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Application of Whole-body Vibration:

Technical and clinical studies
in healthy persons and people with a neurological disorder

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Application of Whole-body Vibration: Technical and clinical studies in healthy persons and people with a neurological disorder

De toepassing van whole-body vibration: Technische en klinische studies bij gezonde personen en mensen met een neurologische aandoening

Proefschrift

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Chapter 1

General introduction

Introduction

History and development

The first use of vibration therapy to improve human function and muscle performance dates back to ancient Greece, a time when physicians used saws covered in cotton to transfer vibrations to specific parts of the body to improve muscle performance and relieve pain. However, these manual devices could only offer vibration locally and in one direction. It was not until the middle of the 19th century that physicians developed machines which produced both vertical and circular movements, which were considered to treat disorders such as neuralgia, muscular atrophy, emaciation and constipation[1-3].

In 1880, the French neurologist Jean-Martin Charcot examined the surprising improvements in the condition of pilgrims suffering from Parkinson's disease. He surmised that such improvements were attributable to the vibration from the horse-drawn and railway carriages. Based on this idea he developed a chair with a helmet that vibrated electrically. Between 1890 and 1910, Charcot's ideas were further developed by various therapists. In 1960, the West German Dr. Biermann published the paper *Influence of cycloid vibration massage on trunk flexion* in the *American Journal of Physical Medicine*[4].

Since 1970, Professor Vladimir Nazarov developed a vibration training program as an effective method for athletes. Using Biermann's ideas, he observed an improvement in power and flexibility in practical exercises. A little later, this local vibration training was used by the Russians in their space program to prevent bone density changes in astronauts. They recognized that this new idea for exercise had the potential to provide suitable countermeasures for preventing bone and muscle loss for astronauts under microgravity conditions. Whole-body vibration (WBV) was later used to enhance the performance of Soviet athletes during their exercise training[5]. However, the Russians kept the technology secret until after the Berlin Wall came down in November 1989. Since 1990, the European Space Agency and NASA also used vibration technology in ongoing studies on the maintenance of muscle strength, mass, and bone density. Simultaneously, extensive research was started on WBV in other areas of the world. In 1999, the Dutch Olympic coach, Guus van de Meer, introduced vibration training technology in Western Europe. He introduced a new way of WBV application, with emphasis on optimizing natural human function while preserving joint health and maximizing power. Nowadays, there is increasing interest in the use of WBV as a therapeutic modality to improve muscle strength, postural stability, and to increase bone density in groups of people of different types and ages.

Characteristics of WBV and conventional devices

Vibration is a mechanical oscillation, i.e. a periodic alteration of force, acceleration and displacement over time. Vibration exercise, in a physical sense, is a forced oscillation, where energy is transferred from an actuator (i.e. the vibration device) to a resonator (i.e. the human body, or parts of it). In most vibration exercise devices, these oscillations have sinusoidal shape, and are therefore described by amplitude (A), frequency (*f*), and the direction of the oscillation (Figure 1).

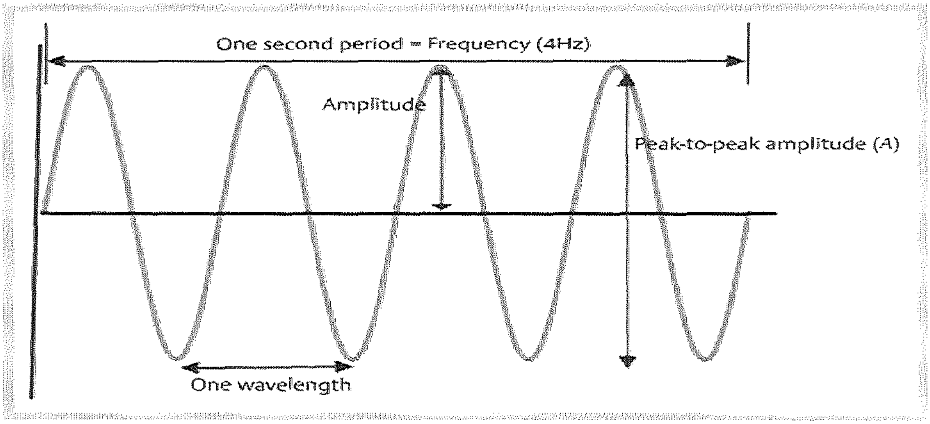

Figure 1. Parameters of sinusoidal oscillation.

Frequency indicates the number of oscillations per second, expressed in Hz. The angular frequency ω is derived from it, as $2\pi f$.

Amplitude represents the maximum displacement of an oscillating body from its equilibrium position, expressed in mm. Other terms are peak-to-peak amplitude and peak-to-peak displacement. During vibration exercise, the human body is accelerated, which causes a reactive force by and within the human body. Importantly, the peak acceleration (a_{peak}) in sinusoidal oscillation is given by: $a_{peak} = \omega^2 . A$.

Vibration exercise is mostly practiced as WBV, i.e. applied to the whole body while standing on an oscillating platform. Several commercial and non-commercial devices are available to apply WBV. Although the amplitude and frequency can be set within device-specific ranges, devices differ in their direction of vibration. Among the different platforms, two different types of energy transfer can be distinguished. One type (e.g. PowerPlate) transfers vibration to both feet synchronously, that means that the direction and timing of vibration is similar for the whole platform. This results in simultaneous and symmetrical movement of both sides of the body during the exposure (vertical vibration; VV). The second type operates in a side-alternating way, such as the Galileo. This device has a teeterboard that produces side-alternating vertical sinusoidal vibration to the body. It rotates around an anterior-posterior horizontal axis. As a result, the movements of both legs are out of phase (radial vibration; RV). Additionally, when the feet are further from the axis, this results in a larger vibration amplitude (Figure 2). In addition to the professional devices, some devices for use at home are also available. One example is the PowerMaxx, which can differ in mechanical properties and other characteristics such as size of the platform, strength of the generator, etc. The low price and easier access to this kind of device are their main advantages.

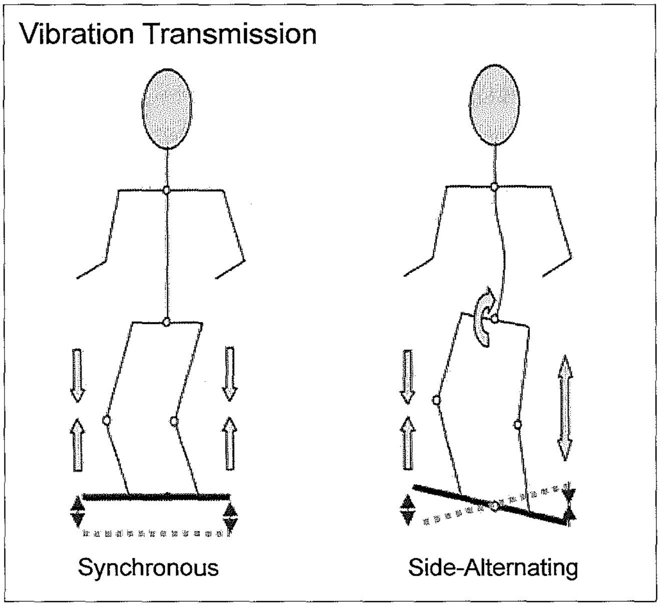

Figure 2. Two principle modes of vibration transmission in whole-body vibration exercise and two types of devices based on the way of vibration.

Potential physiological mechanisms of WBV

During exposure to WBV, vibrations are transmitted to the human body. As a result, muscles are vibrated resulting in subsequent elongation and shortening. Because of this phenomenon, several physiological mechanisms are thought to play a role. Although the mechanisms by which WBV affects the body are still under debate, the one most often proposed is the Tonic Vibration Reflex (TVR)[6-8]. This implies that mechanical vibration applied to the muscle belly will stimulate sensory receptors, mainly length-detecting muscle spindles. The primary endings of the muscle spindle (the Ia afferent fibers) are stimulated by the changing of the length of the muscle, resulting in activation of the α-motoneurons by monosynaptic pathways, causing reflex muscle contractions. Additionally, this input will simultaneously modulate α-motoneurons by polysynaptic pathways via higher centers. Since the primary and secondary somatosensory cortex, together with the supplementary motor area, constitutes the central processing unit of afferent signals[9], applied vibration is capable of activating the supplemental motor area. However, current evidence does not provide an explanation for the specific neural adaptations that accompany a vibration (Figure 3).

As seen in Figure 3, also other mechanoreceptors (e.g. joint receptors, skin receptors) are stimulated by vibration[10]. These receptors are also connected to higher centers by interneurons, and will also

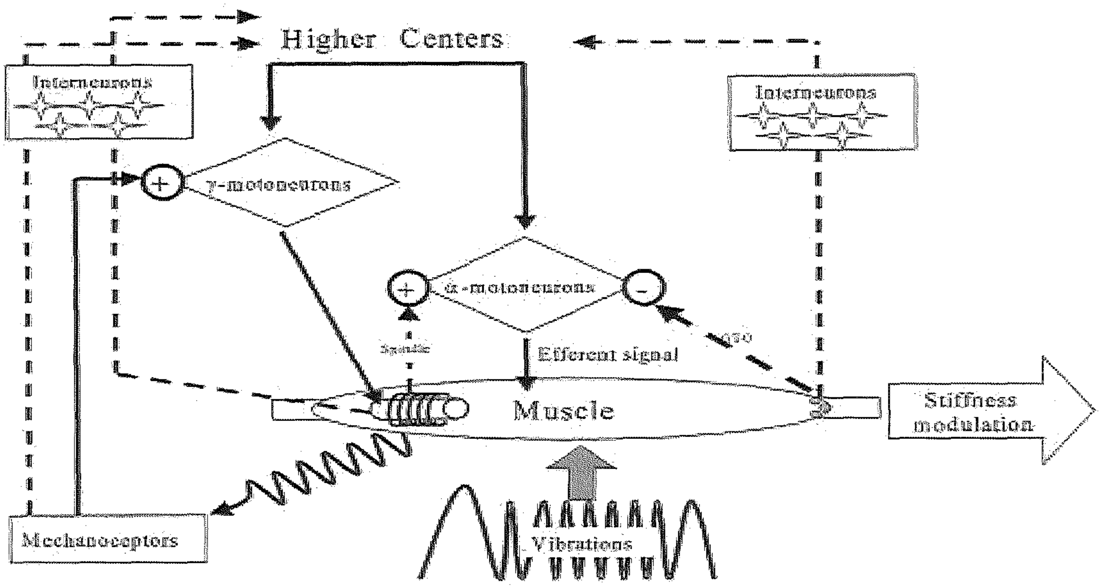

Figure 3. Schematic diagram illustrating stiffness regulations during vibration stimulation. Quick change in muscle length and the joint rotation caused by vibration trigger both alpha and gamma motor neurons to fire to modulate muscle stiffness. Higher centers are also involved via a long loop.

modulate α-motoneuron activity. Additionally, stimulation of these receptors provides sensory input to the gamma motor system, increasing the sensitivity and responsiveness of the muscle spindle to further mechanical perturbations[11-12].

The higher centers have two descending neural pathways: one pathway will modulate α-motoneurons, and the other will modulate γ-motoneurons. At the level of the muscle, during WBV not only muscle spindles are stimulated, but also Golgi tendon receptors that activate Ib neurons. These neurons inhibit the alpha motoneurons to regulate the stiffness of the muscle and subsequently prevent damage to the muscle. Like the muscle spindles, Golgi tendon receptors also inform somatosensory cortex via other series of interneurons in order to enhance orientation of supplementary motor area.

General aspects of WBV

Nowadays, vibration exercise is broadly available to therapists, exercise trainers and individuals who want to exercise. However, despite many studies that aimed to identify the effectiveness of WBV, there is no agreement about the efficacy of this modality. The differences in results can probably be attributed to differences in therapeutic goals, mechanical characteristics of the devices, study outcomes, study populations, acute or training effects, and/or treatment protocols.

Important goals of WBV

The effects of WBV are related to different goals, such as improving muscle strength, postural stability, bone mass, sensorimotor performance, and muscle tonicity. This variety in goals probably illustrates the uncertainty about the mechanism of action of WBV. In addition, the heterogeneity of the goals probably contributes to the heterogeneity in findings; e.g. reported differences in the effectiveness of WBV might depend on the outcomes defined in the study protocol. From a rehabilitation point of view, neuromuscular performance is considered to be very important. Therefore, this thesis focuses on muscle strength, postural stability and muscle tonicity, based on experimental studies with WBV and a systematic review of the literature.

Mechanical behavior of devices

Another reason for differences in study outcomes might be differences in the mechanical behavior of the WBV devices. In addition, several settings such as amplitude (1-5 mm), frequency (15-50 Hz), and duration of exposure (1-8 min) may influence the effects of WBV on the neuromuscular system of the human body[11-13]. Although several studies have explored the optimal parameters to achieve therapeutic goals in the human body, no consensus has been reached. Moreover, individuals react differently to the applied frequency, i.e. each individual may have a different optimum frequency of vibration that elicits the greatest reflex response during WBV[14]. Therefore, part of this thesis focuses on the mechanical behavior of different devices, on the way they react to loading, and on differences in physiological effects resulting from it.

Target population

The different findings on WBV might also be related to differences between study populations. Especially age and fitness level can be of importance. For instance, more consistent positive results have been reported in people with low levels of fitness than in young people or athletes. In athletes, results on muscle power vary from none[15-16] to favorable[17-18], whereas in older persons almost always positive results were found[12,19-20].

Acute effects vs. training effects

The studies on WBV can be categorized according to the type of intervention. There are two kinds of vibration studies. Firstly, studies that focus on the immediate/acute effects, which generally explore short-term exposure to WBV. Secondly, studies focusing on the training effects of WBV, which generally follow several sessions of WBV. Short-term exposure can consist of a single bout of WBV, ranging from several seconds to several minutes, or of multi-bout exposures with rest intervals during one session. Long-term exposure is related to exposure to several sessions of vibration during several weeks or months (ranging from 3 weeks[21] to one year[20]). Studies focusing on the acute effects are mainly performed to determine the underlying mechanisms of WBV, and also because that approach is time and cost-effectiveness. When acute effects of vibration are found, studies with a long-term exposure are the next logical step. Because of the conceptual difference between these two types of studies, and the effect of differences in therapeutic goals and target populations, below we provide a brief overview of the related literature.

