539±218
		SV	464±148	541±243

Note *=significant difference,

Vibration had no significant acute residual effect on the biceps EMGrms ($p>0\ 05$) Only test time had a significant effect on EMGrms ($p<0\ 05$) Main effects analysis showed that EMGrms in post-training test decreased significantly from pre-training test (0 68 vs 0 71, $p<0\ 05$) (table 10 10)

Vibration had no significant acute residual effect on the biceps EMGmpf (p>0 05) Only test time had significant effect on EMGmpf (p<0 05) Main effects analysis showed that the EMGmpf in post-trianing was significantly increased from the pre-training test (82 6 vs 81 3 Hz, p<0 05) (table 10 10)

Table 10 10 Acute residual effect of training on EMG variables (mean±S D)

Variable	Condition		Pre		Post
EMGrms (mV)	40%	Vib	0 80±0 59	*	0 77±0 58
		SV	0 63±0 50	*	0 62±0 49
	70%	Vib	0 75±0 46	*	0 70±0 48
		SV	0 69±0 43	*	0 67±0 41
EMGmpf (Hz)	40%	Vib	82 5±8 1	*	84 6±8 1
		SV	82 0±18 8	*	83 1±13 9
	70%	Vib	80 4±6 3	*	83 8±7 9
		SV	80 1±9 1	*	82 0±9 4

Note *=significant difference

10 4 Discussion

The mam goal of this study is to determine whether the different loads employed had an effect on the acute response of neuromuscular performance with vibration training when maximal isotonic contraction is performed No previous studies have directly examined this

When the lighter load (40% 1RM) was used, the velocity of the movement was significantly greater than with the heavier load (70% 1RM) while the moment was significantly smaller (table 10.3 and 10.4). This is in line with our understanding of muscle mechanics (force-velocity relationship), whereby the lower the force used the greater the magnitude of velocity produced (31). The present study also found that the 70% 1RM load could achieve greater mean power during and after training. This may be due to the heavier load of 70% 1RM being able to optimize the force (moment) production contribution to power output (81). The peak power output, however, was not significantly affected by the use of the two different loads. As the angular power is equal to the product of moment and angular velocity, the values of angular velocity (40%1RM > 70% 1RM) and moment (70%1RM > 40%1RM) appear to nullify each other, leading to the reported no effect.

The results showed that with both training loads (40% and 70% 1RM), vibration seems to have no facilitatory effect on the muscle activity and mechanical output during training (acute effect). This is in consistent with our findings in the previous experiments which demonstrated that vibration stimulation had no facilitatory effect on neuromuscular performance in three sets of vibration training with the bicep curl exercise (chapter 8) and a ballistic knee extension exercise (chapter 9). In fact, it was found in this study that vibration had a suppression effect on mechanical variables. The mean power in vibration training group was significantly smaller (37.9 vs. 45.1 W, $p<0.05$, table 10.5) than those in sham vibration group when the training load was 70% 1RM. The initial power was decreased significantly by vibration in both the 40% and 70% 1RM load conditions (27.1 vs. 33.7 W, $p<0.05$, table 10.5). These results are in line with our previous study on the acute effect of vibration training on ballistic knee extension exercise (see chapter 9). It is thus suggested that no matter what training load is used in the maximal isotonic contraction exercise, vibration appears to have no facilitatory effect. On the other hand, vibration tends to have a negative effect on the neuromuscular performance.

However, it was found in study 3 (chapter 7) that the resistance load did have an acute effect on the enhancement from vibration training. When a sub-maximal isometric knee extension was performed, vibration could induce greater neuromuscular response with the heavier load (20% 1RM) than with the lighter load (10% 1RM). The possible reason for these contrasting findings on the influence of resistance load on the vibration training effect, may be related to the different exercise protocols employed. It was suggested that the increased tension of intrafusal fibers induced by the greater resistance load in sub-maximal contraction could increase the sensitivity of muscle spindle endings, and subsequently enhance the effectiveness of the vibration training (30). However, Bongiovanni and Hagbarth(84) found that although the Ia afferent inflow induced by vibration may be able to exceed the pre-existing fusimotor-driven Ia afferent discharges and induce reflex contractions to increase the contraction force when sub-maximal contraction are performed, vibration may not be able to cause further increase of Ia afferent inflow when the maximal voluntary contraction is employed, and thus may not have a facilitatory effect on maximal voluntary contractions.

Again in this study no acute residual effect of vibration was found (table 10.7 to 10.10). This may still result from the short duration of vibration stimulation during the training (15 seconds each set for three sets).

10 5 Conclusion

This study found that with both resistance loads (40% and 70% 1RM), direct vibration did not have an acute or an acute residual facilitatory effect on the neuromuscular performance of maximal isotonic contractions On the contrary, vibration appears to have a suppression effect on some muscle mechanical and EMG output meausres

Chapter 11

Summary, conclusions and directions for future research

11 1 Summary

As a novel strength training method, vibration training has gained popularity in the last five years However, there are still controversies in current findings on whether vibration training is an effective training method for strength and power development A critical review of the literature in this area indicated that the vibration training effect is dependent on a number of factors, in particular vibration characteristics (vibration amplitude and frequency) and exercise protocols (type of exercise and exercise intensity) However, there is a lack of research into many of these factors Therefore, the aim of this thesis was to investigate these issues

Vibration amplitude and frequency determine the load that vibration training imposes on the neuromuscular system In order to examine the influence of different vibration loads on vibration training, a portable muscle-tendon vibrator with variable vibration amplitude and frequency capacity has been developed in the present study The vibrator was designed to produce vibrations with amplitudes ranging from 0 2 mm to 2 mm and frequencies from 30 to 200 Hz The portable vibrator can be strapped to the muscle tendon during various strength training exercises

Two studies [study 1 (chapter 5) and study 2 (chapter 6)] showed that the vibrator could produce the different vibration amplitudes and frequencies required for a series of studies In addition, it could also produce a repeatable vibration load on the muscle under different operational conditions, including different test days, joint angles and strapping forces, leading to a consistent muscle activity (EMG) response under these operational conditions. This ensured that valid and reliable data could be attained from use of the vibrator in the later studies on vibration training effect.

<u>Sub-maximal isometric contractions</u>

The influence of vibration amplitude, frequency and exercise intensity on the acute effect of vibration training with sub-maximal contractions were examined in studies 1, 2 and 3 (chapter 5, 6 and 7, respectively). It was found that direct vibration could induce a significant increase ($p<0.05$) in EMGrms response to vibration, with the larger vibration amplitude (1.2 mm) producing greater increase in EMGrms than the smaller vibration amplitude (0.5 mm) ($p<0.05$). Among the three vibration frequencies (30, 65 and 100 Hz) tested, both 65 and 100 Hz could induce significantly greater EMGrms increase than 30 Hz ($p<0.05$), with no significant difference between 65 and 100 Hz ($p>0.05$). Since the use of 100 Hz resulted in many subjects reporting discomfort from the vibration, the use of 65 Hz was preferred. Therefore, an optimal vibration amplitude and frequency (1.2 mm and 65 Hz) that could induce the greatest EMGrms increase was determined from the above results. This vibration amplitude and frequency was used in the later studies.

The results of study 3 demonstrated that both resistance loads (10% 1RM and 20% 1RM) had significant effect on the acute effect of vibration with sub-maximal isometric contractions ($p<0.05$). However, significantly greater muscle activation was achieved when vibration was applied with the higher load (20% 1RM). This indicates that if muscle performance is to be maximised through vibration training, higher loads should be employed

Maximal isotonic contractions

The acute effect of vibration training with maximal isotonic contractions was studied in the three remaining studies (study 4, 5 and 6), as maximal isotonic contractions are more commonly employed in strength training than sub-maximal isometric contractions Vibration training in this area has greater potential for application

In study 4, it was found that superimposed direct vibration did not enhance the acute mechanical and EMG output of a maximal effort bicep curl contraction with 70% 1RM load (p>0 05) It was also found that the neuromuscular performance of maximal effort bicep curl was not enhanced after vibration training, both with exercise or no exercise

As the subjects in study 4 had to decelerate the free weights in each concentric phase, which may inhibit the enhancement of neuromuscular performance associated with vibration, study 5 examined the acute effect of direct vibration on a ballistic knee extension in which the need for deceleration was reduced No facilitatory acute or acute residual effect of vibration was found in this study On the contrary, the results showed that vibration appears to have a suppression effect on some mechanical and/or EMG output measures, both during and after training

Study 6 examined the possible influence of the resistance load on vibration training with maximal isotonic contractions Two ranges of loads (40% 1RM and 70% 1RM) were employed The results showed that no matter what resistance load was employed, direct vibration did not have any facilitatory acute or acute residual effect on neuromuscular performance of maximal isotonic contractions On the contrary, vibration appears to have a suppression effect on some mechanical and EMG output measures

11 2 Conclusions

A review of literature indicated that vibration training effect is dependent on a number of factors, but in particular vibration characteristics (vibration amplitude and frequency) and exercise protocols (type of exercise and exercise intensity) However, there is a lack of study on this dependence to date By developing a portable vibrator that can directly stimulate the muscle-tendon during strength training exercise, this thesis systematically examined the influence of these factors It is demonstrated in this thesis that the acute vibration training effect on neuromuscular system is dependent on vibration amplitude, frequency, type of exercise and the exercise intensity Therefore, the work in this thesis is important for the better understanding and application of this novel strength training method

In general, for sub-maximal isometric contractions, vibration could induce a significant increase of EMG The enhancement was greater with the increase of vibration amplitude (1 2 vs 0 5 mm) and frequency (100 and 65 Hz vs 30 Hz) A higher resistance load could induce greater EMG enhancement to vibration training with sub-maximal isometric contractions However, for maximal isotonic contractions, vibration did not enhance neuromuscular performance, and had a negative effect on some mechanical and EMG outputs, both during and after training Vibration alone (with no exercise) had no significant acute residual effect on the mechanical and EMG outputs of maximal isotonic contractions

11 3 Directions for future research

This thesis is the first study that employs a portable muscle-tendon vibrator in vibration training Although the results demonstrated that it is an effective way to stimulate the muscle during strength training, there is still a need to improve the design of the vibrator In addition, a number of questions that arise from this thesis about the effect of vibration training on neuromuscular performance need further investigations All these issues will be discussed below as the directions for future research

11 3 1 Vibrator design

The size and weight of the vibrator was limited by the radial load capacity of the motor shaft The lightest motor that fulfils our requirement of maximal rotating speed, power and torque was not chosen because of the low eccentric load capacity To optimise the vibrator design, a lighter and smaller motor may be selected by incorporating a small bearing outside of the motor that could still be housed in the vibrator This bearing will absorb most of the eccentric load produced by eccentric mass and therefore a smaller motor may be used This optimization may also decrease the cost of the vibrator

In addition, the present design has only one operating vibrator However, muscles on both sides of the limbs are usually trained together in strength training exercises Thus two or more vibrators are needed to operate simultaneously to fulfil this requirement This problem should be solved in the future design of the vibrator

11 3 2 Vibration training with the sub-maximal contraction exercise

The present study showed that vibration had an acute faciliatory effect on neuromuscular performance when sub-maximal efforts were employed This finding suggests that vibration training may be an effective training method for rehabilitation of athletes with injury or the improvement of muscle strength in elderly people In addition, vibration training may also be an effective way for athletes to warm-up in order to enhance their maximal strength and power in their subsequent movements However, studies are still needed to solve the following questions

1) The optimal vibration training programs with sub-maximal contraction exercises

We examined in this thesis the influence of vibration amplitude, frequency and resistance load on the acute vibration training effect However, the effectiveness of these findings needs to be examined in chronic vibration training studies

2) The acute residual effect and the influence of vibration characteristics and exercise intensity

In the present study, we only investigated the acute effect of vibration on the neuromuscular performance of sub-maximal isometric contractions. In the future studies, the acute residual effect of vibration training with sub-maximal contractions should also be examined, together with the influence of the factors such as vibration amplitude, frequency, duration of vibration and the resistance load. This could facilitate the application of vibration training as an effective means of warm-up.

3) Sub-maximal dynamic contractions

We only investigated the acute vibration training effect on sub-maximal isometric contractions. Future study should also examine the vibration training effect on dynamic contractions with sub-maximal effort, as this type of contraction may be more common during some strength training programs.

11.3.3 Vibration training with maximal effort dynamic exercises

It was found in this study (chapter 8, 9 and 10) that direct vibration did not have an acute facilitatory effect on maximal isotonic contraction and ballistic contractions. This is different from the studies that demonstrate that indirect vibration can facilitate the maximal strength and power of isotonic contractions (21,49). In addition, it was found in this study that vibration actually had a suppression effect on some mechanical and EMG output during maximal isotonic contractions. As discussed in chapter 8, several reasons may account for this difference and research in the following issues should be undertaken in future studies.

1) Indirectly applied vibration vs. directly applied vibration

Indirect vibration was applied in all of the previous studies that found a facilitatory effect of vibration on maximal isotonic contraction, implying that the difference in method of application (indirect vs. direct) may be a possible reason. Indirect vibration may be able to stimulate more muscle groups during its transmission to the target muscle. In addition, it has been found that a 'muscle tuning' mechanism regulating the muscle stiffness may exist in indirect vibration to dampen the vibration transmission (39,40). Recent studies have shown that the stiffness regulation may play an important role in the power performance of contractions such as drop jumps (83). Therefore it is possible that the increase of muscle stiffness of the whole limb to dampen the vibration, rather than the vibratory stimulation of the muscle spindles of the target muscle, is the reason for the enhancement of maximal isotonic contraction force and power. This hypothesis could be tested by an experiment directly comparing the indirectly applied vibration and the directly applied vibration.

2) The timing of vibration

It has been found that the timing of the mechanical stimulation may be important for the neuromuscular response (87). The study by Layne et al. (87) found that if the mechanical stimulus was applied shortly before the agonist muscle activation, the neuromuscular performance of a contraction with maximal effort could be greatly enhanced. If the stimulus was applied during the agonist activation, the enhancement in neuromuscular performance was less. It is possible that the same timing effect may be important in vibration training This could be examined by a study employing two types of vibration one is a continuous one as used in this thesis, the second is a short duration of vibration before each contraction with no vibration during the contraction

3) Subject prior training

It has been previously found that vibration induces greater enhancements in maximal strength and power in isotonic contractions for elite athletes than amateur athletes (21) In the studies that found the positive effect of vibration training, elite athletes and/or recreational athletes were recruited as subjects (6,21,26) In the present thesis however, untrained subjects were recruited for the vibration training studies These untrained subjects may not have a sufficiently developed neural and muscular system necessary for vibration to have a similar affect as in the studies in which athletes were usually used Future studies are needed to examine this possibility

Bibliography

1 Fleck SJ, Kraemer WJ Designing resistance training programs Human kinetics, 1997

2 Nazarov V, Spivak G Development of athlete's strength abilities by means of biomechanical stimulation method [in Russian] Theory and practice of physical culture (Moscow) 1987, 12 37-39

3 Delecluse C, Roelants M, Verschueren S Strength increase after whole-body vibration compared with resistance training Med Sci Sports Exerc 2003, 35(6) 1033-1041

4 Rittweger J, Mutschelknauss M, Felsenberg D Acute changes in neuromuscular excitability after exhausive whole body vibration exercise as compared to exhaustion by squatting exercise Clin Physiol Funct Imaging 2003, 23 81-86

5 Bosco C, Cardinale M, Tsarpela O, Colli R, Tihanyi J, von Duvillard SP et al The influence of whole body vibration on jumping performance Biology of sport 1998, 15(3) 157-164

6 Issurin VB, Liebermann DG, Tenenbaum G Effect of vibratory stimulation training on maximal force and flexibility J Sports Sci 1994, 12 561-566

7 Torvinen S, Kannus P, Sievanen H, Jarvinen TA, Pasanen M, Kontulainen S et al Effect of a vibration exposure on muscular performance and body balance Randomized cross-over study Clin Physiol Funct Imaging 2002, 22 145-152

8 De Ruiter CJ, Van Raak SM, Schilperoort JV, Hollander AP, De Haan A The effects of 11 weeks whole body vibration training on jump height, contractile properties and activation of human knee extensors Eur J Appl Physiol 2003, Epub

9 de Ruiter CJ, van der Linden RM, van der Zijden MJ, Hollander AP, de Haan A Short-term effects of whole-body vibration on maximal voluntary isometric knee extensor force and rate of force rise Eur J Appl Physiol 2003, 88(4-5) 472-475

10 Humphries B, Warman G, Purton J, Doyle TLA, Dugan E The influence of vibration on muscle activation and rate of force development during maximal isometric contractions J Sports Sci Med 2004,16-22

11 Cardinale M, Bosco C The use of vibration as an exercise intervention Exerc Sport Sci Rev 2003, 31(1) 3-7

12 Torvinen S, Sievanen H, Jarvinen TA, Pasanen M, Kontulainen S, Kannus P Effect of 4-min vertical whole body vibration on muscle performance and body balance A randomized cross-over study Int J Sports Med 2002, 23(5) 374-379

13 Bongiovanni LG, Hagbarth KE, Stjernberg L Prolonged muscle vibration reducing motor output in maximal voluntary contractions in man J Physiol 1990, 423 15-26

14 Jackson SW, Turner DL Prolonged vibration reduces maximal voluntary knee extension performance in both the ipsilateral and the contralateral limb in man Eur J Appl Physiol 2003, 88 380-386

15 Harns CM Introduction to the handbook In Harns CM, editor Shock and vibration handbook New York McGraw-Hill, 1996 1 1-1 27

16 Dimarogonas A Vibration for engineers second ed London Prentice Hall international, 1996

17 Mester J, Spitzenpfeil P, Yue ZY Vibration loads potential for strength and power development In Komi PV, editor strength and power in sport Blackwell, 2002 488-501

18 Curry EL, Clelland JA Effects of the asymmetnc tonic neck reflex and high-frequency muscle vibration on isometnc wnst extension strength in normal adults Phys Ther 1981, 61(4) 487-495

19 Ling Dynamic vibration system 2004
http //www davidson com au/products/vibration/lds/pdf/permanent magnet pdf

20 Rittweger J, Schiessl H, Felsenberg D Oxygen uptake dunng whole-body vibration exercise companson with squatting as a slow voluntary movement Eur J Appl Physiol 2001, 86(2) 169-173

21 Issunn VB, Tenenbaum G Acute and residual effect of vibratory stimulation on explosive strength in elite and amateur athletes J Sports Sci 1999, 17 177-182

22 von Gierke HE, Goldman DE Effects of shock and vibration on man In Harns CM, editor Shock and vibration handbook New York McGraw-Hill, 1987 44-1-44-58

23 Kihlberg S, Attebrant M, Gemne G, Kjellberg A Acute effects of vibration from a chipping hammer and a gnnder on the hand-arm system Occup Environ Med 1995, 52(11) 731-737

24 Samuelson B, Jorfeldt L, Ahlborg B Influence of vibration on endurance of maximal isometnc contraction Clin Physiol 1989, 9 21-25

25 Liebermann DG, Katz L, Hughes MD, Bartlett RM, McClements J, Franks IM Advances in the application of information technology to sport performance J Sports Sci 2002, 20(10) 755-769

26 Liebermann DG, Issunn VB Effort perception dunng isotonic muscle contractions with supenmposed mechanical vibration stimulation J human movement studies 1997, 32 171-186

27 De Luca CJ. The use of surface electromyography in biomechanics. J applied biomechanics 1992; 13(2):135-163.

28 Kupa EJ, Roy SH, Kandarian SC, De Luca CJ. Effects of muscle fibre typw and size on EMG median frequency and conductive velocity. J appl Physiol 1995; 79:23-32.

29 Linnamo V, Newton RU, Hakkinen K, Komi PV, Davie A, McGuigan M et al. Neuromuscular responses to explosive and heavy resistance loading. J Electromyogr Kinesiol 2000; 10(6):417-424.