Effects of WBV

As mentioned above, the results of WBV depend on the target population, the goals of WBV treatment, and on whether acute effects or training effects are studied. In this section we summarize the literature on the acute effects and training effects of WBV on neuromuscular performance in healthy subjects and neurological patients.

Acute effects of WBV in healthy subjects

Muscular performance and balance

So far, studies examining the acute effects of WBV on muscular performance in healthy persons show a broad range of results, ranging from no effects[22-25] to favorable effects[26-28]. However, according to the review by Rittweger[29], WBV appears to provide no or only minor additional effects on muscle strength and jump performance as compared with performing the same exercises without WBV. Similarly, the effects of WBV on postural stability are still under debate. For instance, in young subjects no acute effects of WBV were found on balance[25, 30].

Motor neuron excitability

Unlike muscular performance, motor neuron excitability is a new topic in the field of WBV. A few studies aimed to determine whether WBV has excitatory or inhibitory effects on motor units. Armstrong et al.[31] concluded that a significant suppression of the Hoffman reflex occurred during the first minute following exposure to a single bout of WBV. Similarly, Kipp et al.[32] found that WBV significantly decreases spinal reflex excitability; this effect was independent of muscle group but was only temporary.

Training effects of WBV in healthy subjects

In studies to identify training effects of WBV, the training period ranges from four weeks to one year. For instance, to increase bone density WBV is applied for at least for 6 months[33], but improvement of muscle strength is reported to need 3-4 weeks training[34-35]. Training effects of WBV are not always the mirror image of acute effects. It is assumed that chronic exposure to WBV could be effective on the musculoskeletal system due to a change in the structure of muscles and will result in histological changes in the muscular system. However, different protocols and settings are applied (most programs involve three or more training sessions per week). Moreover, in most studies participants were encouraged to change exercises and postures, e.g. to use different types of squats and lunges.

Muscular performance and balance

Some training studies focused on the effects on several aspects of neuromuscular performance, such as muscle strength[12,36-37], muscle power[8,38], maximal rate of force rise[39], and postural stability[11,40-41]. Additionally, other studies focused specifically on elderly nursing home residents to analyze the effects of WBV on functional capacity, muscle performance, prevention of falls, and body balance[42]. However, the results of these studies remain inconclusive.

Acute effects of WBV in neurological patients

Problems in voluntary muscle strength, balance, and spasticity are among the most common motor impairments associated with neurological disorders. WBV was introduced in the last decade to solve these problems. Although this modality is not accepted as an effective therapeutic approach in neuro rehabilitation, it is still open to discussion with regard to its potential applicability. There are several reasons to support the possibility that WBV might be effective in neurological patients: the displacement of the platform is reported to mimic human gait, vibration of the foot soles could evoke postural responses, and WBV as a somatosensory stimulator may have several musculoskeletal benefits.

Muscular performance and balance

Several studies focused on the acute effects of WBV in neurological patients, such as those with Parkinson disease, stroke, and multiple sclerosis. Schuhfried et al.[43] examined postural stability following a single bout of WBV in patients with multiple sclerosis and reported that the effects were strongest one week after the intervention; posturography and Timed-Up-and-Go (TUG) test improved significantly compared to a placebo group. Jackson et al.[44] evaluated muscle strength and reported that there were no significant differences in isometric torque production between the application of 2 Hz and 26 Hz. Application of a single bout of vibration[45-46] in patients with Parkinson's disease showed that WBV has some potential to improve balance and function. However, the acute effect of WBV in neurological conditions remains inconclusive.

Spasticity

This aspect has scarcely been studied; the only study to explore whether WBV decreases spasticity was performed by Ness and Field-Fote[47] in patients with spastic hypertonia. There was no significant reduction in quadriceps spasticity immediately after a single session, although a reduction was found after participation in a prolonged WBV training intervention.

Training effects of WBV in neurological patients

Several studies aimed to identify the effects of a WBV training program in neurological patients. The literature on this topic is systematically reviewed in ***Chapter 2*** of this thesis.

Aims and research questions

The aims of this thesis are:

1) To examine the training effects of WBV on neuromuscular performance in neurological patients.
2) To compare three different WBV devices with respect to mechanical behavior and effects on jump force and neuromuscular activity.
3) To investigate the immediate effects of WBV on postural stability and motor neuron excitability.
4) To investigate the immediate effects of WBV on spasticity of calf muscle in patients with chronic stroke.

The main research questions addressed in this thesis are:

1) Does literature indicate that training with WBV has an effect on neuromuscular performance in neurological patients?
2) What are the technical differences and differences in mechanical behavior of three devices of WBV, including the effect of loading?
3) Do different WBV devices result in different immediate effects on jump force and neuromuscular activity in healthy subjects?
4) Does exposure to a single bout of WBV have an effect on postural stability and motor neuron excitability in older adults?
5) Does exposure to a single bout of WBV reduce spasticity of calf muscles in stroke patients?

Structure of the thesis

Chapter 2 presents a review of the studies on neuromuscular effects of WBV training in patients with different neurological disorders.

Chapter 3 describes the platform accelerations of two commonly used professional WBV devices (the PowerPlate and Galileo) and that of one home-use device (the PowerMaxx) under different loading conditions. In addition, for the three devices the transmission of platform accelerations to the lower limbs is investigated.

Chapter 4 focuses on differences in the acute effects of WBV on jump force and jump rate of force development between the three devices

Chapter 5 presents a study that compares differences in the acute effects of the three WBV devices on neuromuscular response of the quadriceps muscle (vastus lateralis muscle) by means of surface electromyography.

Chapter 6 presents a study on the immediate effect of WBV on postural stability and motor neuron excitability in older adults.

Chapter *7* aims to elucidate the acute effects of WBV on spasticity of calf muscles in individuals with chronic stroke. Effects of sitting and standing position on the vibration platform are compared to verify the effects on calf muscle spasticity.

Finally, ***Chapter 8*** presents a general discussion of the findings emerging from these studies.

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Chapter 2

Effects of whole-body vibration training on neuromuscular performance in patients with neurological disorders: A systematic review

J. Bagheri, H. Kooijmans, H.J. Stam, J.B.J. Bussmann

Submitted

Abstract

Whole-body vibration (WBV) is a modality in physical rehabilitation with the potential to improve neuromuscular performance in neurological patients. This review examines the effectiveness of WBV to improve muscle strength and balance and reduce spasticity in patients with different neurological disorders.

Four electronic databases (MEDLINE, Embase, PEDro, and CINAHL) were searched from 1995 to January 2012. We included randomized controlled trials and controlled clinical trials with multiple sessions of WBV (training protocols). The main outcome categories were muscle strength, balance/postural stability, and spasticity. Two reviewers independently selected trials, assessed methodological quality, and extracted data. Disagreement was resolved by discussion or referred to a third expert. Results were summarized in a best-evidence synthesis based on population and outcome category.

Of the 9 included trials, 3 focused on multiple sclerosis, 2 on Parkinson disease, 2 on cerebral palsy, and 2 on stroke. The best-evidence synthesis revealed conflicting evidence that WBV training is effective for improvement of muscle strength in multiple sclerosis. There was no evidence, or there were no included studies, on the other combinations of neurological disorder and outcome category.

In conclusion, there is insufficient evidence for the effectiveness of WBV training on neuromuscular performance in patients with neurological disorders. More comprehensive studies are needed to further explore the potential of WBV in these patients.

Introduction

Patients with neurological disorders represent a major group within Rehabilitation Medicine and Physical Therapy. Neurological disorders often result in a variety of physical impairments. A major category is that of impaired neuromuscular performance, e.g. decreased voluntary muscle strength, balance, and muscle tone. Medical and paramedical treatment frequently focuses on improving neuromuscular performance in order to minimize disability in daily functioning.

Whole-body vibration (WBV) - the application of a vibratory stimulus to the entire human body[1]- has been proposed as a modality to improve neuromuscular performance. For example, beneficial effects on muscle strength[2], motor unit excitability[3], balance[4], and proprioception[5] have been reported. In the past decade, WBV has become increasingly popular and many studies on the effects and mechanisms of WBV have been performed[2,6-8].

So far, most studies included athletes and healthy volunteers and focused on the effects of WBV on muscular performance[6,9]. However, general conclusions about the effectiveness of WBV in these populations are hampered by the heterogeneity in outcomes, the devices used, settings (e.g. frequency, amplitude), treatment aim, treatment protocol, and target population. The conflicting results might also be related to the fitness and training level of the study group involved; it is reported that WBV might be more effective in people with fitness levels lower than that in athletes. For example, Torvinen et al.[10] concluded that older people should have a greater potential to improve balance than young people, possibly due to the lower fitness level or the aging process in older individuals. Since chronic diseases are often related to poorer fitness levels, it is feasible that WBV might be beneficial in the treatment of chronic disease.

Although WBV has also been applied with other treatment aims, such as increasing bone density and hormonal responses, most studies on the training effects of WBV in various disorders have aimed at outcome parameters related to neuromuscular performance. We found one review that examined the effectiveness of WBV specifically in people with Parkinson disease[11]. In their review, Lau et al. focused on the effectivenes of WBV (either acute exposure or training effects) and concluded that there is insufficient evidence to prove or refute the effectiveness of WBV in enhancing sensory motor performance in this group of patients.

To our knowledge, there is no systematic review on the effectiveness of WBV training on neuromuscular performance in neurological disorders. Such a review, focusing on evidence for the effects of WBV in chronic diseases, will support the therapeutic choices made by therapists and physicians working with or interested in WBV in chronic disease. Therefore, this systematic review assesses the effectiveness of WBV training on neuromuscular performance in patients with chronic neurological disorders.

Methods and materials

Search strategy

An extensive literature search of electronic databases (1995 to January 2012) was undertaken to identify relevant randomized clinical trials (RCTs) or clinical controlled trials (CCTs). The databases included MEDLINE, CINAHL, Embase, and PEDro. A combination of search terms was used to perform the search: WBV training or therapy in the human body and the most common neurological disorders (Appendix 1). A forward search with the Science Citation Index was made to identify and examine all subsequent articles that referenced the selected articles.

Inclusion criteria

RCTs and CCTs were considered for inclusion if they met the following criteria: 1) participants have a neurological disease; 2) the treatment is a long-term intervention of WBV (i.e. the intervention lasts more than two weeks, and the interval between pre- and follow-up assessment is more the two weeks); 3) the results include measures related to neuromuscular performance, and 4) the publication is written in English.

Selection of papers

The literature search was performed by two independent researchers who are experienced and involved in rehabilitation research. A third reviewer was consulted for consensus purposes. Based on the inclusion criteria, titles and abstracts of the selected articles were first screened to eliminate irrelevant articles. Then, the remaining full-text articles were assessed to determine eligibility.

Data extraction

Data were extracted by two reviewers independently. If needed, a third reviewer was consulted for consensus. The following data were extracted: 1) participant characteristics (disease, age and gender); 2) description of the WBV and control intervention (e.g. training period, session characteristics, position of the patient, device, settings, content); 3) measurement protocol; and 4) outcome measures (Appendix 2). Outcome measures were subdivided into three categories: muscle strength, balance/postural stability, and spasticity. Most papers presented a large number of outcome measures. For practical reasons we defined some selection rules. First, we gave preference to outcome measures with a strong connection to the three outcome categories; for that reason, general disability questionnaires were not included. Clinical tests were included if they were specifically related to muscle strength, balance (e.g. the Berg Balance Test and Tinetti test) or spasticity (e.g. the Ashworth test), or if they were general motor performance tests (e.g. the Timed Up & Go test, 10-meter walk test, Gross Motor Function Test). In case of multiple tests focusing on the same construct, the test mostly used was selected. We prioritized objective tests such as dynamometry and posturography. In case of dynamometry and if applicable, we selected dynamic measurements (in preference to static), knee flexion/extension (in preference to other joints), concentric (in preference to eccentric), force/torque (in preference to work), and the angular speed with the largest overlap between studies.

Methodological quality assessment

The 12 criteria of the quality assessment of Furlan et al.[12] were used to assess the quality of the articles in terms of risk of bias. Each item was scored as 'yes', 'no', or 'unsure'. High-quality was defined as a percentage 'yes' score of ≥ 50. Two reviewers independently assessed the methodological quality of each RCT. Again, the consensus procedure was used to solve any disagreement between the reviewers (Table 1).

Table 1. Risk of bias (based on the quality assessment of Furlan et al.[12])

First author	Adequate randomization	Concealed treatment allocation	Patient blinded	Care provider blinded	Assessor blinded	Drop-out rate described & acceptable	All randomized participants analyzed	Being free of suggestion	Groups similar at baseline	Co-interventions avoided / similar	Acceptable compliance in all groups	Timing of the outcome assessment similar	Total score	Percentage	Quality
Broekmans[14] (2010)	?	?	–	–	–	+	+	+	+	+	+	+	7/12	58	High
Schyns[15] (2009)	+	–	–	–	+	–	+	+	+	+	+	+	8/12	67	High
Claerbout[16] (2011)	+	+	–	–	+	+	+	+	+	?	?	+	8/12	67	High
Arias[17] (2009)	?	–	–	–	+	+	+	+	+	+	+	+	8/12	67	High
Ebersbach[18] (2008)	?	?	–	–	+	+	+	+	+	+	?	+	7/12	58	High
Ahlborg[19] (2006)	?	?	–	–	+	+	+	+	+	+	+	+	8/12	67	High
Ruck[20] (2010)	+	?	–	–	?	+	+	+	+	–	?	+	6/12	50	High
Merkert[21] (2011)	?	?	–	–	?	–	+	+	+	?	?	+	4/12	33	Low
Van Nes[22] (2006)	+	+	–	–	+	+	+	+	+	?	+	+	9/12	75	High

+ = Positive – = Negative ? = Unknown

Data synthesis

Due to heterogeneity of the outcome measures, diseases and training protocols of WBV we were unable to pool data of the studies and perform a meta-analysis. Data of studies were categorized based on neurological disorder and outcome category (muscle strength, balance/postural stability, and spasticity). We summarized the results using a best-evidence synthesis adopted from others[12-13] (Table 2). A study was included in the best-evidence synthesis if a comparison between the groups could be made (e.g. intervention versus control treatment) and if differences between groups were statistically tested.

Table 2. Best-evidence synthesis.

Strong evidence (A)	Consistently one positive (significant) finding within multiple high-quality RCTs.
Moderate evidence (B)	Consistently one positive (significant) finding within multiple low-quality RCTs and/or one high-quality RCT.
Limited evidence (C)	Positive (significant) findings within one low-quality RCT.
Conflicting evidence (D)	Provided by conflicting (significant) findings in the RCTs (<75% of the studies reported consistent findings).
No evidence (E)	No (significant) differences between intervention and control groups were reported.
No review (F)	No systematic review or RCT found.

Results

The initial literature search identified 1302 studies from PubMed, 237 Embase, 207 CINAHL, and 24 from PEDro. Papers found in PubMed included all papers in the other three databases (Figure 1).

Our search strategy finally identified 9 papers (8 RCTs[14-20,22] and one CCT[21]). Three studies investigated multiple sclerosis[14-16], two Parkinson diseases[17-18], two cerebral palsy[19-20], and two investigated stroke[21-22]. Four studies mainly focused on muscle strength[14-16,19], two of them in combination with spasticity[15,19], and the other two papers combined with balance[14,16]. One paper entitled evaluation of muscle tone[21], but data about muscle tonicity was not reported in the paper. Six papers evaluated effects of WBV on balance and postural stability either objectively[18,22] or clinically[14,16-18,21-22], with two of them[14,16] - as already indicated - in combination with muscle strength. The main focus of one paper[20] could not be categorized as strength, spasticity or balance.

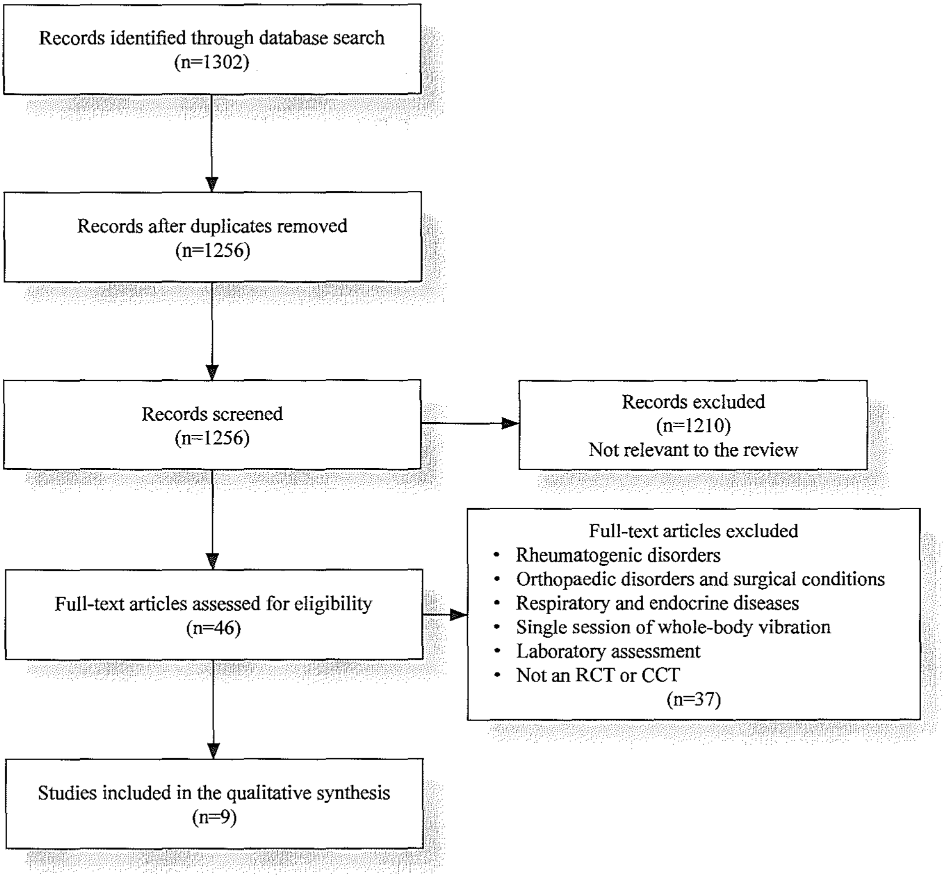

Figure 1. Flow chart showing selection of the studies in this review.

Methodological quality

Based on the quality assessment of Furlan et al.[12], a risk of bias score was given to each study. The score range was 4-9, with a median of 8. With the exception of one study on patients with stroke[21] the studies had a high quality. Generally, most studies had poor scores on concealed allocation, and blinding for patients, assessors, and therapists. The results of methodological quality for the other items were more diverse. In addition to the Furlan assessment, it can be reported that three studies[15,16,20] presented change scores, tested differences between them, and reported p-values. Five studies[14,17-19,22] tested differences between change scores, without reporting the change scores and exact p-values. In one study[21] neither testing nor reporting of change scores took place.

Effects of WBV by disease

Multiple sclerosis

Three studies[14-16] aimed to determine effectiveness of WBV in multiple sclerosis. All multiple sclerosis studies investigated muscle strength. One of them[15] also measured spasticity and the other ones[14,16] also included balance measurements. Claerbout et al.[16] reported improvement of muscle strength in quadriceps ($p<0.05$) and hamstrings ($p<0.01$) in comparison to a multidisciplinary rehabilitation program. Broekmans et al.[14] and Schyns et al.[15] found no improvement of muscle strength compared to the control group following either a 4-week[15] or even a 20-week[14] training.

Parkinson disease

Arias et al.[17] and Ebersbach et al.[18] determined the effects of WBV in Parkinson disease. Both studies focused on balance/postural stability, which was evaluated by clinical tests. The study of Ebersbach et al.[18] also included posturography. Arias et al.[17] found a within-group effect in the intervention group and Ebersbach et al.[18] an overall time effect. However, in both studies no added effect of the WBV was found compared to the control intervention. In both studies, there was also no significant difference in other outcome measures between the WBV group and either conventional physiotherapy[18] or the placebo groups[17].

Cerebral palsy

Ahlborg et al.[19] and Ruck et al.[20] explored the effectiveness of WBV in patients with cerebral palsy after 8-weeks or 6-month training period, respectively. Ahlborg et al.[19] aimed at muscle strength and spasticity, whereas Ruck et al.[20] explored general function. The only significant effect of WBV in these studies was found in the study of Ruck et al.[20] where significant improvements were found only on the 10-meter walk test when WBV was compared with a school-based physiotherapy program. There were no effects of WBV on other outcome parameters.

Stroke

The two stroke studies[21-22] focused on balance/postural stability. Although Merkert et al.[21] did not report clear and interpretable statistical data between groups and related values, they concluded that WBV is more effective than control group. In the study of van Ness et al.[22], no significant differences were found between the WBV group and control groups.

Effects of WBV by outcome measures

Muscle strength

Four studies[14-16,19] determined the effectiveness of WBV on muscle strength. In only one study[16] a significant difference was found between vibration training and the control intervention, which was a multidisciplinary rehabilitation program.

Balance/Postural stability

In six papers[14,16-18,21-22] the effects of WBV on balance and postural stability were reported. In no study a difference in effect was between the WBV intervention and the control intervention. As a result, no differences were found between objective (posturography) and clinical (Berg Balance scale or Tinetti test) measurements.

Spasticity

Schyns et al.[15] and Ahlborg et al.[19] determined the effectiveness of WBV training on spasticity by means of the Ashworth scale; no significant differences were found between vibration training and a control intervention.

Evidence synthesis

Of the 9 studies, one[21] could not be used for the best-evidence synthesis (Table 3). There is conflicting evidence that WBV training is effective for improvement of muscle strength in multiple sclerosis. There was no evidence, or there were no included studies, on the other combinations of neurological disorder and outcome category.

Table 3. Overview of the effectiveness of whole-body vibration on outcome measurements in neurologic disease.

Disease	Muscle Strength	Balance/postural stability	Spasticity
Stroke	NS	NE	NS
Cerebral Palsy	NE	NS	NE
Parkinson	NS	NE	NS
Multiple sclerosis	CE	NE	NE

CE: Conflicting evidence; NE: No evidence; NS: No study available

Discussion

This systematic review presents an overview of the available literature on the effectiveness of WBV on the neuromuscular performance of patients with neurological disorders. This review included 9 studies that focused on the effectiveness of WBV in neurological patients compared with conventional exercise groups or control groups. Besides the small numbers, the studies are characterized by a lack of consistency and robustness regarding methodology, and by a large variety in treatment and measurement protocols.

To determine the methodological quality of the studies, the quality assessment of Furlan et al.[12] was used (Table 2). This assessment indicated that 8 articles[14-20,22] were of high quality, i.e. they scored ≥ 50% (range 50-75%). Only one study was of low quality (score of 33%)[21]. However, the Furlan method for quality assessment has some limitations. First, because no distinction is made between 'not done' and 'not reported', both options will result in similar score. Second, we feel that some items overlap or are not applicable for WBV studies. For example, blinding the patient and therapist is not possible or difficult to achieve in the case of WBV. Finally, some important issues, such as reporting and testing differences between two groups of intervention, are not part of the Furlan's assessment. Nevertheless, this method of assessment is generally accepted and widely used in systematic reviews. Based on the results of the included studies (Appendix 2), the effectiveness of WBV on neuromuscular performance in neurological patients could not be supported. Only one study[16] reported significant effects of WBV, in that case improvement of muscle strength in multiple sclerosis following a 3-week vibration training compared to a general rehabilitation program. Other studies on this topic and in this population did not confirm this finding.

With respect to the effectiveness of vibration training on balance/postural stability, Arias et al.[17] concluded that balance (measured by the Berg Balance Scale) improved after five weeks within WBV group. However, there was no difference between vibration training versus placebo. The remaining studies on groups with different neurological disorders showed no additional effects of vibration training on either posturography or clinical evaluation. Regarding the effectiveness of vibration training on spasticity, studies on patients with multiple sclerosis[15] and cerebral palsy[19] showed no reduction in spasticity.

Shortly after our data analysis was completed, del Pozo-Cruz et al.[23] published a review with a similar aim to ours. These authors also concluded that there is limited evidence for the effectiveness of WBV training to improve muscle strength, proprioception, gait, and balance in neurological patients. Although there is some overlap with our review, there are some differences. First, del Pozo-Cruz et al. included all published articles (RCTs or any other study design) whereas our review included only RCTs and CCTs. Second, they included both short-term exposure and longer-term training with WBV, whereas we included only WBV training studies. Thirdly, del Pozo-Cruz et al. evaluated any outcome measure, while we focused on neuromuscular performance such as muscle strength, balance and spasticity. Finally, they used the PEDro for methodological quality assessment, whereas ours was based on the assessment of Furlan et al.[12]. The review of Lau et al.[11] (known to us when we started our review) focused specifically on Parkinson disease and (similar to del Pozo-Cruz et al.) included both acute effects and training effect studies of WBV. Besides that, they focused on sensorimotor performance in these patients. However, their conclusions are similar to ours, i.e. there is insufficient evidence to support or refuse the effectiveness of WBV in enhancing sensorimotor performance in people with Parkinson disease. Several reviews also aimed to show the effectiveness of WBV on neuromuscular performance in healthy subjects (older individuals)[24-26]. Despite having a different outcome measures, those reviews also reported no or conflicting evidence for the effectiveness of WBV training.

The present review has some limitations that should be addressed. First, the number of studies evaluating the effects of WBV in neurological diseases is small. This might be because WBV is a relatively new intervention; the completed studies date from 2006[19,22]. Second, the studies are characterized by a wide variation in methodology and approach, heterogeneity in reported outcome measurements, and differences in the settings and protocols of WBV. For example, different types of vibration platforms, amplitude and frequency settings, and a wide range in the duration of training. This lack of homogeneity between studies might contribute to the inconsistent results and, together with the small number of studies, prevented a meta-analysis of the results.

In conclusion, our review does not support the effectiveness of whole-body vibration in neurological disease such as Parkinson disease, multiple sclerosis, stroke and cerebral palsy. For most diseases and outcomes we found either no evidence or no studies. For the effects of WBV on muscle strength in multiple sclerosis conflicting evidence was found. However, the present results should be interpreted with caution because of the small numbers of and large variation between the studies. More well-designed studies on WBV in neurological patients will allow more valid conclusions to be drawn on the effectiveness of WBV in patients with neurological disorders.

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Appendix 1

Pubmed

1- Whole body vibration

2- (Vibration stimulat*[tw] OR Oscillation stimulat*[tw] OR Vibratory stimulat*[tw] OR Oscillatory stimulat*[tw] OR Vibration therap*[tw] OR Oscillation therap*[tw] OR Vibratory therap*[tw] OR Oscillatory therap*[tw] OR Vibration train*[tw] OR Vibratory train*[tw] OR Vibration platform*[tw] OR Vibration device*[tw] OR Oscillation device*[tw] OR Oscillatory device*[tw]) NOT whole body vibration[tw] NOT (animals[mesh] NOT humans[mesh])

#1 OR #2

Embase

'whole body vibration'/exp OR 'whole body vibration' AND ('backache'/exp OR 'backache' OR 'fracture'/exp OR 'fracture' OR 'hearing impairment'/exp OR 'hearing impairment' OR 'injury'/exp OR 'injury' OR 'intervertebral disk degeneration'/exp OR 'intervertebral disk degeneration' OR 'muscle fatigue'/exp OR 'muscle fatigue' OR 'neck pain'/exp OR 'neck pain' OR 'noise injury'/exp OR 'noise injury' OR 'occupational accident'/exp OR 'occupational accident' OR 'occupational disease'/exp OR 'occupational disease' OR 'osteoporosis'/exp OR 'osteoporosis' OR 'pain'/exp OR 'pain' OR 'spine disease'/exp OR 'spine disease' OR 'spine injury'/exp OR 'spine injury' OR 'vibration disease'/exp OR 'vibration disease') AND ('animal experiment'/de OR 'animal model'/de OR 'animal tissue'/de OR 'biological model'/de OR 'case report'/de OR 'cohort analysis'/de OR 'interview'/de OR 'model'/de OR 'nonhuman'/de OR 'normal human'/de OR 'questionnaire'/de OR 'statistical model'/de)

PEDro

"Whole body vibration"

CINAHL

"Whole body vibration"
"Whole body vibration" AND (MH "diseases" OR nerv* OR neuro*)