30 Eklund G, Hagbarth KE. Normal variability of tonic vibration reflexes in man. Exp neurol 1966; 16(1):80-92.

31 Enoka RM. Neuromechanical basis of kinesiology. Human kinetics, 1994.

32 Park HS, Martin BJ. Contribution of the tonic vibration reflex to muscle stress and muscle fatigue. Scand J Work Environ Health 1993; 19(1):35-42.

33 Desmedt JE, Godaux E. Ballistic contractions in man: characteristic recruitment pattern of single motor units of the tibialis anterior muscle. J Physiol 1977; 264(3):673-693.

34 Hagbarth KE, Kunesch EJ, Nordin M, Schmidt R, Wallin EU. Gamma loop contribution to maximal voluntary contractions in man. J Physiol 1986; 380(Nov):575-591.

35 Zatsiorsky VM. Science and practice of strength training. 1st ed. Champaign, IL. USA: Human Kinetics, 1995.

36 Moritani T. Time course of adaptations during strength and power training. In: Komi PV, editor. Strength and power in sport. Boston: Blackwell Scientific Publications, 1992.

37 Lebedev MA, Polyakov AV. Analysis of surface EMG of human soleus muscle subjected to vibration. J Electromyogr Kinesiol 1992; 21(1):26-35.

38 Martin BJ, Park HS. Analysis of the tonic vibration reflex: influence of vibration variables on motor unit synchronization and fatigue. Eur J Appl Physiol Occup Physiol 1997; 75(6):504-511.

39 Nigg BM, Wakeling JM. Impact forces and muscle tuning: a new paradigm. Exerc Sport Sci Rev 2001; 29(1):37-41.

40 Wakeling JM, Nigg BM, Rozitis AI. Muscle activity damps the soft tissue resonance that occurs in response to pulsed and continuous vibrations. J appl Physiol 2002; 93(3):1093-1103.

41 Cardinale M, Lim J. The acute effect of two different whole body vibration frequencies on vertical jump performance. Med Sport 2003; 56:287-292.

42 Cronin JB, Oliver M, McNair PJ. Muscle stiffness and injury effects of whole body vibration. Physical therapy in sport 2004; published on line on 14 March 2004.

43 Romaiguere P, Vedel JP, Pagni S. Effects of tonic vibration reflex on motor unit recruitment in human wrist extensor muscles. Brain Res 1993; 602(1):32-40.

44 GRANIT R. Reflex rebound by post-tetanic potentiation; temporal summation-spasticity. J Physiol 1956; 131(1):32-51.

45 Arcangel CS, Johnston R, Bishop B. The achilles tendon reflex and the H-reponse during and after tendon vibration. Phys Ther 1971; 51(8):889-902.

46 Van Boxtel A. Differential effects of low-frequency depression, vibration-induced inhibition, and posttetanic potentiation on H-reflexes and tendon jerks in the human soleus muscle. J Neurophysiol 1986; 55(3):551-568.

47 Kossev A, Siggelkow S, Schubert M, Wohlfarth K, Dengler R. Muscle vibration: different effects on transcranial magnetic and electrical stimulation. Muscle Nerve 1999; **22(7)**:946-948.

48 Bosco C, Cardinale M, Tsarpela O. Influence of vibration on mechanical power and electromyogram activity in human arm flexor muscles. Eur J Appl Physiol 1999; 79(4):306-311.

49 Warman G, Humphries B, Purton J. The effects of timing and application of vibration on muscular contractions. Aviat Space Environ Med 2002; 73(2):119-127.

50 Kerschan-Schindl K, Grampp S, Henk C, Resch H, Preisinger E, Fialka-Moser V et al. Whole-body vibration exercise leads to alternations in muscle blood volume. Clin Physiol 2001; 21(3):377-382.

51 Nakamura H, Okazawa T, Nagase H, Yoshida M, Ariizumi M, Okada A. Change in digital blood flow with simultaneous reduction in plasma endothelin induced by hand-arm vibration. Int Arch Occup Environ Health 1996; 68(2):115-119.

52 Olivier DJ, Lynn K, Hong CZ. Increased skin temperature after vibratory stimulation. Am J Phys Med Rehabil 1989; 68(2):81-85.

53 Necking LE, Lundstrom R, Lundborg G, Thornell LE, Friden J. Skeletal muscle changes after short term vibration. Scand J Plast Reconstr Hand Surg 1996; 30:99-103.

54 Falempin M, In-Albon SF. Influence of brief daily tendon vibration on rats soleus muscle in non-weight-bearing situation. J appl Physiol 1999; 87(1):3-9.

55 Bosco C, Iacovelli M, Tsarpela O, Cardinale M, Bonifazi M, Tihanyi J et al. Hormonal responses to whole-body vibration in men. Eur J Appl Physiol 2000; 81(6):449-454.

56 Bosco C, Collı R, Bonomı R, von Duvıllard SP, Vıru A Monıtorıng strength traınıng neuromuscular and hormonal profile Med Scı Sports Exerc 2000, 32(1) 202-208

57 McCall GE, Grındeland RE, Roy RR, Edgerton VR Muscle afferent actıvıty modulates bıoassayble growth hormone ın human plasma J appl Physıol 2000, 89 1137-1141

58 Martın BJ, Roll JP, Gauthıer GM Inhıbıtory effects of combıned agonıst and antagonıst muscle vıbratıon on H-reflex ın man Avıat Space Envıron Med 1986, 57(7) 681-687

59 Pyyko I, Farkkıla M, Toıvanen J Transmıssıon of vıbratıon ın the hand-arm system wıth specıal reference to changes ın compressıon force and acceleratıon Scand J Work Envıron Health 1976, 2(2) 87-95

60 Unholtz K Vıbratıon testıng machınes In Harrıs CM, edıtor Shock and vıbratıon handbook New York McGraw-Hıll, 1988 1-26

61 Blake RE Basıc vıbratıon theory In Harrıs CM, edıtor Shock and vıbratıon handbook New York McGraw-Hıll, 1988 2-1-2-27

62 Wakelıng JM, Nıgg BM Soft-tıssue vıbratıon ın the quadrıceps measured wıth skın mounted transducers J Bıomech 2001, 34(4) 539-543

63 Sodeberger GL Recordıng technıques In Soderberg GL, edıtor Selected topıcs ın surface electromyography for use ın the occupatıonal settıng expert perspectıves U S Department of Health and Human Servıces, Natıonal Instıtute for Occupatıonal Safety and Health, 1992 24-41

64 SENIAM 2004 http //www senıam org/

65 Gabrıel DA Changes ın kınematıc and EMG varıabılıty whıle practıcıng a maxımal performance task J Electromyogr Kınesıol 2002, 12 407-412

66 Smıth SW Wındowed-sınc filters The scıentıst and Engıneer's guıde to dıgıtal sıgnal processıng Calıfornıa Technıcal Publıshıng, 1997 285-296

67 Wınter DA Kınematıcs Bıomechanıcs and motor control of human movement John Wıley & Sons, 1990 11-50

68 Harman EA The measurement of human mechanıcal power In Maud PJ, Foster C, edıtors Physıologıcal assessment of human fitness Champaıgn Human kınetıcs, 1995 87-113

69 Aagaard P, Sımonsen EB, Trolle M, Bangsbo J, Klausen K Moment and power generatıon durıng maxımal knee extensıons performed at low and hıgh speeds Eur J Appl Physıol 1994, 69(5) 376-381

70 Nakazawa K, Kawakami Y, Fukunaga T, Yano H, Miyashita M. Differences in activation patterns in elbow flexor muscles druing isometric, concentric and eccentric contractions. Eur J Appl Physiol 1993; 66(3):214-220.

71 Cordo P, Gandevia SC, Hales JP, Burke D, Laird G. Force and displacement-controlled tendon vibration in humans. Electroencephalogr Clin Neurophysiol 1993; 89(1):45-53.

72 Martin BJ, Roll JP, Gauthier GM. Spinal reflex alternations as a function of intensity and frequency of vibration applied to the feet of seated subjects. Aviat Space Environ Med 1984; 55(1):8-12.

73 Rittweger J, Beller G, Felsenberg D. Acute physiological effects of exhaustive whole-body vibration exercise in man. Clin Physiol 2000; 20(2):134-142.

74 Roll JP, Vedel JP, Ribot E. Alternation of proprioceptive messages induced by tendon vibration in man: a microneurographic study. Exp Brain Res 1989; 76(1):213-222.

75 Roelants M, Delecluse C, Goris M, Verschueren S. Effects of 24 weeks of whole body vibration training on body composition and muscle strength in untrained females. Int J Sports Med 2004; 25(1):1-5.

76 Baechle TR, Earle RW, Wathen D. Resistance training. In: Baechle TR, Earle RW, editors. Essentials of strength training and conditioning. Champaign: Human kinetics, 2000: 395-425.

77 Thomas JR, Nelson JK. Measuring research variables. Research methods in physical activity. Champaign: Human Kinetics, 2001: 181-200.

78 Zhang LQ, Wang G, Nuber GW, Press JM, Koh JL. In vivo load sharing among the quadriceps components. J Orthop Res 2003; 21(3):565-571.

79 Rittweger J, Ehrig J, Just K, Mutschelknauss M, Kirsch KA, Felsenberg D. Oxygen uptake in whole-body vibration exercise: influence of vibration frequency, amplitude, and external load. Int J Sports Med 2002; 23(6):428-432.

80 Burke D, Hagbarth KE, Lofstedt L, Wallin BG. The response of human muscle spindle endings to vibration of non-contracting muscles. J Physiol 1976; 261(3):673-693.

81 Cronin JB, McNair PJ, Marshall RN. The role of maximal strength and load on initial power production. Med Sci Sports Exerc 2000; 32(10):1763-1769.

82 Coakes SJ, Steed LG. Reliability analysis. SPSS: analysis without anguish: version 10.0 for Windows. John Wiley&Sons Australia, Ltd, 2001: 147-153.

83 Horita T, Komi PV, Nicol C, Kyrolainen H. Interaction between pre-landing activities and stiffness regulation of the knee joint musculoskeletal system in the drop jump: implications to performance. Eur J Appl Physiol 2002; 88(1-2):76-84.

84 Bongiovanni LG, Hagbarth KE Tonic vibration reflexes elicited during fatigue from maximal voluntary contractions in man J Physiol 1990, 423(Apr) 1-14

85 Desmedt JE, Godaux E Mechanism of the vibration paradox excitatory and inhibitory effects of tendon vibration on single soleus muscle motor units in man J Physiol 1978, 285(Dec) 197-207

86 Kraemer WJ, Adams K, Cafarelli E, Dudley GA, Dooly C, Feigenbaum MS et al American College of Sports Medicine position stand Progression models in resistance training for healthy adults Med Sci Sports Exerc 2002, 34(2) 364-380

87 Layne CS, Forth KE, Baxter MF, Houser JJ Voluntary neuromuscular activation is enhanced when paired with a mechanical stimulus to human plantar soles Neurosci Lett 2002, 334(2) 75-78

88 Maxon motor UK Ltd Maxon – the leading manufacturer of high precision drives and systems Catalog 2001

Appendix A List of vibration training studies excluded for literature review

Table A_1 Vibration training studies without control

Author (year)	Title	Journal	Reason for exclusion
Bosco et al (2000)	Hormonal responses to whole-body vibration in men	Eur J Appl Physiol 2000, 81(6) 449-54	No control group
Bosco et al (1999)	Effect of acute whole body vibration treatment on mechanical behavior of skeletal muscle and hormonal profile	In Muscolo-skeletal interactions, Lyritis(ed) Proceedings of the 2nd International 1999b Vol 2 67-76	No control group
Clarkson et al (1980)	Post vibratory effects on fractionated reaction time and maximum isometric strength	Am J Phys Med 1980 Dec,59(6) 271-9	No control group
De Ruiter et al (2003)	Short-term effects of whole-body vibration on maximal voluntary isometric knee extensor force and rate of force rise	Eur J Appl Physiol 2003, 88 472-5	No control group
Rittweger et al (2000)	Acute physiological effects of exhaustive whole-body vibration exercise in man	Clinical Physiology 2000 Mar, 20(2) 134-142	No control group

Table A_2 Vibration training studies with intervention (vibration) and control not randomised

Author (year)	Title	Journal	Reason for exclusion
Cardinale et al (2003)	Electromyography activity of vastus lateralis muscle during whole-body vibrations of different frequencies	J strength cond res 2003, 17(3) 621-624	Intervention (vibration) and control not randomised
Gabriel et al (2002)	Vibratory facilitation of strength in fatigued muscle	Arch Phys Med Rehabil, 2002, 83 1202-5	Intervention (vibration) and control not randomised
Griffin et al (2002)	Muscle vibration sustains motor unit firing rate during submaximal isometric fatigue in humans	J Physiol 2001 Sep 15, 535(Pt 3) 929-36	Intervention (vibration) and control not randomised
Kouzaki et al	Decrease in maximal voluntary contraction by tonic vibration applied to a single synergist muscle in humans	J applied Physiology 2000, 89(4) 1420-24	Treatment and control not randomised
Martin et al (1997)	Analysis of the tonic vibration reflex influence of vibration variables on motor unit synchronization and fatigue	Eur J Appl Physiol 1997, 75 504-511	Treatment and control not randomised
Park et al (1993)	Contribution of the tonic vibration reflex to muscle stress and muscle fatigue	Scan J Work Environ Health 1993, 19 35-42	Treatment and control not randomised
Warman et al (2002)	The effects of timing and application of vibration on muscular contractions	Aviat Space Environ Med 2002 Feb 73(2) 119-27	Treatment and control not randomised

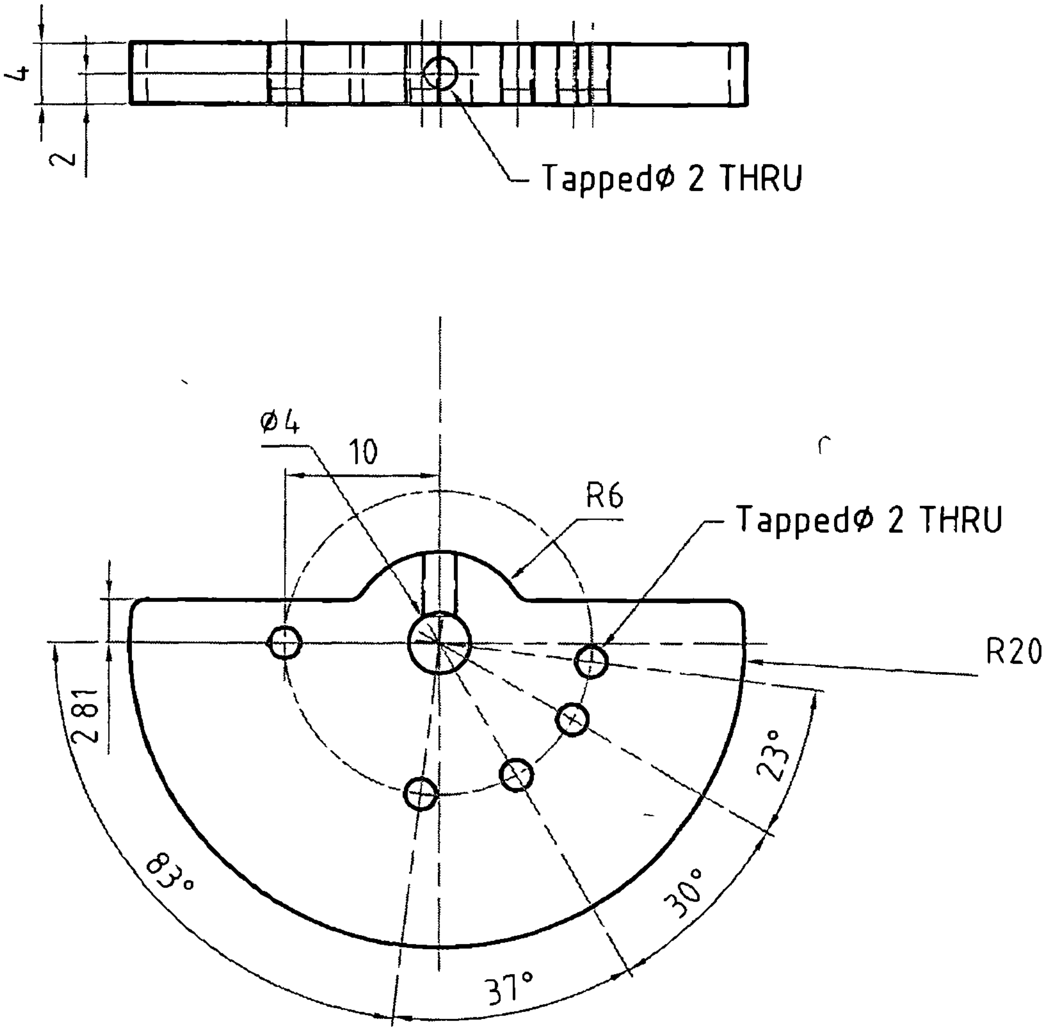
Table A_3 Vibration training studies with control group and vibration group undertake different exercise

Author (year)	Title	Journal	Reason for exclusion
Bosco et al. (1998)	The influence of whole body vibration on jumping performance	Biology of sport. 1998; 15(3): 157-64	Vibration group: squatting Control group: maintain usual
Bosco et al. (1999)	Influence of vibration on mechanical power and electromyogram activity in human arm flexor muscles.	Eur J Appl Physiol Occup Physiol. 1999 Mar;79(4):306-11.	Vibration group: elbow flexion Control group: rest
Bosco et al. (1999)	Adaptive responses of human skeletal muscle to vibration exposure.	Clin Physiol. 1999 Mar;19(2):183-7.	Vibration group: squatting Control group: rest
Torvinen et al. (2002)	Effect of four-month vertical whole body vibration on performance and balance.	Med Sci Sports Exerc. 2002 Sep;34(9):1523-8.	Vibration group: standing on platform with light exercise Control group: not change the subjects' current physical activity
Torvinen et al. (2003)	Effect of 8-month vertical whole body vibration on bone, muscle performance, and body balance: a randomized controlled study.	J Bone Miner Res. 2003 May;18(5):876-84	Vibration group: standing on platform with light exercise Control group: not change the subjects' current physical activity
Russo et al. (2004)	High-frequency vibration training increase muscle power in postmenopausal women	Arch Phys Med Rehabil. 2003 Dec; 84: 1854-7	Vibration group: standing on platform with knee joint flexed Control group: not receive any training
Roelants et al. (2004)	Effects of 24 weeks whole body vibration training on body composition and muscle strength in untrained females	Int J Sports Med. 2004; 25:1-5	Vibration group: standing on platform with light exercise Control group: not receive any training

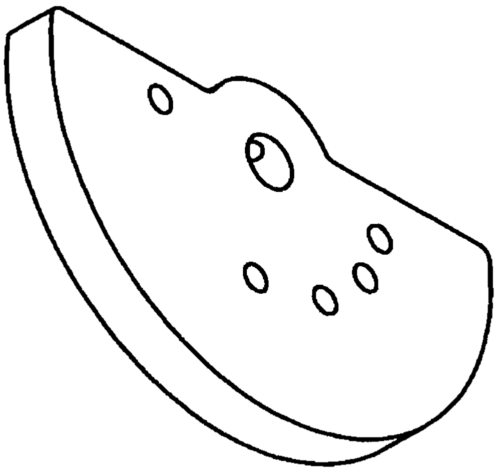
Table A_3 (continued) Vibration training studies with control group and vibration group undertake different exercise

Author (year)	Title	Journal	Reason for exclusion
Verschueren et al (2004)	Effect of 6-month whole body vibration training on hip density, muscle strength, and postural control in postmenopausal women a randomized controlled pilot study	J Bone Miner Res 2004 Mar,19(3) 352-9	Vibration group standing on platform with light exercise Control group not receive any training
Roelants et al (2004)	Whole-body-vibration training increases knee-extension strength and speed of movement in older women	J Am Geriatr Soc 2004 Jun,52(6) 901-8	Vibration group standing on platform with light exercise Control group not receive any training