Authors (year)	Study population	WBV intervention group (IG)	Control group (CG)	Measurement protocol	Outcome measures	P-values	Results
Broekmans et al. [14] (2010)	**Multiple sclerosis** Ambulatory with EDSS score (4.3 ± 0.2) Mild to moderate ***Total group:*** N=25 Age: 47.9±1.9 yrs Sex: 70% female ***IG:*** N=11 Age: 46.1±2.1 yrs Sex: 64% female ***CG:*** N=14 *(N=12 analyzed)* Age: 49.7± 3.3 yrs Sex: 79% female	**Training period** 5 sessions/wk over 20 weeks **Session** Progressive from 30-60 sec with 120-30 sec interval (total duration: 2.5-16.5 min) **Position** Standing with knee 120-130° **Device** Alpha Vibe Nijverdal Vertical Vib. **Settings** **Frq:** 20-45 Hz **Amp:** 2.5 mm	**Control:** Usual life style **Training period** N/R **Session** N/R **Content** N/R	**T1**: Baseline **T2**: Follow-up at 10 weeks **T3**: Follow-up at 20 weeks	**Maximal isometric 90°(Nm)** - Knee extensor	**0.23** NR NR	**Pre-post scores T1/T2/T3 mean (SE)** **overall between group effect** *no change scores provided* IG: 101.8 (11.6) / 103.8 (12.5) / 100.1(13.2) CG: 94.4 (8.9) / 90.3 (9.9) / 86.3 (9.1)
					- Knee flexor	**0.57** NR NR	**overall between group effect** *no change scores provided* IG: 37.3(5.7) / 36.7(6.4) / 34.4(6.0) CG: 44.3(4.6) / 41.0(4.7) / 39.1(3.8)
					Berg balance Scale	**0.15** NR NR	**overall between group effect** *no change scores provided* IG: 44.9(4.1) / 43.6(5.2) / 41.9(5.9) CG: 49.6(4.2) / 51.3(3.3) / 51.2(3.8)
					TUG (sec)	**0.26** NR NR	**overall between group effect** *no change scores provided* IG: 13.7(2.6) / 14.0(2.8) / 13.2(2.4) CG: 9.3(1.7) / 9.6(1.6) / 10.3(2.2)
					2-minute walk Test (sec)	**0.25** NR NR	**overall between group effect** *no change scores provided* IG: 130.5(15.6) / 137.3(16.0) / 135.4(15.6) CG: 154.8(12.6) / 153.9(12.8) / 167.5(6.8)
					25-Foot walk Test (sec)	**0.64** NR NR	**overall between group effect** *no change scores provided* IG: 8.7(1.8) / 8.7(1.8) / 8.4 (1.4) CG: 6.7(0.9) / 6.8(1.0) / 7.2(1.5)

Schyns et al. [15] (2009)	**Multiple sclerosis** ***Cross-over study [all subject receiving both WBV and control intervention (CI)]*** ***Total group:*** N=16 *(N=12 analyzed)* Age: N/R Sex: 75% female ***Group 1: (first WBV, than CI)*** N=8 *(N=5 analyzed)* Age: 45.8±8.4 yrs Sex: 63% female ***Group 2: (first CI, than WBV)*** N=8 *(N=7 analyzed)* Age: 49.5±6.14 yrs Sex: 88% female	**Training period** 3 sessions/wk over 4 weeks (followed by 2 weeks rest) **Session** 50 Hz for 60 sec doing 10 different types of exercises on device and 40 Hz for 30 sec **Position** Dynamic **Device** VibroGym Vertical Vib. **Settings** **Frq:** 40-50 **Amp:** 2-4 mm	**Control:** Same exercise as IG, without WBV **Training period** 3 sessions/wk over 4 weeks (followed by 2 weeks rest) **Session** N/R **Content** Doing the same 10 types of exercise without vibration	**Cross-over study** **T1:** baseline **T2:** follow-up at 4 or 6 week	**Maximal muscle force (N)**		**Change scores** **Median (IQR)*** Data of group 1 and 2 were pooled
					- Quadriceps left	**0.742** NR NR N/R	**WBV vs. CI** **WBV:** -13.98 (-54.32;-1.35) vs. **CI:** -14.22 (-51.99;17.66) *no pre-post scores provided*
					- Quadriceps right	**0.846** NR NR N/R	**WBV vs. CI** WBV: -19.13 (-47.82;-14.47) vs. CI: -22.07 (-44.5; 9.81) *no pre-post scores provided*
					- Hamstrings left	**0.844** NR NR N/R	**WBV vs. CI** **WBV:** -18.64 (-23.79;-9.20) vs. **CI:** -12.75 (-15.70;-5.40) *no pre-post scores provided*
					- Hamstrings right	**1.00** N/R N/R N/R	**WBV vs. CI** **WBV:** -7.11 (-34.70;7.60) vs. **CI:** -14.47 (-24.40;3.56) *no pre-post scores provided*
					Modified Ashworth scale	**N/R** N/R	**WBV vs. CI** *no change scores provided* *no pre-post scores provided*
					TUG (sec)	**0.72** N/R N/R N/R	**WBV vs. CI** **WBV:** 1.25 (-0.50;2.25) vs. **CI:** 1.50 (0.13;2.38) *no pre-post scores provided*
					10 meter walk test (m/sec)	**0.561** N/R N/R N/R	**WBV vs. CI** **WBV:** 1.00 (0.50;2.13) vs. **CI:** 0.50 (-0.50;2.38) *no pre-post scores provided*

Authors (year)	Study population	WBV intervention group (IG)	Control group (CG)	Measurement protocol	Outcome measures	P-values	Results
Claerbout et al. [16] **(2012)**	**Multiple Sclerosis** EDSS between 3 and 7 ***Total group:*** N=55 Age: N/R Sex: 38% female ***IG_A:*** N=20 *(N=16 analyzed)* Age: 39.1±8.2 yrs Sex: 30% female ***IG_B:*** N=18 *(N=14 analyzed)* Age: 43.8±12.6 yrs Sex: 22% female ***CG:*** N=17 Age: 47.6±8.3 yrs Sex: 64% female	IG_A: WBV Full: standard mat (2 cm thick) IG_B: WBV Light: standard plus another mat (10 cm thick) **Training period** 10 sessions over 3 weeks **Session** 30-60 sec WBV with 30-60 sec intervals (7-13 min) **Position** Static and Dynamic **Device** Vibrafit (Fysiomed) Vertical Vib. **Settings** **Frq:** 30-40 Hz **Amp:** 1.6 mm	**Control:** Multidisciplinary rehabilitation program **Training period** 10 sessions over 3 weeks **Session** Progressive; from 30 to 60sec with 30-60 sec interval (7-13 min)	**T1:** Baseline **T2:** Follow-up at 3 weeks	**Muscle strength manual dynamometer**		**Change and pre-post scores mean ± SD**
					- Quadriceps (Nm)	< 0.05 < 0.01 < 0.01 **NS**	**overall between group effect** **IG_A vs. IG_B:** 40.6±42.3 vs. 1±38.8 **IG_A vs. CG:** 40.6±42.3 vs. 9.3±28.6 **IG_B vs. CG:** 28.1±38.8 vs. 9.3±28.6
						< 0.01 N/R N/R N/R	**overall time effect** **IG_A:** 146.4±63.5 / 187.0±77.9 **IG_B:** 188.3±77.3 / 216.5±77.0 **CG:** 165.4±63.9 / 174.8±65.0
					- Hamstrings (Nm)	< 0.01 < 0.001 < 0.001 **NS**	**overall between group effect** **IG_A vs. IG_B:** 45.3±48.0 vs. 22.0±33.6 **IG_A vs. CG:** 45.3±48.0 vs. 1.0 ±31.9 **IG_B vs. CG:** 22.0±33.6 vs. 1.0 ±31.9
						< 001 N/R N/R N/R	**overall time effect** **IG_A:** 112.0±49.6 / 157.3±68.6 **IG_B:** 136.7±49.2 / 158.7±55.6 **CG:** 124.4±46.3 / 125.4±47.8
					Berg Balance scale (score)	**NS** N/R N/R N/R	**overall between group effect** **IG_A:** 3.9±4.4 **IG_B:** 4.2±6.1 **CG:** 0.2±7.5
						< 0.05	**overall time effect** **IG_A:** 45.0±12.2 / 49.0±11.5 **IG_B:** 43.0±13.3 / 47.2±12.7 **CG:** 46.7±07.0 / 48.5±7.7
					TUG (sec)	**NS** N/R N/R N/R	**overall between group effect** **IG_A:** - 0.8±2.3 **IG_B:** -3.2±4.7 **CG:** 0.8±5.5
						< 0.01	**overall time effect** **IG_A:** 13.4±9.8 / 12.6±11.3 **IG_B:** 14.5±8.8 / 11.4±5.3 **CG:** 15.6±9.3 / 14.8±10.2

					3-min walk test (meter)	< 0.001 NS N/R N/R N/R	**overall between group effect** IG_A: 45.0±42.6 IG_B: 37.4±34.3 CG: 20.4±28.0 **overall time effect** IG_A: 150.9 ±89.4 / 195.9±103.3 IG_B: 172.2 ±82.7 / 209.6±74.2 CG: 143.3 ±58.7 / 162.3±62.0
Arias et al. [17] (2009	**Primary Parkinson's disease** ***Total group:*** N=23 Age: N/R Sex: 39% female ***IG:*** N=12 *(N=10 analyzed)* Age: 66.9 ± 11.1 yrs Sex: 40% female ***CG:*** N=11 *(N=11analyzed)* Age: 66.6 ± 5.6 yrs Sex: 46% female	**Training period** 12 sessions over 5 weeks **Session** 5 sets of 1 min with 1 min rest interval **Position** Standing with slightly bended knees **Device** N/R Direction: N/R **Settings** **Frq:** 6 Hz **Amp:** N/R	**Placebo** **Training period** See intervention group, without vibration **Session** See intervention group **Content** Standing on platform with minimal oscillation of hip	**T1:** Baseline **T2:** Follow-up at 5 weeks			**Pre-post scores** **mean ± SD**
					Berg Balance scale	**NS** < 0.001 NR	**overall between group effect** *no change scores provided* **IG**: 44.14±8.74 / 48.38±7.44 **CG:** N/R
					URDRS III	**NS** < 0.003 N/R	**overall between group effect** *no change scores provided* **IG:** 27.76±7.50 / 23.00±6.75 **CG:** N/R
					Gait velocity (m/s)	**NS** < 0.001 N/R	**overall between group effect** *no change scores provided* **IG**: 0.74±0.20 / 0.90±0.22 **CG:** N/R

Authors (year)	Study population	WBV intervention group (IG)	Control group (CG)	Measurement protocol	Outcome measures	P-value	Results
Ebersbach et al. [18] **(2008)**	**Idiopathic Parkinson's disease;** Dopa-resistance imbalance ***Total group:*** N=27 Age: 73.8 (62-8) yrs Sex: 33% female ***IG:*** N=13 *(N=10 analyzed)* Age: 72.5±6 yrs Sex: 30% female ***CG:*** N=14 *(N=11 analyzed)* Age: 75.0 ± 6.8 yrs Sex: 36% female	**Training period** Two sessions a day, 5-days/wk over 3 weeks **Session** 15 min **Position** Standing with slightly bended knee **Device** Galileo Radial Vib. **Settings** **Frq:** 25 Hz **Amp:**7-14 mm	**Control:** Conventional physiotherapy [balance train] **Training period** Three sessions a day, 5-days/wk over 3 weeks **Session** 150 minutes **Content:** 120 min exercise plus 30 min dedicated to balance per session	**T1:** Baseline **T2:** Follow-up at 3 weeks **T3:** Follow-up at 7 weeks	**Dynamic posturography (mm)**	**< 0.93** <0.001 N/R N/R	**Pre-post scores mean ± SD** **overall between group effect** *no change scores provided* **overall time effect** IG: 1937±1250 / 1306±331 / 1467±540 CG: 1832± 746 / 2256±681 / 2030±878
					Tinetti balance scale (score)	**NS** < 0.001 N/R N/R	**overall between group effect** *no change scores provided* **overall time effect** IG: 9.3±3.1 / 12.8±1.9 / 12.8±2.3 CG: 8.3±2.9 /11.5±2.4 / 11.7±3.1
					URDRS III (score)	**NS** < 0.001 N/R N/R	**overall between group effect** *no change scores provided* **overall time effect** **IG:** 23.0±4.9 /17.6±4.5 / 17.0±5.4 **CG:** 25.9±8.1 / 16.9±5.0 / 18.5±4.9
					10-meter walk test	**NS** < 0.001 N/R N/R	**overall between group effect** *no change scores provided* **overall time effect** **IG:** 17.6± 5.0 /15.1± 3.5/ 14.5± 3.5 **CG:** 18.4±4.2 /16.5± 2.5 / 16.8± 3.4
					Stand-walk-sit test (sec)	**NS** < 0.003 N/R N/R	**overall between group effect** *no change scores provided* **overall time effect** **IG:** 10.8±2.5 / 8.5± 2.1 / 8.2±1.8 **CG:** 12.0±2.9 / 9.5 ± 2.1 / 8.9±1.4

Ahlborg et al.[19] **(2006)**	**Cerebral palsy** Spastic diplegia with walking ability *Total groups:* N=14 Age: 21-41 yrs Sex: 43% female *IG:* N=7 Age: 32 (24-41) yrs Sex: 43% female *CG:* N=7 Age: 30 (21-39) yrs Sex: 43% female	**Training period** 3 sessions/wk over 8 weeks **Session** various depends on frequency (4 × 30 to 3 × 110 sec)* **Position** Standing with 50° knee flexion **Device** Names-Lsc **Settings** **Frq:** 25-40 Hz **Amp:** N/R *11 intensity of WBV	**Control:** Resistance training **Training period** Three times/wk over 8 weeks **Session** N/R **Content** Leg press exercises 10-15 Repeat with 2-min rest interval	**T1:** Baseline **T2:** Follow-up at 8 weeks	**Isokinetic strength Concentric peak torque (Nm)** *90°/s*		**Pre-post scores Median [range]**
					- Weaker leg	**NS**	*no change scores provided*
						NS	**IG:** 33 [05;70] / 53 [11; 68]
						NS	**CG:** 60 [9;111] / 71 [10;103]
					- Stronger leg	**NS**	*no change scores provided*
						NS	**IG:** 40 [16;87] / 54 [19;97]
						0.031	**CG:** 46 [11;125] / 56 [14;136]
					Ashworth scale:		
					- Weaker Quadriceps	**NS**	*no change scores provided*
						NS	**IG:** 2 [0-3] / 2 [0-3]
						NS	**CG:** 1[0-3] / 1[0-2]
					- Stronger Quadriceps	**NS**	*no change scores provided*
						0.031	**IG:** 3 [0-3] / 1 [0-3]
						NS	**CG:** 1 [0-2] / 1 [0-2]
					- Weaker Hamstring	**NS**	*no change scores provided*
						NS	**IG:** 0 [0-2] / 0 [0-1]
						NS	**CG:** 0 [0-2] / 0 [0-2]
					- Stronger Hamstring	**NS**	*no change scores provided*
						NS	**IG:** 0 [0-2] / 0 [0-0]
						NS	**CG:** 0 [0-0] / 0 [0-0]