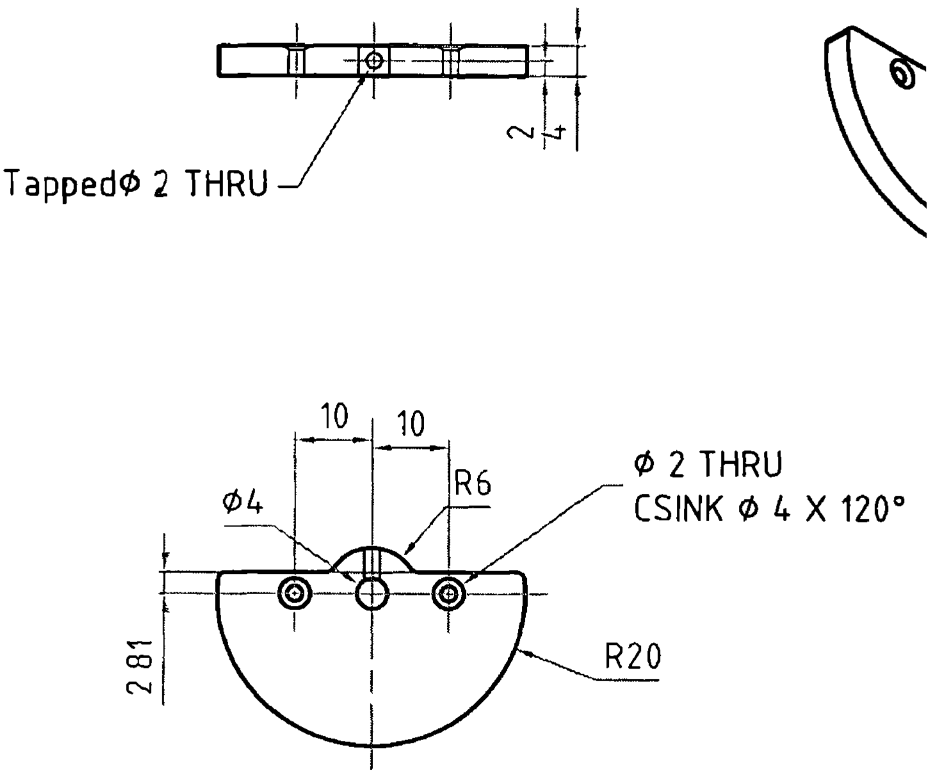
Appendix B Detailed drawings of vibrator design



B__2



Item No #2
Part name Eccentric mass(fixed)X6
Material CopperX2, AluminiumX2, PlasticX2
Designer Luo Jin
Date 30 Apr , 2002


2
4
TappedΦ 2 THRU
10
10
Φ4
R6
Φ 2 THRU
CSINK Φ 4 X 120°
2 81
R20

Item No #3

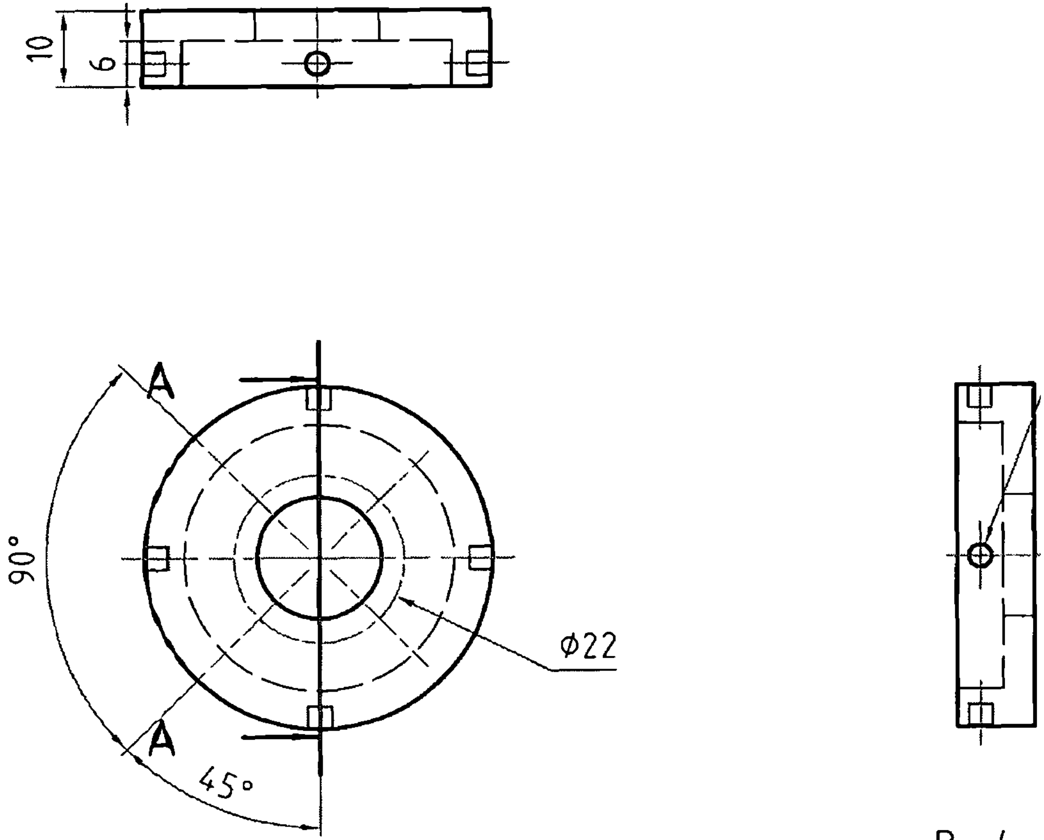
Part name Eccentric mass(adjustable)X6

Material CopperX2, AluminiumX2, PlasticX2

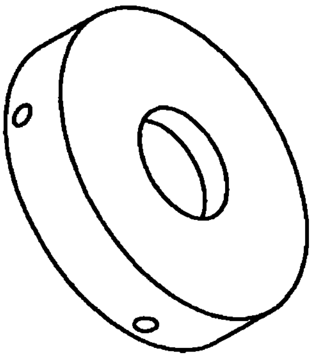
Designer Luo Jin

Date 30 Apr , 2002

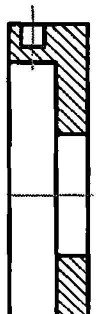
B_3



B_4



Tappedφ 3 X 3 DEEP



A-A

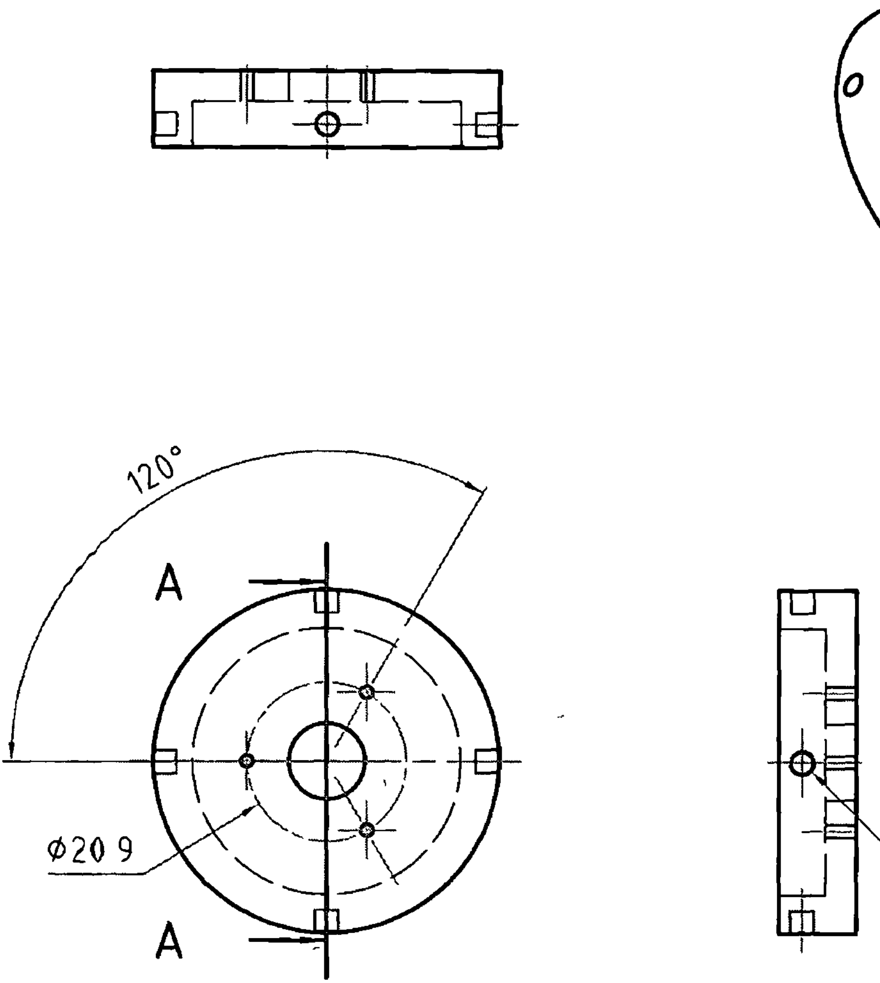
Item No #4

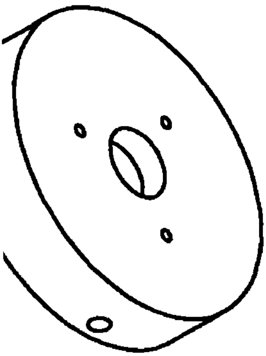
Part name Ring(Front)