Authors (year)	Study population	WBV intervention group (IG)	Control group (CG)	Measurement protocol	Outcome measures	P-value	Results
					GMFM		
					- D domain	**NS**	*no change scores provided*
						NS	**IG:** 79[38-85] / 82 [54-95]
						NS	**CG:** 77[62-90] / 82 [62-90]
					- E domain	**NS**	*no change scores provided*
						NS	**IG:** 69 [22-93] / 72 [22-97]
						NS	**CG:** 57 [25-89] / 61 [31-89]
					- T domain	**NS**	*no change scores provided*
						0.031	**IG:** 76 [30-89] / 77 [38-96]
						NS	**CG:** 70 [44-90] / 69 [47-90]
					TUG (sec)	**NS**	*no change scores provided*
						NS	**IG:** 14 [10-102] / 14 [8-72]
						NS	**CG:** 15 [7 - 30] / 16 [7-30]
					6-min walk test (meter)	**NS**	*no change scores provided*
						NS	**IG:** 384 [84-470] / 376 [83-439]
						NS	**CG:** 215 [110-605] / 237 [98-610]

Ruck et al.[20] **(2010)**	**Cerebral palsy** (levels II, III, VI based on gross function) ***Total group:*** N=20 Age: 8.1 (N/R) yrs Sex: 30% female ***IG:*** N=10 *(N=10 analyzed)* Age: 8.3 (6.6-9.6) yrs Sex: 20% female ***CG:*** N=10 *(N=7 analyzed)* Age: 8.1 (7.3-10.6) yrs Sex: 40% female	**Training period** 5 sessions /wk over 6 months **Session** 3 sets of 3 min with 3-min rest interval **Position** standing with knees 10-45° **Device** Vibraflex Radial Vib. **Settings** **Frq:** 12-18 Hz **Amp:** 2-6 mm	**Control:** School Physiotherapy **Training period** over 6 months **Session** depends on need; 1-2 session/ wk **Content** N/R	**T1:** Baseline **T2:** Follow up at 6 months	**GMFM** - D domain	**0.54**	**Change scores mean (IQR)*** **IG:** 2.5 (0.0;5.2) vs. **CG:** 0.0 (0.0;5.1)
						N/R	*no pre-post scores provided*
					- E domain	**0.14**	**IG:** 4.2 (2.8;9.7) vs. **CG:** 1.4 (0.0;4.2)
						N/R	*no pre-post scores provided*
					10-meter walk test (m/s)	**0.03**	**IG:** 0.18 (0.08;0.66) vs. **CG:** 0.0 (-0.25;0.15)
						N/R	*no pre-post scores provided*

Authors (year)	Study population	WBV intervention group (IG)	Control group (CG)	Measurement protocol	Outcome measures	P-value	Results
Merkert et al.[21] (2011)	**Inpatient acute stroke** *Total group:* N=66 Age: 74.5 Sex: 66% female *IG:* N=33 *(N=25 analyzed)* Age: 74.5±8.3 yrs Sex: 66.7% female *CG:* N=33 *(N=23 analyzed)* Age: 74.5 ± 8.6 yrs Sex: 66.7% female	**Training period** 5 sessions /wk over 3 weeks **Session** 15-90 sec per session for 15 sessions **Position** Supine, sitting, and standing, **Device** Vibrosphere Vertical Vib. **Settings** **Frq:** 20-45 Hz **Amp:** N/R	**Control:** Comprehensive Inpatient geriatric rehabilitation **Training period** 5 sessions/wk over 3 weeks **Session** 15 sessions **Content** Different exercise depends on ability	**T1:** Baseline **T2:** Follow-up at 3 weeks			**Change scores IG vs. CG; mean ± SD**
					Berg Balance scale (score)	**NR** 0.000 0.000 N/R	**overall between group effect** **IG:** 12.2 ± 10.7 **CG:** 9.1 ± 8.3 *no pre-post scores provided*
					Tinetti balance scale (score)	**NR** 0.008 0.017 N/R	**overall between group effect** **IG:** 3.9 ± 3.0 **CG:** 2.5 ± 2.6 *no pre-post scores provided*
					TUG (sec)	**NR** 0.003 NS N/R	**overall between group effect** **IG:** 13.9 ± 13.2 **CG:** 6.8 ± 6.9 *no pre-post scores provided*

Van Nes et al. [22] (2006)	**Acute stroke** Moderate to severe ***Total group:*** N=53 Age: N/R Sex:43% female ***IG:*** N=27 Age: 59.7 ± 12.3 yrs Sex: 41% female ***CG:*** N=26 Age: 62.6 ± 7.6 yrs Sex: 46% female	**Training period** 5 sessions/wk over 6 weeks **Session** 4 × 45 sec by 1-min interval **Position** Standing with knees in 45° flexion **Device** Galileo 900 Radial vibration **Settings** **Frq:** 30 Hz **Amp:** 3 mm	**Control:** Exercise therapy on music (ETM) **Training period** 5 sessions/wk over 6 weeks **Session** 4 × 45 sec by 1-min relaxation **Content:** Regular exercise of trunk, arm, and leg	**T1:** Baseline **T2:** Follow-up at 6 weeks **T3:** Follow-up at 12 weeks	**Trunk Control Test (0-100)**	**NS** < 0.01 N/R N/R	**Pre-post scores mean ± SD** **overall between group effect** *no change scores provided* **overall time effect** **IG:** 75.0±25.9 / 80.5±21.6 / 86.2±17.4 **CG:** 69.5±24.0 / 79.8±21.3 / 83.7±18.5
					Berg Balance scale (score)	**NS** < 0.01 N/R N/R	**overall between group effect** *no change scores provided* **overall time effect** **IG:** 23.9±14.8 / 40.6±12.8 / 44.3±10.9 **CG:** 23.7±18.6) / 41.1±14.3 / 44.9±11.9
					Motoricity Index (score)	**NS** < 0.05 N/R N/R	**overall between group effect** *no change scores provided* **overall time effect** **IG:** 47.4±28.7 / 59.8±25.0 / 65.7±22.9 **CG:** 50.1±28.3 / 61.2±25.4 / 66.7±25.9

Abbreviations: WBV: Whole-Body Vibration; IG: Intervention Group CG: Control Group; Vib: Vibration; N/R: Not Reported; NS: Not Significant; TUG: Timed Up & Go test; URDRS: Unified Dystonia Rating Scale; GMFM: Gross Motor Function; CI: Confidence Interval; SD: Standard Deviation; SE: Standard Error; IQR: Inter Quartile Range; yrs: Years; Wk: Week; Frq: Frequency: Amp: Amplitude; Hz: Hertz; cm: Centimeter; mm: Millimeter; S: M/S: Meter/Second; S or sec: second; N: Number; Lt: Left; Rt: Right.

** Data are expressed as mean ± SD, median [range] or as mean (standard error).

* Interquartile range - mean (IQR)

All p-values involving time x group interactions are bolded (p<0.05 is underlined)

Chapter 3

Platform accelerations of three different whole-body vibration devices and the transmission of vertical vibration to the lower limbs

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Abstract

Physical whole-body vibration (WBV) exercises are available at various levels of intensity. In a first series of measurements, we investigated 3-dimensional platform accelerations of three different WBV devices without and with 3 volunteers of different weight (62, 81 and 100 kg) in squat position (150 degrees knee flexion). The devices tested were two professional devices, the PowerPlate and the Galileo, and one home-use device, the PowerMaxx. In a second series of measurements, the transmission of vertical platform accelerations of each device to the lower limbs was tested in eight healthy volunteers in squat position (100 degrees knee flexion).

The first series showed that the platforms of two professional devices vibrated in an almost perfect vertical sine wave at frequencies of 25-50 Hz and 5-40 Hz, respectively. The platform accelerations were slightly influenced by body weight. The PowerMaxx platform mainly vibrated in the horizontal plane at frequencies of 22-32 Hz, with minimal accelerations in the vertical direction. The weight of the volunteers reduced the platform accelerations in the horizontal plane but amplified those in the vertical direction about 8 times. The vertical accelerations were highest in the Galileo (~15 units of g) and the PowerPlate (~8 units of g) and lowest in the PowerMaxx (~2 units of g). The second series showed that the vertical accelerations at a common preset vibration frequency of 25 Hz were largest in the ankle and that transmission of acceleration reduced ~10 times at the knee and hip.

We conclude that a large variation in 3-dimensional accelerations exists between commercially available devices. The results suggest that these differences in mechanical behaviour induce variations in transmissibility of vertical vibrations to the (lower) body.

Introduction

Because physical condition deteriorates with age, regular endurance training exercises are advised. It has been demonstrated that these exercises have considerable benefits in the prevention of atrophy of muscles[1], functional impairment[2], obesity[3], cardiovascular diseases[4] and fragility fractures among the elderly population[5]. Moreover, the assessment of overall physical fitness has become part of pre-operative screening in patient management. Traditional lower limb training methods, like progressive resistive exercise (PRE), proprioceptive neuromuscular facilitation (PNF) and cycling exercises[6-7], may preserve or improve lower muscle strength. However, the effectiveness of these methods is reduced in elderly patients with balance or vestibular disorders[8]. A relatively new method to recruit muscles is whole-body vibration (WBV). A subject stands or sits on a vibration platform. The vibrations are induced via this platform and control and safety handles provide stability[9-10]. WBV training can be done at home, which reduces therapeutic costs and patient travel expenses.

Recently, effects of WBV training on muscle strength[11-16], bone density[9,17], cardiovascular parameters[18] and body balance have been investigated[19-20]. A proposed physiological impact of WBV on muscle performance is activation of the Tonic Vibration Reflex (TVR)[9]. Some reflexes, i.e. Hoffmann and tendon reflexes, as well as tendon vibration response, are substantially depressed when specific vibration patterns are applied to the body or to the legs of seated human subjects[21-22]. It is possible that vibrations first stimulate primary muscle spindle (Ia) fibres, which subsequently result in a reflex at the level of the spinal cord. It was shown that high platform accelerations are associated with high muscle activity levels[23], but it is still unclear to what extent WBV induces these reflex muscle activations and how this would lead to improved muscle performances.

Research on human responses to whole-body vibration dates back to about 50 years ago[24-25]. Biomechanical models[26-27] and human physiological measurements in sitting[28-31] and standing posture[32-36] have addressed the transmission of WBV to various body segments. Most studies that investigated exposure of vibrations in sitting postures focused on the prevention of low back problems. Besides different postures and the variability in activity levels of the subjects studied, the differences between effects of WBV may also be related to the variability in the vibration devices currently available. WBV is generally induced using either a PowerPlate or a Galileo device. Although some of the technical specifications of these commonly used devices on vibration frequency are available, it is not yet established whether body mass might influence, for example, vibration platform accelerations. One study investigated gravitational forces at the vibration surface of the Galileo[32]. At present, simple and very cheap home-use vibration devices (i.e. the PowerMaxx) have also become available. The platforms deliver different types of vibration. The PowerPlate induces vertical vibrations, the Galileo induces seesaw vibrations, and the PowerMaxx induces vibrations in the horizontal plane.

The purpose of the present study was to compare the mechanical behaviour of these three WBV devices in an "unloaded condition" and "loaded condition".

The aims of the present study were:

1) To study the 3-dimensional (horizontal (X,Y) and vertical (Z) direction) platform accelerations of two commonly used professional WBV devices (PowerPlate and Galileo) and that of one simple home-use device (PowerMaxx) under different loading conditions.
2) To study the transmission of vertical platform accelerations of all three devices to the lower limbs at the lowest common preset frequency.

We expected to find no differences in platform frequency and only small differences in platform acceleration under different loading conditions with respect to the PowerPlate and the Galileo. With respect to the PowerMaxx, we expected relatively large changes in platform acceleration values under loading conditions. Based on these expectations, we hypothesised to find large differences in transmission of vertical vibrations between the devices at the level of the ankle, knee and hip at one common platform frequency.

Methods and materials

In the present study, the PowerPlate (PowerPlate International, The Netherlands), the Galileo2000 (Novotec Medical GmbH, Germany) and the PowerMaxx (DS-produkte GmbH, Germany) were tested (Figure 1). The two professional devices, the PowerPlate and the Galileo, could be set at vibration frequencies of 25-50 Hz and 5-40 Hz, respectively. No frequency specifications were given for the PowerMaxx; 9 levels of vibrations were indicated (S1-S9). Two electro motors, each provided with an eccentric mass, controlled the platform vibrations of the PowerPlate. The platform could be set in two different modes: 'low' or 'high', which implies a low or high platform displacement to alter the level of intensity workout. The Galileo platform oscillated around a central axis. A crankshaft principle on each side of the platform translated the rotating motion of the electro motor into a vertical displacement, inducing a seesaw vibration. Depending on the position of the feet on the platform, the displacement is either small (feet near the axis) or large (feet near the edge of the platform). The vibrations of the PowerMaxx platform were controlled by an eccentric mass that was connected to one electro motor. This mass induced horizontal platform vibrations. In each device, a control panel allowed to preset the vibration frequencies.

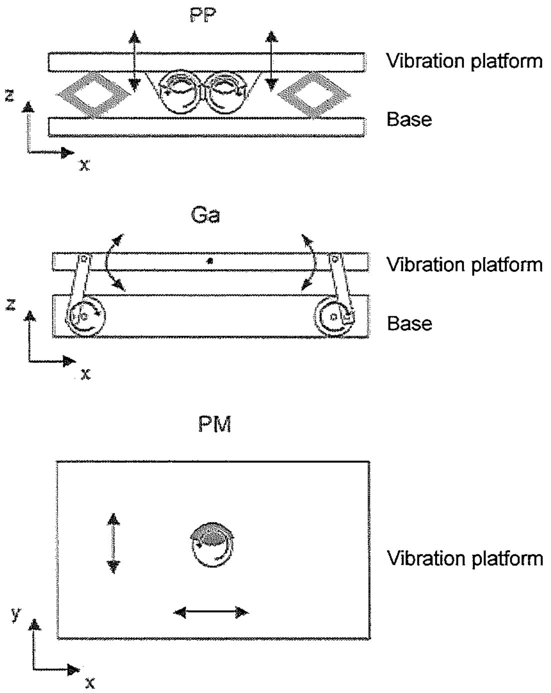

Figure 1. A schematic drawing of the vibration directions of the three WBV devices tested: the PowerPlate (PP), the Galileo (Ga) and the PowerMaxx (PM). Indicated are the vertical (Z) and the two horizontal (X, Y) directions.

To measure the acceleration in the horizontal (X, Y) and vertical (Z) direction, three piezo-resistive accelerometers (ICSensors 3021-005-P, max. ± 50 $m/s^2 \sim 5$ g) were placed in a custom-made PVC container. A fourth accelerometer (Analog Devices ADXL150JQC, max. ± 500 $m/s^2 \sim 50$ g) was placed in the container to measure accelerations exceeding 5g in vertical direction. The container with the accelerometers was fixed in the centre of the PowerPlate and PowerMaxx platform using two bolts. It was fixed at 185 mm from the rotating axis of the Galileo platform. The signal of each ICSensor was electronically amplified and together with the signal of the ADXL fed to a 14bit A/D convector (National Instruments DAQmx USB-6009). The signals were sampled with a frequency of 1000 Hz and stored on a standard PC. Each accelerometer was calibrated on the basis of a two-point calibration by applying zero gravity and the earth's gravity of 1 g (9.81 m/s^2). An offset equal to the earth's gravity was subtracted from all acceleration signals in vertical direction to make all signals start at 0 m/s^2. For each of the 1000 samples, a custom written LabVIEW program calculated the maximum acceleration, a_{max}, and the root mean square value of the acceleration, a_{RMS}, in each direction. The corresponding frequency component, f_{out}, was calculated from the FFT transformed acceleration signal. We selected the lowest frequency; higher harmonic frequencies were not selected for further analysis. At each preset f_{in}, platform accelerations were measured for 10 s starting with the lowest f_{in}. After 10 s, f_{in} was increased in the same recording and the platform accelerations were again measured for 10 s. The first 2-3 s of each measurement was the response time to this stepwise increase of the frequency. We therefore took the last 5 s for further analysis. After 60 s, a measurement was ended and a new measurement was done. The average and standard deviation (SD) of the a_{RMS} and f_{out} values were derived from the set of α_{RMS} and f_{out} values calculated in each second of the last 5 s. In a pilot run, we fitted a sine function through test acceleration signals of each (unloaded) device at a low preset frequency and a high preset frequency. We found very small fit errors for the PowerPlate and the Galileo and for the PowerMaxx at low frequency (S1) of less than 0.5%. At high frequency (S9), the fit error for the PowerMaxx increased, but was still less than 2%. Based on these small errors, we assumed sinusoidal platform motions for each device and calculated the maximum platform displacement, d_{max}, at the location of the accelerometer using the following set of equations

$$d(t) = A \cdot \sin(\omega \cdot t) \tag{1}$$

$$a(t) = d''(t) = \frac{\partial^2 A \cdot \sin(\omega \cdot t)}{\partial t^2} = -\omega^2 \cdot A \cdot \sin(\omega \cdot t) = -\omega^2 \cdot d(t) \tag{2}$$

$$d(t) = -\frac{1}{\omega^2} \cdot a(t) = -\frac{1}{f_{out}^2 \cdot 4\pi^2} \cdot a(t) \tag{3}$$

$$d_{max} = \left| -\frac{1}{f_{out}^2 \cdot 4\pi^2} \cdot a_{max} \right| \tag{4}$$

where $d(t)$ is the displacement in time, A is the amplitude, ω is the angular frequency ($2\pi \cdot f_{out}$) and $a(t)$ is the acceleration.

First measurement series: 3-dimensional platform accelerations

In the first series of measurements, a_{RMS} and f_{out} were determined for preset vibration frequencies, f_{in}, of each device without and with a weight placed on each platform. Initial tests to apply passive weight (masses of 10 kg each up to 80 kg) to each platform failed due to movement of the weights. An additional test using sand bags of 10 kg each also failed, despite the fact that we tried to stabilise this load with large belts. Therefore, we asked two experienced vibration platform users (62 and 81 kg) to test each platform in squat position (knee angle α of 150° measured with a manual goniometer) and a third experienced vibration platform user of 100 kg for additional testing of the PowerMaxx (Figure 2). In this way, the platforms were equally "loaded" and a squat position was chosen to prevent excessive head oscillations. The f_{in} of the PowerPlate was preset at 25 Hz and stepwise increased in steps of 5 Hz to its maximum of 50 Hz in "high" as well as "low" amplitude mode. The f_{in} of the Galileo was preset at 5 Hz and also step wise increased with 5 Hz to its maximum of 40 Hz. All volunteers were asked to take off their shoes and socks. Each volunteer placed his/her feet on the prescribed Galileo platform position (at 185 mm left and right from the central axis) to ensure the same induced platform accelerations. The PowerMaxx had prescribed settings starting from S1 to S9; the magnitude of f_{in} was not specified on the display or in the manual. Acceleration values measured in the "unloaded condition" were reported in units of gravitational force (1 g = 9.81 m/s^2). The acceleration and vibration frequency values measured in the "loaded condition" were normalized by dividing them by the values measured in the "unloaded condition". The ratio of f_{out} values was denoted as f_{ratio}.

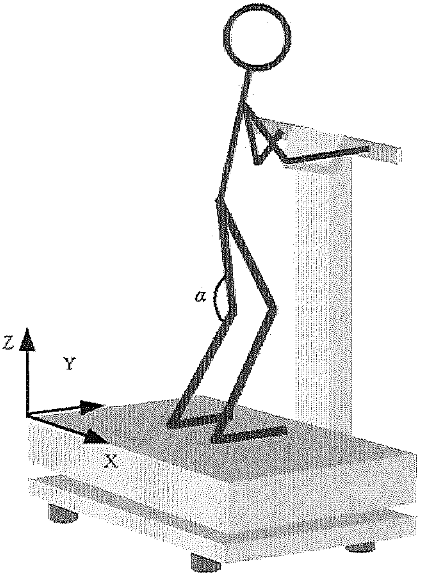

Figure 2. A schematic drawing of a healthy subject standing in squad position with knee angle α on a whole-body vibration device. Indicated are the vertical (Z) and the two horizontal (X, Y) directions.

Second measurement series: transmission of vertical accelerations

In the second measurement series, in 8 healthy volunteers [mean age 34 (SD 12) years and body weight 76 (SD 15) kg] we studied transmission of the vertical platform accelerations of each device to the lower limbs. The accelerations of three different body locations (ankle, knee and hip) were measured in each volunteer. He or she was instructed to maintain a fixed squat position for at least 10 s, head straight forward and with 20 s of recovery between trials. The feet had to be placed 30 cm apart. This distance was indicated with markers on each platform to ensure a reproducible position, which is particularly important for the Galileo. Using this device, both feet were placed 150 mm from the central axis. The f_{in} of each device was set at 25 Hz, the lowest common preset frequency in all devices (calculated on the basis of the first measurement series). Then, a knee angle α of 100° was chosen, which is a typical lower limb training posture: the body weight on the front feet and the back in upright position. The Analog Devices ADXL150JQC accelerometer was used to measure the accelerations in the vertical direction. In random order, this accelerometer was placed on the malleolus lateralis, a relatively flat part of ankle, the epicondylus lateralis, a relatively flat part of the lower part of the thigh bone, and finally on the a anterior superior iliac spin, the edge of the hip bone. We attached the accelerometers to each site using rigid foam tape (Kushionflex Padding tape of about 100 mm length × 25 mm width) to ensure that the position of the sensor was secure. We did not take any potential errors of skin movement into account nor did we correct raw data. Alignment of the accelerometer with earth gravity was on the basis of the sensor's output during the calibration procedure. During the vibration measurement, we visually inspected the direction of the foam tape with respect to the vertical direction. Transmission of vibrations in vertical direction was calculated as a percentage of the measured accelerations at a given location divided by the unloaded platform acceleration at 25 Hz, i.e. PowerPlate 'high mode' 32 m/s^2, Galileo 150/185 × 60 $m/s^2 = 48.6$ m/s^2 and PowerMaxx 1.4 m/s^2.

Results

None of the subjects reported any adverse side-effects to the exposed vibrations, such as hot feet, vertigo, dizziness, itching in the legs, cramp or calf pain.

First measurement series: 3-dimensional platform acceleration

PowerPlate

Figure 3, top panel, shows an example of the unloaded platform accelerations in X, Y and Z direction with f_{in} preset at 30 Hz. The acceleration was mainly in a vertical direction and described an almost perfect sine wave.

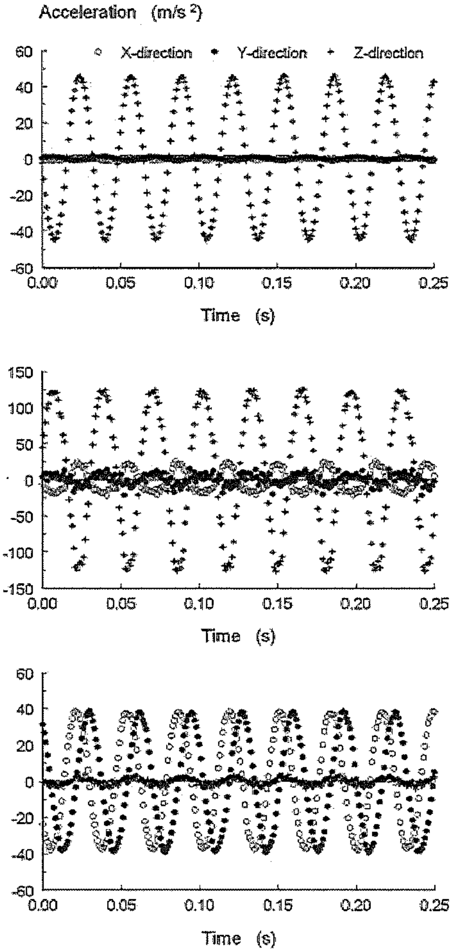

Figure 3. Top panel: example of the PowerPlate unloaded platform acceleration against time *t* showing accelerations in *X*-direction (open circles), *Y*-direction (closed circles) and *Z*-direction (plusses) with f_{in} set at 30 Hz. The platform induced mainly vibrations in vertical direction. Middle panel: example of the Galileo unloaded platform accelerations against time with f_{in} also set at 30 Hz. This platform also induced highest vibrations in vertical directions, and some in the horizontal plane. Lowest panel: example of the PowerMaxx unloaded platform accelerations against time set at 30 Hz. The accelerations of this platform were mainly in the horizontal plane. Note the differences in *y*-axis scaling.

Table 1. Three-dimensional "unloaded" and "loaded" platform accelerations (a) and vibration frequencies (f_{out}) of the PowerPlate device at preset vibration frequencies of 25-50 Hz. In the "unloaded condition", the root mean square values of the accelerations (a_{RMS}) are expressed in units of g (9.81 m/s^2) in all directions. In the "loaded condition", two volunteers with body weight 62 and 81 kg stood in squat position on this platform in 'low mode'. The a_{RMS} and f_{out} values were normalized by dividing them by the a_{RMS} and f_{out} values measured in the "unloaded condition". Thus the f_{ratio} was defined as f_{out} loaded condition divided by f_{out} unloaded condition. a_{RMS} related common frequencies (25 and 30 Hz) are bolded.

"Unloaded condition"				
f_{in} (Hz)	**a_{RMS} (in units g)**			**f_{out}**
	X-direction	Y-direction	Z-direction	
'high mode'				
25	**0.0**	**0.1**	**2.5**	**25**
30	**0.0**	**0.1**	**3.3**	**31**
35	0.0	0.1	4.3	36
40	0.1	0.1	5.3	41
45	0.1	0.2	6.5	45
50	0.1	0.2	7.7	50
'low mode'				
25	**0.3**	**0.0**	**1.2**	**26**
30	**0.2**	**0.0**	**1.6**	**31**
35	0.2	0.1	2.1	36
40	0.2	0.1	2.6	41
45	0.2	0.1	3.3	45
50	0.2	0.1	3.8	50

"Loaded condition"				
low mode-62 kg	**a_{RMS} (normalized)**			**f_{ratio}**
	X-direction	Y-direction	Z-direction	
25	**0.6**	**2.5**	**0.9**	**1.0**
30	**0.3**	**2.2**	**1.0**	**1.0**
35	0.5	1.6	0.9	1.0
40	0.5	1.0	1.0	1.0
45	0.9	0.6	0.9	1.0
50	0.7	0.7	1.0	1.0
low mode-81 kg				
25	**0.2**	**3.6**	**0.9**	**1.0**
30	**0.2**	**2.7**	**1.0**	**1.0**
35	0.3	1.8	0.9	1.0
40	0.3	1.1	1.0	1.0
45	0.4	0.6	1.0	1.0
50	0.4	0.6	1.0	1.0

Table 1 summarises the accelerations a_{RMS} in both "high" and "low" amplitude mode and the frequencies f_{out} at each preset f_{in}. The f_{out} values were within 3% comparable to the preset f_{in} values. The a_{RMS} values in the horizontal plane were less than 0.2 units of g. The a_{RMS} values in vertical direction measured in "low" amplitude mode, up to 3.8 units of g, were half of those measured in "high" amplitude mode at the same preset f_{in}. In "high" mode, the maximum vertical platform displacement, d_{max} was mean 2.2 (SD 0.1) mm peak-to peak; in "low" mode d_{max} was 1.2 (0.05) mm peak-to-peak. It only decreased ~0.2 mm when the preset f_{in} increased from 25 Hz up to 50 Hz in both "high" and "low" mode. Loading the platform did not affect the f_{out} values and the a_{RMS} values in vertical direction changed less than 10% when the preset f_{in} increased from 25 up to 50 Hz.