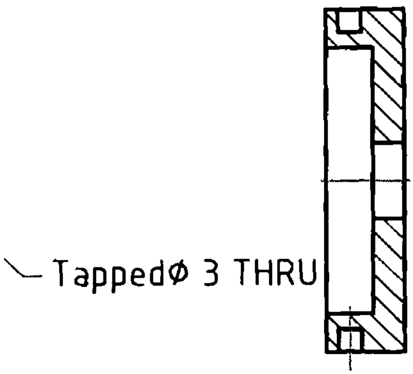
Material Polycarbonate

Designer Luo Jin

Date 30 Apr , 2002


120°
A
A
Ø20 9





A-A

Item No #5

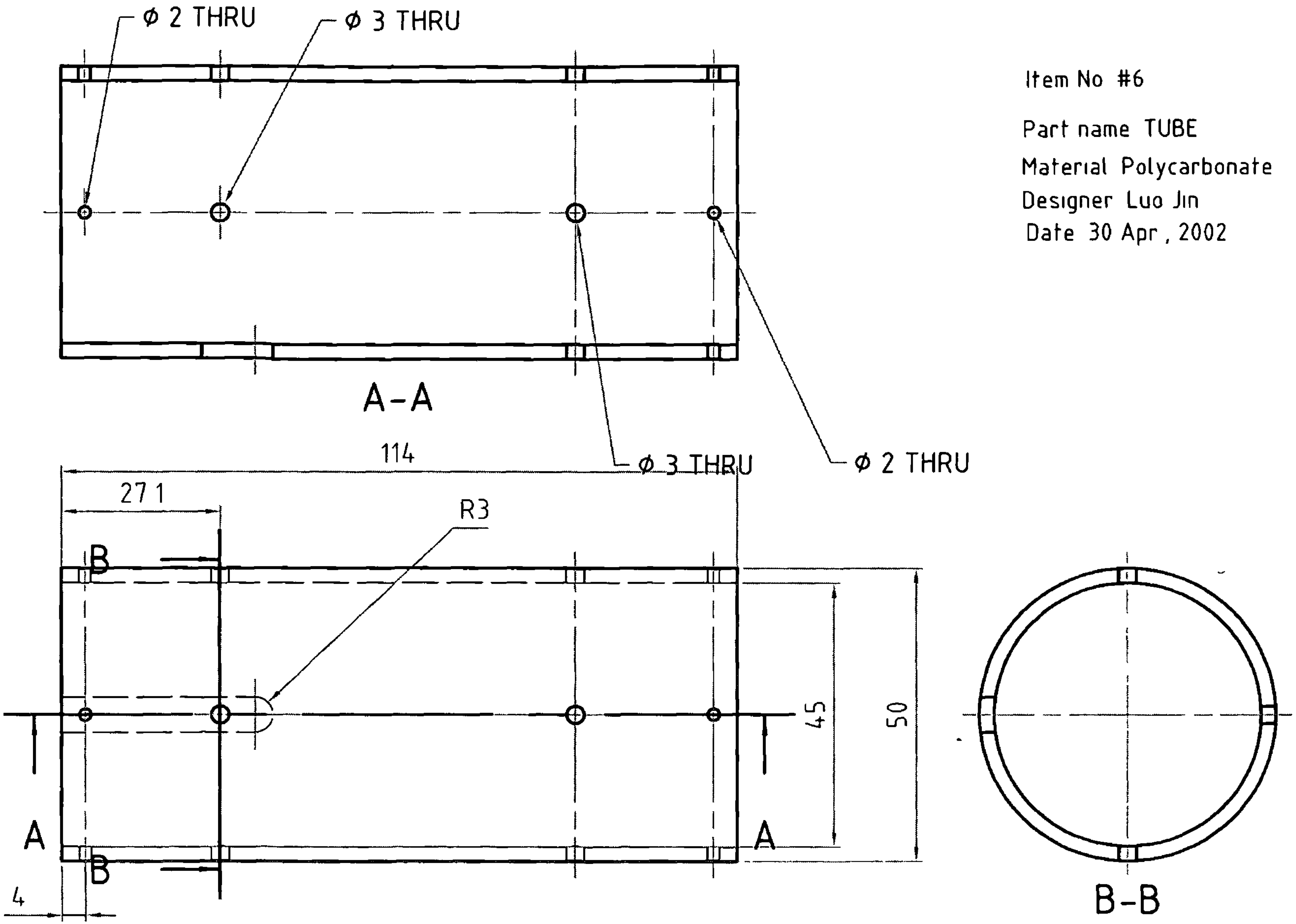
Part name Ring(rear)

Material Polycarbonate

Designer Luo Jin

Date 30 Apr , 2002

B_5



Item No #6

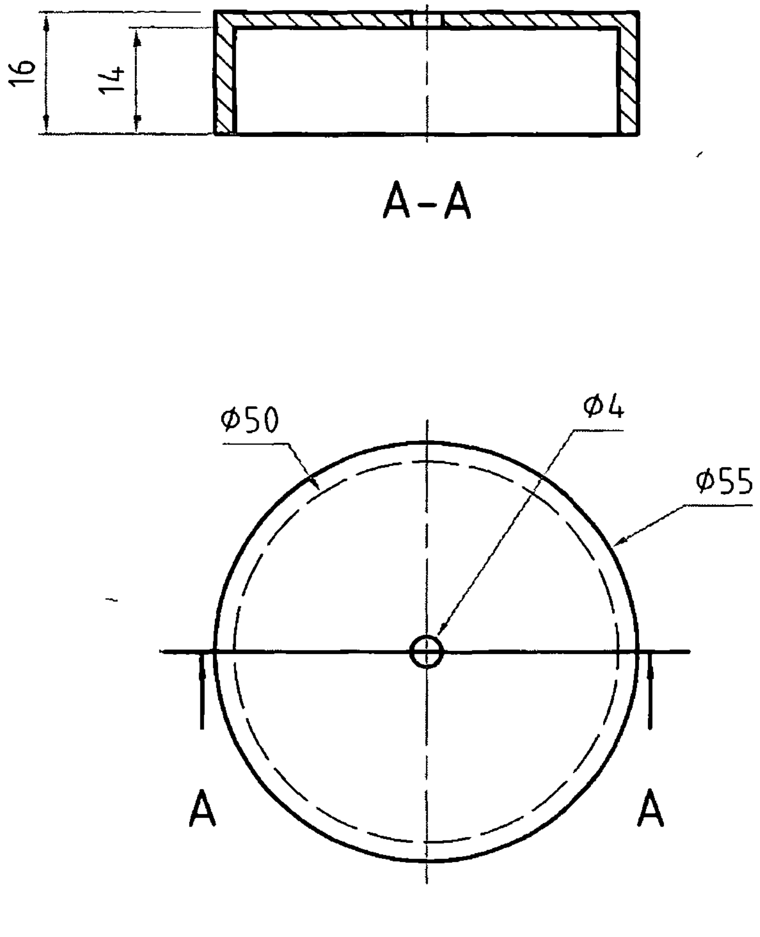
Part name TUBE

Material Polycarbonate

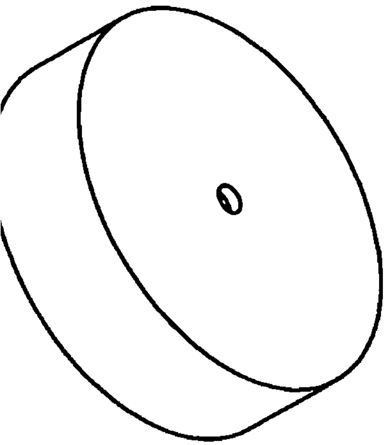
Designer Luo Jin

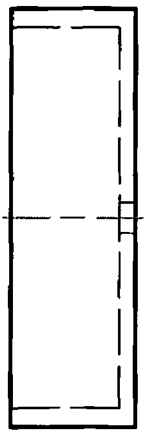
Date 30 Apr , 2002

B_6



B_7





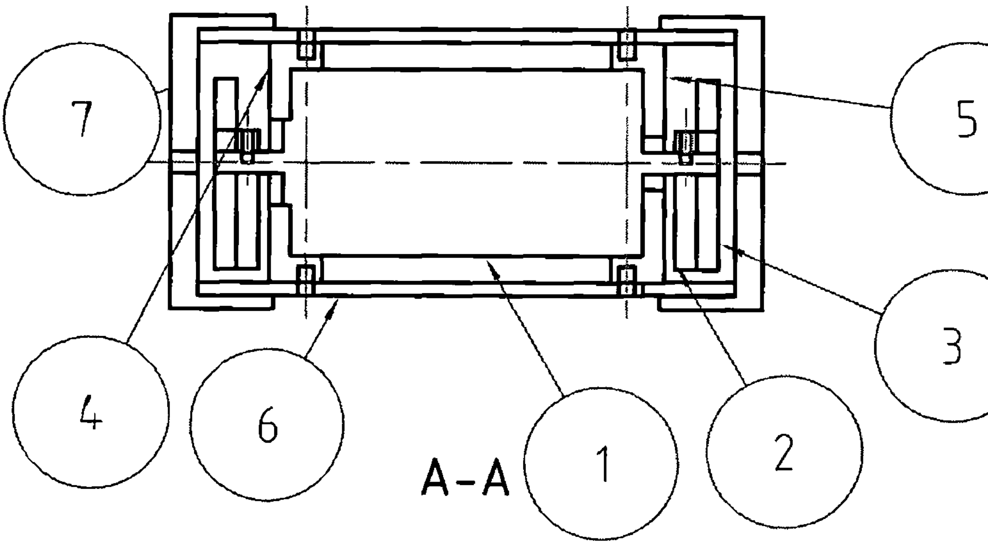
Item No #7

Part name CAP X2

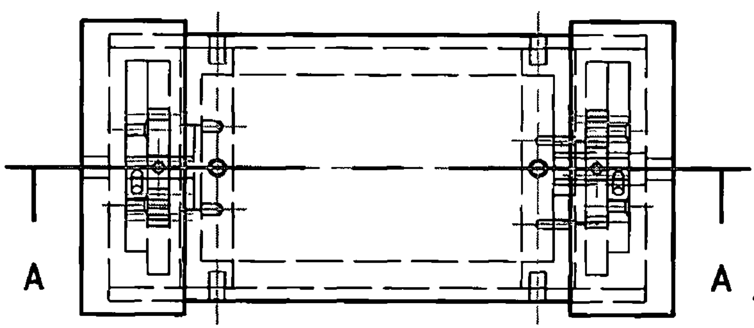
Material Polycarbonate

Designer Luo Jin

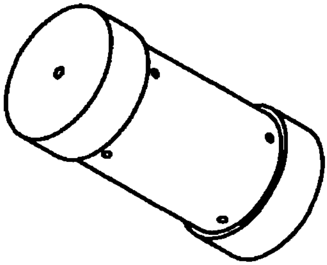
Date 30 Apr , 2002



A-A



B_8



Name	Item	Qty	Material
MOTOR	1	1	
ECCENTRIC MASS(FIXED)	2	2	copper, Aluminium, plastic
ECCENTRIC MASS(ADJUSTABLE)	3	2	Copper, Aluminium, Plastic
RING(FRONT)	4	1	plastic
RING(REAR)	5	1	Plastic
TUBE	6	1	Plastic
CAP	7	2	Plastic

Appendix C Health questionnaire form

Name______________________________

Date ________________________________

Age________________________________

Height ______________________

Weight_____________________________

Please tick the appropriate boxes, answering all questions

	YES	NO
I am currently in general good health	☐	☐
I presently have no injuries to the muscles	☐	☐

Signature _________________________________

Date _____________________________

Appendix D Informed consent forms for studies 1 to 6

DUBLIN CITY UNIVERSITY

RESEARCH - INFORMED CONSENT FORM

I <u>Project Title</u> Mechanical characteristics of muscle-tendon vibrator and EMG response to vibration of different amplitudes

II <u>Introduction to the study</u> Applying an external vibration to muscle has emerged in recent years as a potential for developing muscle strength We have developed a portable vibrator that can be strapped to the skin above a muscle during various strength-training exercises The aim of this study is to investigate the response of muscle to different sizes of vibration with the purpose of finding out which size of vibration is best, that is, which size of vibration will result in the largest muscle contraction

III I am being asked to take part in this research study The purpose of the study is to determine the size of vibration that will cause the largest contraction of my bicep muscle (upper arm)

IV This research study will take place at Dublin City University and will require me to attend the University on four occasions Each occasion will last for a period of approximately one hour

V This is what will happen during the first visit to the laboratory

1 I will be asked by the investigator to see if I am suitable for the study and asked to fill out a questionnaire on my health
2 I will be asked to read and sign this consent form to show that I understand the study and my role within the study
3 One muscle electrode, one accelerometer and one goniometer will be placed on my skin, with sticky tape, in order to measure the response of my muscle to vibration
4 A muscle-tendon vibrator will be strapped to my arm above my bicep muscle
5 I will then be asked to sit in a bench and grasp a 2 kg dumbbell with my dominant hand
6 I will be asked to feel the different size of vibration and check whether I am comfortable with them
7 I will be asked to lift and hold the weight on eight occasions, during four of them the vibration will be applied The vibration will last about 20 seconds
8 I will be given plenty of time to rest between each experimental condition

On my second and third visits to the laboratory, steps 3 to 8 of the above steps will be repeated on me On the fourth visits to the laboratory, the strapping force of the vibrator to the muscle will be increased and steps 3 to 8 of the above steps will be repeated on me

VI Sometimes there are problems associated with this type of study These are

1 I may find it mildly uncomfortable when my muscle is vibrated, but I understand that it will only be for a short time, and that it will not do harm to my arm I know that I am free to withdraw from the study whenever I want

VII There will be no direct benefit to me form participating in this study other than helping to increase knowledge in the area

VIII My confidentiality will be guarded Dublin City University will make reasonable efforts to protect the information about me and my part in this study and no identifying data will be published This will be achieved by assigning me an ID number against which all data will be stored Details linking my ID number and name will not be stored with the data The results of the study maybe published and used in further studies

IX If I have any questions about the study, I am free to call Jin Luo at (01) 7008470 or Dr Kieran Moran at (01) 7008011

X Taking part in this study is my decision If I do agree to take part, I may withdraw at any point including during the exercise test There will be no penalty if I withdraw before I have completed all stages of the study

XI I have read and understood the information in this form My questions and concerns have been answered by the researchers, and I have a copy of this consent form Therefore, I consent to take part in this research project entitled ' Mechanical characteristics of muscle-tendon vibrator and EMG response to vibration of different amplitudes'

Signature ____________________

____

Printed name

Date ____________________

Witness ____________________

Signature

Witness ____________________

Printed name

DUBLIN CITY UNIVERSITY

RESEARCH - INFORMED CONSENT FORM

I. Project Title: Mechanical characteristics of muscle-tendon vibrator and EMG response to vibration of different frequencies

II. Introduction to the study: Applying an external vibration to muscle has emerged in recent years as a potential for developing muscle strength. We have developed a portable vibrator that can be strapped to the skin above a muscle during various strength-training exercises. The aim of this study is to investigate the response of muscle to different frequencies of vibration with the purpose of finding out which frequency of vibration is best; that is, which frequency of vibration will result in the largest muscle activation

III. I am being asked to take part in this research study. The purpose of the study is to determine the frequency of vibration that will cause the largest contraction of my bicep muscle (upper arm)

IV. This research study will take place at Dublin City University and will require me to attend the University on one occasion. This occasion will last for a period of approximately one hour

V. This is what will happen during this visit to the laboratory
I will be asked by the investigator to see if I am suitable for the study and asked to fill out a questionnaire on my health

1. I will be asked to read and sign this consent form to show that I understand the study and my role within the study
2. One muscle electrode, one accelerometer and one goniometer will be placed on my skin, with sticky tape, in order to measure the response of my muscle to vibration.
3. A muscle-tendon vibrator will be strapped to my arm above my bicep muscle.
4. I will then be asked to sit in a bench and grasp a 2 kg dumbbell with my dominant hand
5. I will be asked to feel the different frequencies of vibration and check whether I am comfortable with them
6. I will be asked to lift and hold the weight on eight occasions, during six of them the vibration will be applied. The vibration will last about 20 seconds.
7. I will be given plenty of time to rest between each experimental condition

VI. Sometimes there are problems associated with this type of study. These are:

1. I may find it mildly uncomfortable when my muscle is vibrated, but I understand that it will only be for a short time, and that it will not do harm to my arm. I know that I am free to withdraw from the study whenever I want.

VII There will be no direct benefit to me form participating in this study other than helping to increase knowledge in the area

VIII My confidentiality will be guarded Dublin City University will make reasonable efforts to protect the information about me and my part in this study and no identifying data will be published This will be achieved by assigning me an ID number against which all data will be stored Details linking my ID number and name will not be stored with the data The results of the study maybe published and used in further studies

IX If I have any questions about the study, I am free to call Jin Luo at (01) 7008470 or Dr Kieran Moran at (01) 7008011

X Taking part in this study is my decision If I do agree to take part, I may withdraw at any point including during the exercise test There will be no penalty if I withdraw before I have completed all stages of the study

XI I have read and understood the information in this form My questions and concerns have been answered by the researchers, and I have a copy of this consent form Therefore, I consent to take part in this research project entitled ' Mechanical characteristics of muscle-tendon vibrator and EMG response to vibration of different frequencies'

Signature ______________________________

____

Printed name

Date ______________________________

Witness ______________________________
Signature

Witness ______________________________
Printed name

DUBLIN CITY UNIVERSITY

RESEARCH - INFORMED CONSENT FORM

I. Project Title: Influence of load on acute vibration training effect – a study on sub-maximal isometric contraction

II. Introduction to the study: Applying an external vibration to muscle has emerged in recent years as a potential for developing muscle strength. We have developed a portable vibrator that can be strapped to the skin above a muscle during various strength-training exercises. The aim of this study is to investigate the influence of load on muscle response to vibration when sub-maximal knee extension is performed

III. I am being asked to take part in this research study. The purpose of the study is to investigate the acute neuromuscular effect of a bout of knee extension strength training with superimposed vibration.

IV. This research study will take place at Dublin City University and will require me to attend the University on two occasion. Each occasion will last for a period of approximately one and half hour

V. This is what will happen during the first visit to the laboratory
I will be asked by the investigator to see if I am suitable for the study and asked to fill out a questionnaire on my health

1. I will be asked to read and sign this consent form to show that I understand the study and my role within the study
2. I will be asked to perform knee extensions with a sub-maximal load to my exhaustion. This is for the measurement of my knee extension strength (1RM).

This is what will happen during the second visit

1. Three EMG electrodes will be placed on my rectus femoris, vastus lateralis and vatus medialis respectively. One goniometer will be attached to my leg. A muscle-tendon vibrator will be strapped to my right leg on the tendon of quadriceps.
2. I will be asked to sit on a leg extension machine and extend my knee to a specific angle which is monitored by the investigator. Four experiment conditions will be randomly tested on me: A- no vibration with light load; B- no vibration with heavy load; C- vibration with light load; D – vibration with heavy load. Each condition will last for about 20 seconds. There will be a 3 minutes rest between each condition.

The same will happen in the third visit as in the second visit

VI. Sometimes there are problems associated with this type of study. These are:

1 I may find it mildly uncomfortable when my muscle is vibrated, but I understand that it will only be for a short time, and that it will not do harm to my arm I know that I am free to withdraw from the study whenever I want

VII There will be no direct benefit to me form participating in this study other than helping to increase knowledge in the area

VIII My confidentiality will be guarded Dublin City University will make reasonable efforts to protect the information about me and my part in this study and no identifying data will be published This will be achieved by assigning me an ID number against which all data will be stored Details linking my ID number and name will not be stored with the data The results of the study maybe published and used in further studies

IX If I have any questions about the study, I am free to call Jin Luo at (01) 7008470 or Dr Kieran Moran at (01) 7008011

X Taking part in this study is my decision If I do agree to take part, I may withdraw at any point including during the exercise test There will be no penalty if I withdraw before I have completed all stages of the study

XI I have read and understood the information in this form My questions and concerns have been answered by the researchers, and I have a copy of this consent form Therefore, I consent to take part in this research project entitled 'Influence of load on acute vibration training effect – a study on sub-maximal isometric contraction'

Signature ______________________________

____

Printed name

Date ______________________________

Witness ______________________________

Signature

Witness ______________________________

Printed name

DUBLIN CITY UNIVERSITY

RESEARCH - INFORMED CONSENT FORM

I. Project Title: Acute and acute residual effect of vibration training on neuromuscular performance with maximal isotonic contractions

II. Introduction to the study: Applying an external vibration to muscle has emerged in recent years as a potential for developing muscle strength. We have developed a portable vibrator that can be strapped to the muscle tendon during various strength-training exercises. The aim of this study is to investigate acute neuromuscular response to a bout of vibration training with maximal effort bicep curl exercise

III. I am being asked to take part in this research study. The purpose of the study is to investigate the acute neuromuscular effect of a bout of bicep curl exercise with superimposed vibration.