Galileo

The middle panel of Figure 3, shows an example of the unloaded platform accelerations in X, Y and Z direction with f_{in} preset at 30 Hz. Again, the acceleration in vertical direction, the most prominent acceleration, described a sine wave. Table 2 summarises the overall findings of this platform. In the unloaded situation, the f_{out} values were up to 30 Hz within 1% accurate. Between 30-40 Hz, the f_{out} values decreased by 5% at f_{in} of 40 Hz. The accelerations in the horizontal X- and Y-direction increased to about 2 and 1 units of g, respectively. The accelerations in vertical direction ranged from 0.3-14.7 units of g (f_{in} values from 5-40 Hz). Note that the maximum accelerations were location dependent: the accelerations were linearly related to the distance between the rotating axis and the location of the accelerometers. The maximum vertical platform displacement, averaged over all measurements from 5-40 Hz, was 3.5 (SD 0.1) mm peak-to-peak. Loading the platform did not affect the f_{out} values or the maximum platform displacements. However, the platform accelerations in vertical direction at f_{in} values of 30-40 Hz reduced by ~12% and 7%, respectively, when loaded by a body weight of 62 kg and 81 kg, respectively. This might have been caused by some resonance above 30 Hz, which decreased the maximum platform displacement and thus the vertical accelerations.

Table 2. Three-dimensional “unloaded” and “loaded” platform accelerations (a) and vibration frequencies (f_{out}) of the Galileo device at preset vibration frequencies of 5-40 Hz. In the “unloaded condition”, the root mean square values of the accelerations (a_{RMS}) are expressed in units of g (9.81 m/s^2) in all directions. In the “loaded condition” two volunteers with body weight 62 and 81 kg stood in squat position on this platform. a_{RMS} related common frequencies (25 and 30 Hz) are bolded.

“Unloaded condition”

f_{in} (Hz)	a_{RMS} (in units g)			f_{out} (Hz)
	X-direction	Y-direction	Z-direction	
5	0.1	0.1	0.3	5
10	0.2	0.1	1.0	10
15	0.3	0.1	2.2	15
20	0.7	0.2	3.9	20
25	**1.0**	**0.3**	**6.1**	**25**
30	**1.3**	**0.6**	**7.9**	**30**
35	1.7	0.8	10.4	34
40	2.1	0.7	14.7	38

“Loaded condition”

f_{in} (Hz)	a_{RMS} (normalized)			f_{ratio}
	X-direction	Y-direction	Z-direction	
62 kg				
5	1.0	0.8	1.0	1.0
10	1.0	0.8	1.0	1.0
15	0.7	0.9	1.0	1.0
20	0.6	1.0	1.0	1.0
25	**1.1**	**1.4**	**1.0**	**1.0**
30	**0.9**	**1.3**	**0.9**	**1.0**
35	0.8	1.6	0.8	1.0
40	1.0	1.6	0.9	1.0
81 kg				
5	1.0	0.8	1.0	1.0
10	1.0	0.9	1.0	1.0
15	0.6	1.3	1.0	1.0
20	0.7	0.7	1.0	1.0
25	**1.2**	**1.6**	**1.0**	**1.0**
30	**1.1**	**0.8**	**1.1**	**1.0**
35	0.9	1.3	0.9	1.0
40	0.9	1.7	0.9	1.0

PowerMaxx

The bottom panel of Figure 3 shows an example of the platform accelerations at a preset setting S7. This setting corresponded to an f_{out} of 31 Hz. The overall findings of this device are listed in Table 3. The platform vibrated in the horizontal (XY) plane between 22 Hz (S1) and 32 Hz (S9). The a_{RMS} values in the vertical direction, between 0.1 and 0.2 units of g, were small compared to those in the horizontal XY plane, between 1.5 and 3.4 units of g. The average platform displacement was in the X-direction 2.2 (0.01) mm peak-to-peak, in Y-direction 2.0 (0.05) mm peak-to-peak and in Z-direction 1.2 (0.02) mm peak-to-peak. When our volunteers of 62, 81 and 100 kg loaded this platform, the f_{out} values were within 6% comparable to those measured in the unloaded condition. However, the a_{RMS} values in vertical direction increased about 8 times at preset S9, while the a_{RMS} values in the horizontal plane decreased. This was confirmed in the total displacement values: displacement in the X-direction decreased to 1.8 (0.1) mm peak-to-peak, in Y-direction to 1.4 (0.1) mm peak-to-peak and increased in Z-direction to 0.6 (0.1) mm peak-to-peak. The decrease in accelerations was thus more pronounced in Y-direction (up to 40%) than in X-direction (up to 25%). The magnitude of these changes did not seem to depend on the weight of the volunteers.

Table 3. Three-dimensional “unloaded” and “loaded” platform accelerations (a) and vibration frequencies (f_{out}) of the PowerMaxx device at preset settings S1-S9. In the “unloaded condition”, the root mean square values of the accelerations (a_{RMS}) are expressed in units of g (9.81 m/s^2) in all directions. In the “loaded condition”, three volunteers with body weight 62, 81 and 100 kg stood in squat position on this platform. The a_{RMS} and f_{out} values were normalised by dividing them by the a_{RMS} and f_{out} values measured in the “unloaded condition”. a_{RMS} related common frequencies (25 and 30 Hz) are bolded.

“Unloaded condition”

Preset settings	**a_{RMS} (in units g)**			**f_{out} (Hz)**
	X-direction	Y-direction	Z-direction	
s1	1.5	1.7	0.1	22
s3	**1.9**	**1.8**	**0.1**	**25**
s5	2.4	2.2	0.1	28
s7	**2.8**	**2.8**	**0.2**	**31**
s9	3.3	3.4	0.2	33

“Loaded condition”

	a_{RMS} (normalized)			**f_{ratio}**
	X-direction	Y-direction	Z-direction	
62 kg				
s1	0.7	0.6	2.1	1.0
s3	**0.9**	**0.6**	**2.9**	**1.0**
s5	0.9	0.6	4.3	1.0
s7	**0.9**	**0.7**	**7.2**	**1.0**
s9	0.9	0.7	7.6	1.0
81 kg				
s1	0.7	0.4	2.1	1.0
s3	**0.7**	**0.5**	**2.9**	**1.0**
s5	0.7	0.5	4.3	1.0
s7	**0.8**	**0.6**	**8.9**	**0.9**
s9	0.8	0.6	8.1	1.0
100 kg				
s1	0.5	0.6	2.1	1.0
s3	**0.7**	**0.5**	**2.9**	**1.0**
s5	0.8	0.5	3.6	1.0
s7	**0.8**	**0.6**	**5.0**	**0.9**
s9	0.9	0.7	7.6	1.0

Second measurement series: transmission of accelerations

Table 4 summarises the percentage of platform accelerations in vertical direction transmitted to the ankle, knee and hip joints of 8 healthy volunteers who stood in squat position on each of the three tested devices. In unloaded condition the platforms generated vertical accelerations of 32 m/s^2 (PowerPlate "high" mode, 48.6 m/s^2 Galileo, and 1.4 m/s^2 PowerMaxx). We calculated that the PowerPlate and Galileo transmitted 55% and 85%, respectively, of the vibrations to the ankle, 9% and 8%, respectively, to the knee and only 3% and 2%, respectively, to the hip. Thus, the platform accelerations were 1.8 and 4.2 units of g at the ankle, respectively, less than ~0.45 units of g at the knee, and ~0.15 units of g at the hip. Loading the PowerMaxx resulted in amplification of the accelerations in vertical direction (Table 3). We calculated that the vertical accelerations were ~ 1 unit of g at the ankle, ~ 0.2 units of g at the knee, and ~ 0.1 units of g at the hip.

Table 4. The percentage of vertical accelerations transmitted from the PowerPlate, Galileo and PowerMaxx platforms at 25 Hz to the ankle, knee and hip joints of eight healthy volunteers. The volunteers were instructed to maintain a fixed squad position with the feet 30 cm apart and the knees flexed at an angle α of 100° for at least 10 s. Summarised are the accelerations measured in vertical direction as a percentage of the "unloaded" platform acceleration at 25 Hz (PowerPlate 'high mode' 32 m/s^2, Galileo 48.6 m/s^2 and PowerMaxx 1.4 m/s^2).

Subjects	BW (kg)	a_{RMS} in vertical direction (%)								
		Ankle			Knee			Hip		
		PP	Ga	PM	PP	Ga	PM	PP	Ga	PM
1	63	59	101	610	11	6	90	2	2	60
2	80	23	41	360	8	10	140	3	2	90
3	63	52	70	890	6	6	130	3	2	100
4	75	67	111	980	9	6	190	3	4	60
5	100	89	113	1230	6	6	60	2	4	50
6	80	53	97	390	7	8	70	2	1	40
7	90	56	84	400	19	12	210	3	2	60
8	55	44	66	710	10	10	170	3	2	110
Mean	76	55	85	700	9	8	130	3	2	70
SD	15	19	25	320	4	2	60	1	1	25

PP: PowerPlate; Ga: Galileo; PM: PowerMaxx; BW: Body weight

Discussion

Three-dimensional platform accelerations

An overall finding of the "unloaded condition" was that with increasing platform frequency, a large increase in vertical platform accelerations was measured in the PowerPlate (up to 8 units of gravitational force g) and in the Galileo (up to 15 units of g) and a modest increase in horizontal platform accelerations in the PowerMaxx (up to 3.5 units of g). When comparing the three test devices at two common preset frequencies (25 and 30 Hz; printed bold in Tables 1-3), the Galileo is capable of producing the highest a_{RMS} values. However, its magnitude depends on the platform location, since it rotates around a central axis inducing pelvis and lumbar spine oscillations. This result, however, is different from the gravitational forces measured in a similar device, the Galileo. It was shown by Crewther et al.[33] that an increase in platform amplitude (1.25, 3 and 5.25 mm) resulted in only a slight increase in g forces in vertical direction at platform frequencies of 10, 20 and 30 Hz, i.e. 9.67 units of g at 1.25 mm displacement and 10 Hz up to 10.88 units of g at 5.25 mm and 30 Hz[33] (Table 1). We firmly attached our accelerometers between foot position 3 and 4, at which the platform displacement was 3.5 mm. At this location, vertical accelerations ranged from 1 unit of g (10 Hz) to 7.9 units of g (30 Hz). We were unable to find the cause of the differences between the results of Crewther et al.[33] and of our study. It might be due to differences in the linear accelerometers used (their 10 g versus our 50 g sensor), the data analysis (their 6 Hz low pass Hamming filter versus our FFT analysis procedure) or to the measurement setup, but information on attachment of the accelerometer to the platform surface was missing. Our Galileo test device showed some resonance, but it was above 30 Hz. Platform displacement reduced and as a result so did the magnitude of the vertical accelerations. This device also showed moderate vibrations (~1-1.5 units of g) in the X-direction. On the other hand, the PowerPlate induced very stable vibration patterns, i.e. its platform moved only in a vertical direction and showed very little horizontal vibrations. In the "high" amplitude mode, the a_{RMS} value was about half of that measured in the Galileo at a preset frequency of 25 Hz. The platforms of both these professional WBV devices mainly vibrated in vertical direction and loading both platforms did not influence their performance. The performance of the 'unloaded' PowerMaxx, however, was completely different from the two professional ones. The main accelerations (up to 3.5 units of g) were mainly in the horizontal plane. The a_{RMS} values in vertical direction were about a factor 7 less than that of the Galileo at a comparable preset frequency. However, loading this platform altered vibrations primarily in the horizontal plane to vertical vibrations. It is suggested that this change in vibration direction is most likely caused by changes in the dynamics of the eccentric drive of the PowerMaxx and the added eccentricity of the body weight of the three volunteers. However, these altered properties did not seem to depend on the weight of the volunteers. As we expected, each device has its specific properties, mainly in terms of accelerations (displacements).

Transmission of vertical accelerations

It is reported that the magnitude of acceleration of the lumbar spine depends on the knee angle[10]. In that study highest accelerations of hip and lumbar spine were measured in upright position (knee in full extension), but these accelerations did not exceed 50% of the induced accelerations of the platforms with both knees in only 20 degrees flexion; in that study, the accelerations were measured invasively. Others reported significantly greater vertical accelerations in squat position compared to standing postures[33]. It was speculated that greater muscle activation in this posture may increase total muscle stiffness, thereby enhancing the force transmission. In squat position we found that the transmission of vertical accelerations at a preset vibration frequency of 25 Hz was largest in the ankle and that transmission reduced ~ 6 to 10 times at the knee and hip. We calculated that the PowerPlate and the Galileo transmitted 1.8 and 4.2 units of g, respectively, at the ankle and less than ~0.45 units of g at the knee. Although loading the PowerMaxx resulted in amplification of the accelerations in vertical direction, the vertical accelerations at the ankle were ~ 1 unit of g and at the knee were ~ 0.2 units of g. This indicates that storage of the vibration energy was mainly limited to the lower legs. This damping effect at frequencies > 20 Hz has been reported by others[18,32-33,36]. It was also shown that the transmission of vibration to the head, expressed as a transmissibility factor, decreased rapidly for frequencies > 15-20 Hz[18]. These results suggest that no enhancement of muscle power can be expected in the upper body. A special point of concern is whether the head is free from vibrations during a WBV exercise. Although accelerations are small, it may induce high gain vestibular responses that alter visual perception and/or balance[37]. Especially in elderly, this might negatively influence the risk of falling during or shortly after a WBV exercise. From a safety point of view, it is suggested that the frequencies in vibration training for various groups should be ≥ 20 Hz to avoid vibration of the head by resonance frequencies of the human body[18,33]. Furthermore, typical WBV training regimens (30 Hz, 10 min per day) exceed the recommended daily vibration exposure as defined by ISO 2631-1 and are thus potentially harmful to the human body[35,38]. A potential hazard for the fragile human musculoskeletal system may also exist at amplitudes ≥ 0.5 mm due to great peak accelerations[36]. The results of the present study suggest that short training sessions on a PowerMaxx would comply with most of these safety regulations. Its minimum vibration frequency is 22 Hz, its platform displacements are ~0.6 mm and its (vertical) acceleration are within 2 units of g. However, a potential hazard of this device could be the large accelerations in the horizontal plane (up to 3 units of g). More studies are needed to test the impact of these vibrations on the human musculoskeletal system. Finally, it is reported that transmission of vibration to the human body is a complicated phenomenon due to nonlinearities in the musculoskeletal system, meaning that the sinusoidal waveform in terms of amplitude and frequency is modified at higher body segments[36]. We were able to partly confirm these findings in our data set. The vibration frequencies at the level of the ankle, knee and hip were within 5% comparable to the preset frequency of 25 Hz in all test persons on each tested device. However, the fit errors calculated by fitting a sine function through the vertical accelerations signals increased from ~ 4% at the level of the ankle to ~ 30% at the level of the hip (irrespective of the test device used) thus confirming this non-linear behaviour above the knee. It should be noted that the platforms may also induce substantial rotational vibration; especially the PowerMaxx may induce these vibrations around the vertical axis, although the vibrations along the translational axes alone were characterized. However, the human muscles respond also to rotational vibrations. Although the effects of radial vibrations are not known (whether beneficial or detrimental), these may also have contributed to activation of some of the muscles in the lower/ upper legs and pelvic region.