IV. This research study will take place at Dublin City University and will require me to attend the University on five occasions. Each occasion will last for a period of approximately one and half hour

VI. This is what will happen during the first visit to the laboratory
I will be asked by the investigator to see if I am suitable for the study and asked to fill out a questionnaire on my health

1. I will be asked to read and sign this consent form to show that I understand the study and my role within the study
2. I will be asked by the investigator about my height and weight
3. The 1RM strength of my elbow flexor muscles will be measured by the investigator
4. I will be asked to perform some training protocol that will be used in the experiment to let me be familiar with the experiment

This is what will happen during the second, third, fourth and fifth visit to the laboratory

1. I will be asked to do a warm-up exercise (12 repetition biceps curl and triceps curl with 25% of 1RM load, rest for 3 min, 12 repetition biceps curl and triceps curl with 50% of 1RM load).
2. My skin will be prepared over the bicep brachii and the tricep brachii muscles for attaching EMG electrodes
3. Two EMG electrodes (for biceps and triceps), one accelerometer and one goniometer will be attached to my dominant arm using double sided tape
4. A muscle-tendon vibrator will be strapped to my dominant arm.
5. I will be asked to perform 5 repetitions of maximal dynamic elbow flexion with 70% 1RM load as a pre-training test
6. The vibration will be applied to my muscle for several seconds and I will be asked if there is any discomfort

7 I will be asked to do 3 sets 10 repetitions elbow flexor strength training with 70% 1RM load I will be asked to do the concentric phase of each repetition as hard and fast as possible There will be 2 minutes rest between each set

8 Immediately after training, I will be asked to perform a test protocol again which is a 5 repetitions maximal dynamic elbow flexion with 70% of 1RM load Then I will perform this test protocol again at 10 minutes after the training

VI Sometimes there are <u>problems</u> associated with this type of study These are

1 I may find it mildly uncomfortable when my muscle is vibrated, but I understand that it will only be for a short time, and that it will not do harm to my arm I know that I am free to withdraw from the study whenever I want

2 There will be no direct benefit to me form participating in this study other than helping to increase knowledge in the area

VII There will be no direct benefit to me form participating in this study other than helping to increase knowledge in the area

VIII My confidentiality will be guarded Dublin City University will make reasonable efforts to protect the information about me and my part in this study and no identifying data will be published This will be achieved by assigning me an ID number against which all data will be stored Details linking my ID number and name will not be stored with the data The results of the study maybe published and used in further studies

IX If I have any questions about the study, I am free to call Jin Luo at (01) 7008470 or Dr Kieran Moran at (01) 7008011

X Taking part in this study is my decision If I do agree to take part, I may withdraw at any point including during the exercise test There will be no penalty if I withdraw before I have completed all stages of the study

XI I have read and understood the information in this form My questions and concerns have been answered by the researchers, and I have a copy of this consent form Therefore, I consent to take part in this research project entitled 'Acute and acute residual effect of vibration training on neuromuscular performance with maximal isotonic contractions

Signature ____

____

Printed name

Date ____

Witness ____
Signature

Witness ____

Printed name

DUBLIN CITY UNIVERSITY

RESEARCH - INFORMED CONSENT FORM

I. Project Title: Acute and acute residual effect of vibration training on neuromuscular performance with ballistic knee extension exercise

II. Introduction to the study: Applying an external vibration to muscle has emerged in recent years as a potential for developing muscle strength. We have developed a portable vibrator that can be strapped to muscle tendon during various strength-training exercises. The aim of this study is to investigate acute neuromuscular response of quadriceps to a bout of vibration training with ballistic knee extension exercise

III. I am being asked to take part in this research study. The purpose of the study is to investigate the acute neuromuscular effect of a bout of knee extension strength training with superimposed vibration.

IV. This research study will take place at Dublin City University and will require me to attend the University on three occasions. Each occasion will last for a period of approximately one and half hour

V. This is what will happen during the first visit to the laboratory
I will be asked by the investigator to see if I am suitable for the study and asked to fill out a questionnaire on my health

1. I will be asked to read and sign this consent form to show that I understand the study and my role within the study
2. I will be asked to perform knee extensions with a sub-maximal load to my exhaustion. This is for the measurement of my knee extension strength (1RM).

This is what will happen during the second and third visits to the laboratory

1. Two EMG electrodes will be placed on my rectus femoris and vastus lateralis respectively. One goniometer will be attached to my leg. A muscle-tendon vibrator will be strapped to my right leg on the tendon of quadriceps.
2. I will be asked to do a warm-up exercise (12 repetition knee extension with 25% of 1RM load, rest for 3 min, 12 repetition knee extension with 50% of 1RM load).
3. I will be asked to do a maximal isometric knee extension with the joint angle of 120°.
4. I will be asked to perform 5 repetitions of maximal dynamic knee extension with 60-70% 1RM load as a pre-training test
5. The vibration will be applied to my muscle for several seconds and I will be asked if there is any discomfort
6. I will be asked to do 3 sets 5 repetitions knee extension strength training with 60-70% 1RM load. I will be asked to do the concentric phase of each repetition as hard and fast as possible. There will be 5 minutes rest between each set

7. Immediately (with 2 minutes) after training, I will be asked to perform a test protocol again which is a 5 repetitions maximal dynamic knee extension with 70% of 1RM load. Then I will perform this test protocol again at 10 minutes.

VI. Sometimes there are <u>problems</u> associated with this type of study. These are:

1. I may find it mildly uncomfortable when my muscle is vibrated, but I understand that it will only be for a short time, and that it will not do harm to my arm. I know that I am free to withdraw from the study whenever I want.

VI. There will be no direct benefit to me form participating in this study other than helping to increase knowledge in the area.

VIII. My confidentiality will be guarded. *Dublin City University* will make reasonable efforts to protect the information about me and my part in this study and no identifying data will be published. This will be achieved by assigning me an ID number against which all data will be stored. Details linking my ID number and name will not be stored with the data. The results of the study maybe published and used in further studies.

IX. If I have any questions about the study, I am free to call Jin Luo at (01) 7008470 or Dr. Kieran Moran at (01) 7008011.

X. Taking part in this study is my decision. If I do agree to take part, I may withdraw at any point including during the exercise test. There will be no penalty if I withdraw before I have completed all stages of the study.

XI. I have read and understood the information in this form. My questions and concerns have been answered by the researchers, and I have a copy of this consent form. Therefore, I consent to take part in this research project entitled 'Acute and acute residual effect of vibration training on neuromuscular performance with ballistic knee extension exercise'

Signature:______________________________

____

Printed name

Date:______________________________

Witness ____
Signature

Witness ____

Printed name

DUBLIN CITY UNIVERSITY

RESEARCH - INFORMED CONSENT FORM

I Project Title Influence of load on neuromuscular response to vibration training – a study on maximal isotonic contractions

II Introduction to this study Recent findings suggest that vibration could represent an effective exercise intervention for enhancing neuromuscular performance (muscular strength) in athletes   While a number of studies in the area have found an enhancement in the neuromuscular system after vibration, others have found no effect   This controversy over the effect on the neuromuscular system may be due to the lack of control groups in some of the published studies   It is also unclear whether the level of intensity (the load lifted) during the vibration has a significant result on the acute effect of training, for example the rate of force development   A greater understanding of the acute effect will increase our understanding of the possible chronic effect of vibration training   In turn which will lead to better- designed resistance training programs for athletes   This study aims to see what acute effect muscle vibration has on the varying intensity of resistance power training of the biceps

III I am being asked to participate in this research study The study has the following purpose This study aims to see what acute effects of muscle vibration has on the varying intensity of resistance power training of the biceps

IV This research study will take place at the Centre for Sport Science and Health, Dublin City University, and will last approximately 2 week

V This is what will happen during the research study
I will visit the Centre for Sport Science and Health on 5 separate days   I will be required to abstain from resistance training and heavy physical work that requires use of my upper arm during this time

During the first visit I will perform a one repetition maximum test for my dominant (writing) arm   This will involve seeing how much weight I can lift one time maximally in an arm curl

During the remaining visits I will be asked to lift a percentage of my one repetition maximum i e 70% while my arm is vibrated   I will be asked to follow certain instructions and perform the lifts as demonstrated   A warm up of the arm muscles will precede all of the above

To gain data several small pieces of equipment that measure the angle of the arm during motion (goniometer) and the electrical activity of the arm muscle (electromyogram machine) will be placed on my arm and secured with medical tape They will not cause any pain and can be removed easily at any time if I feel discomfort

VI Sometimes there are side effects from performing exercise tests These side effects are often called risks, and for this project, the risks are Resistance training often causes delayed muscle soreness in the area after it was trained This usually appears 12-24 hours after training and disappears 48 hours after training Some mild discomfort such as shaking and/or tickling of the muscle may occur when the muscle is vibrated However the experimental procedure has been designed so the likely occurrence of this is minimal

VII There may be benefits from my participation in this study These are No benefits have been promised to me

VIII My confidentiality will be guarded
Dublin City University will protect all the information about me and my part in this study My identity or personal information will not be revealed, published or used in future studies The study results will be used as part of a study involving an undergraduate student at DCU In addition, the study findings may be presented at scientific meetings and published in scientific journals

IX If I have questions about the research project, I am free to call Jin Luo at 01-7008470 or Dr Kieran Moran at 01-7008011

IX Taking part in this study is my decision If I do agree to take part in the study, I may withdraw at any point, including during the test There will be no penalty if I withdraw before I have completed all stages of the study However, once I have completed the study, I will not be allowed to have my personal information and results removed from the database

XI Signature
I have read and understood the information in this form I have completed the questionnaire The researcher has answered my questions and concerns, and I have a copy of this consent form Therefore, I consent to take part in this research project entitled "Influence of load on neuromuscular response to vibration training – a study on maximal isotonic contraction"

Signature ______________________________

____
Printed name

Date ______________________________

Witness ______________________________
Signature

Witness ______________________________
Printed name