Study limitations

We measured relatively high accelerations (maximum of ~15 units of g) using a 50 g accelerometer. However, calibration of this sensor was based on a two-point calibration procedure, i.e. zero gravity and only 1 unit of g; this raises some doubt about the accuracy of the measured acceleration. In the first measurement series the large accelerations were measured with the sensors placed in the container that could be perfectly aligned to the platform's surface in all three dimensions, allowing sensitive and correct calibration of the individual sensors. In a previous report using a vertical vibration platform (similar to the PowerPlate we used), it was shown that given a peak-to-peak amplitude of a vertical vibration of 2 mm, the theoretical maximal accelerations would be ~2.5 units of g at 25 Hz, 3.6 units of g at 30 Hz, 4.9 units of 9 at 35 Hz and 6.4 units of g at 40 Hz[19]. These theoretical values are ~15% higher at $f_{out} > 30$ Hz than we measured with the PowerPlate platform. However, we did not calculate the maximum acceleration values but the root mean square acceleration values. In addition, the peak-to-peak displacements of the PowerPlate platform were calculated ~10% higher (2.2 mm versus 2.0 mm), which presumably caused higher accelerations in the PowerPlate (see equation 4). When taking these items into account, we conclude that the absolute magnitude of the accelerations might be slightly too high compared to the theoretically expected values, but accurate enough for comparison between the devices. In the second series of measurements vertical alignment of the accelerometer to the ankle, knee and hip was much more complicated. Although the two-point calibration at these locations was less accurate, the maximum accelerations measured in this series did not exceed 4 units of g.

It is reported that measurement of acceleration with skin mounted accelerometers can also be subject to inaccuracy, because of movement of the skin and soft tissues[28]. The foam tape used to securely attach the sensor to the skin probably reduced the amplitude of the displacement and thus the acceleration to some extent. Besides reliable mounting of the accelerometer, also inter-subject variability is expected to have a substantial impact on measurement accuracy[29,32,36]. In the present study, measurements were not repeated within each subject for a test-retest analysis to avoid an 'overload' of WBV. Indeed, the results in our subjects also showed relatively large variations. Knowing that individual responses may be large, caution is required when prescribing unified physically tolerable protocols for WBV. One of our future aims is the training of lower limb muscles. Therefore, in the first measurement series (small head oscillations) we changed the knee angle α of 150° to a knee angle of 100°. This position is known to be optimum for triggering and training of the main lower leg muscle, i.e. quadriceps muscle[34,39]. It is possible that the outcome of the second series might change when the squat position (thus knee angle) of each subject is altered. However, body position was not directly related to our main research question. Based on the present results, we think that posture only slightly influences the platform properties of the PowerPlate and the Galileo; these two devices have shown robust mechanical properties. The platform properties of the PowerMaxx may depend to some extent on differences in posture, but more research is needed to test this property.

We conclude that a large variation in 3-dimensional acceleration exists between the commercially available devices. The results of the present study suggest that these differences in mechanical behaviour induce variations in transmissibility of vertical vibrations to the (lower) body. We support the call for biomechanical and/or biological markers that help determine the correct timing of a vibration overload stimulus to assist in the safe and effective use of WBV as a rehabilitation and training tool[33].

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Chapter 4

Acute effects of whole-body vibration on jump force and jump rate of force development: A comparative study of different devices

J. Bagheri, H.J.G. van den Berg-Emons, J.J.M. Pel, H.L.D. Horemans, H.J. Stam

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Abstract

The goal of this study was to compare the acute effects of whole-body vibration delivered by three devices with different mechanical behavior on Jump Force (JF) and Jump Rate of Force Development (JRFD).

Twelve healthy persons (4 females and 8 males; age 30.5±8.8 years; height 178.6±7.3 cm; body mass 74.8±9.7 kg) were exposed to whole-body vibration for 15 and 40 seconds using two professional devices, PowerPlate and Galileo (radial vibration) and a home-use device (PowerMaxx; horizontal vibration). JF and JRFD were evaluated prior to, immediately after, and 5 minutes after whole-body vibration.

There were no significant differences in the acute effects of whole-body vibration (15 or 40 seconds) on JF and JRFD between the three devices. JF measured immediately after 40 seconds of vibration by the Galileo device was reduced (3%, $p=0.05$), and JRFD measured after 5 minutes of rest following 40 seconds of vibration by the PowerMaxx device was reduced (12%, $p<0.05$) compared to baseline.

In conclusion, our hypothesis that whole-body vibration devices with different mechanical behaviors would result in different acute effects on muscle performance was not confirmed.

Introduction

Whole-body vibration (WBV) is a relatively new approach to train the muscular system of the human body[1-4]. WBV initiates a rapidly and repeating eccentric-concentric action which brings about muscular work and an elevation in metabolic rate[5]. WBV is applied through a vibrating surface that supports the person. WBV studies are usually performed with the user standing on a motor-driven vibrating plate. The machine mainly affects the muscles that transmit the vibrations to the body via the upright position[6]. Previous studies have shown WBV to be a safe and well-tolerated method for improving muscle performance[1,7-11].

It is suggested that WBV exercises muscles primarily through activation of the tonic vibration reflex[12-14]. Applying a vibratory stimulus to the body, all sensory receptors within the epidermis, dermis, joint capsules, and muscles (Ia afferents) will be stimulated and thereby the stretch reflex will be activated. The magnitude of muscle activation during vibration is determined by Ia-afferent sensitivity[12,15]. Both excitation and inhibition of the stretch reflex during vibration have been reported[3,12, 13,16].

However, the effects of WBV on muscle performance are not conclusive[3,7,10,17-18]. In athletes, results range from no effect to a favorable effect on muscle performance[3,20-23]. In the elderly, improvement in muscle performance is almost always reported[24-27]. Favorable effects on the neuromuscular system are also reported in patients with Parkinson's disease[28] , multiple sclerosis[29], stroke[11], and cystic fibrosis[30].

The observed variation in the effects of WBV on muscle performance might partly be explained by differences in the mechanical behavior of the WBV devices[31]. The Galileo and PowerPlate are professional devices that have been used in many studies. A simpler and less costly device is the PowerMaxx, which is designed for home use. Galileo creates an oscillatory motion around the horizontal axis in addition to vertical vibration, whereas PowerPlate creates only a vertical vibration, and PowerMaxx vibrates primarily in the horizontal plane[31]. We hypothesized that these technical differences between the WBV devices could influence the effects of WBV on muscle performance. Effects of differences in device mechanical behavior on muscle performance would most likely be observable directly after vibration. Hence, the goal of this study was to determine whether there are differences among these vibration devices in terms of acute effects on muscle performance.

Methods and materials

Experimental approach to the problem

Within 2 weeks and on separate days, each participant was exposed to 6 different WBV interventions (3 different devices with 2 different durations of intervention for each device, Table 1).

Table 1. Whole-body vibration devices and specifications for intervention sessions. Results are expressed as mean ± SD.

Device	Frequency (Hz)	Displacement (mm)	Peak-to-peak α_{RMS} (g*)	Duration (s)
PowerMaxx	28	0.6 ± 0.02	0.4	40
	28	0.6 ± 0.02	0.4	15
PowerPlate	30	2.2 ± 0.1	3.3	40
	30	2.2 ± 0.1	3.3	15
Galileo	24	2.6 ± 0.1	5.5	40
	24	2.6 ± 0.1	5.5	15

* 1 g = 9.81 m/s^2

At the start of each session participants warmed up for 3 min by pedaling a stationary cycle. After that, 3 maximum vertical countermovement jumps were performed. Sets of 3 jumps were also performed immediately after and 5-min after the vibration intervention. During the 5-min period following the intervention the participants rested sitting on a chair (Table 2).

Table 2. Sequence of measurements in each whole-body vibration session.

3-min stationary cycling	First set of 3 jumps	Vibration intervention	Second set of 3 jumps	5-min rest on a chair	Third set of 3 jumps

To evaluate the acute effect of the different devices (independent variable) on muscle performance, we measured Jump Force (JF) and Jump Rate of Force Development (JRFD) as dependent variables by force plate measurements.

Subjects

Twelve healthy volunteers were recruited (4 females and 8 males, age 30.5±8.8 years, height 178.6±7.3 cm, and body mass 74.8±9.7 kg). Five of these participants were recreationally trained (participating in a variety of recreational sports/exercise for about 2 h per week) and 7 were athletes (participating in regular sports/exercise for 8 h per week). Each subject read and signed a University Institutional Review Board (Erasmus MC) approved informed consent form before participation.

Candidates were excluded if they had recent or possible thrombosis, severe headache, vestibular disorder, advanced arthritis, lower limb implant, synthetic implant (e.g. pacemaker), lumbar disc disorder, vertebral discopathy, acute systemic infection or inflammation, medication that could interfere with postural control, pregnancy, recent fracture, gall bladder or kidney stone, or malignancy.

Procedures

We used three WBV devices with different mechanical behaviors (Figure 1).

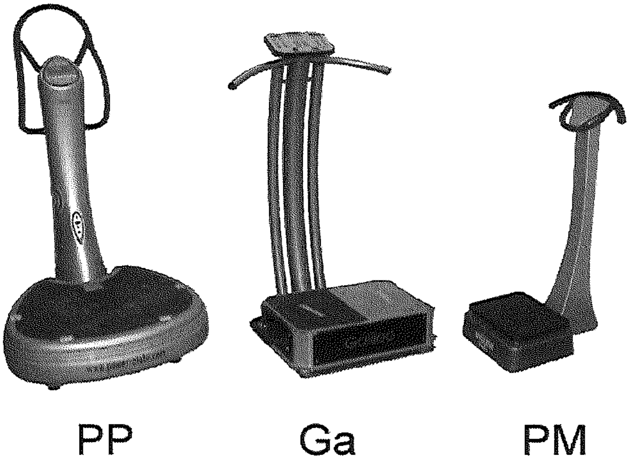

Figure 1. Whole-body vibration devices: PowerPlate (PP), Galileo (Ga), and PowerMaxx (PM).

PowerPlate and Galileo vibrate in near-perfect vertical sine waves at 25-50 Hz and 5-40 Hz frequencies (Figure 2). PowerPlate creates only vertical vibrations, and every point on the platform has the same motional property. Galileo creates an oscillatory motion around the x-axis in addition to vertical vibration. Unlike PowerPlate, points on the Galileo platform have different motional properties; oscillatory effects depend on both the distance between the feet and the position of the axial axis. In a previous study we showed that, for both devices, platform loading does not influence mechanical behavior[31]. The platform of the PowerMaxx vibrates primarily in the horizontal plane at 22-34 Hz, with minimal vertical acceleration (maximum ~20 m/s^2). Loading the PowerMaxx platform can increase vertical accelerations. Vertical accelerations are highest in the Galileo (maximally ~130 m/s^2) and PowerPlate (maximally ~70 m/s^2) devices[31].

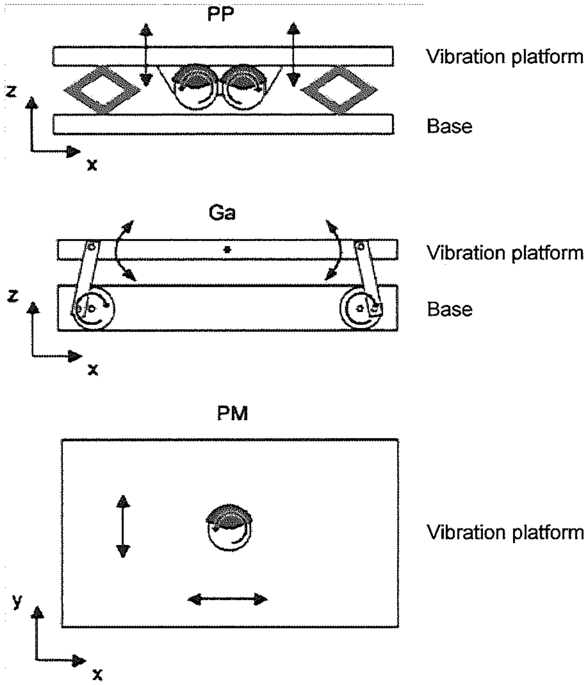

Figure 2. Different directions of vibration in whole-body vibration devices: PowerPlate (PP), Galileo (Ga), and PowerMaxx (PM).

The interventions consisted of exposure to WBV provided by one of the devices for either 15 or 40 s. Since experts from PowerPlate and Galileo advised different durations (15 s and 40 s, respectively) to activate the tonic vibration reflex physiologically, we decided to use both durations. The order of the interventions for each participant was randomly determined. Participants stood on the platform with bare feet, with 90-degree knee flexion and a straight trunk. They kept their balance by holding the device handle with their hands. During this study, comparable platform frequencies were chosen for all three devices. Table 1 summarizes the physical properties of each platform used, i.e. the platform frequencies, average platform displacements (peak-to-peak), average platform accelerations in units of g (1g=9.81 m/s^2) and the applied duration of vibration in each subject.

To perform the jump measurements, participants stood on a force plate (including two plates; 30 × 60 cm) (Novotec, Pforzheim, Germany) with their bare feet parallel to each other and hands on their waist. They were instructed to jump as quickly and as high as possible. Before jump, participants did one practice jump to become familiar with the procedure. In order to reduce the variability of the jump performance, sets of 3 jumps were performed before the WBV intervention, immediately after and 5 min after the intervention. The variation of the jump measurement was evaluated by the coefficient of variation (based on jumps prior to the WBV intervention). Vertical (Z-plane) Ground Reaction Force was collected on the force plate sampled at 100 Hz using an external A/D converter and was analyzed offline using customized software. JF and JRFD were calculated for every jump and were averaged over a set of 3 jumps. JRFD was defined as the peak slope of the force time curve generated (Figure 3).

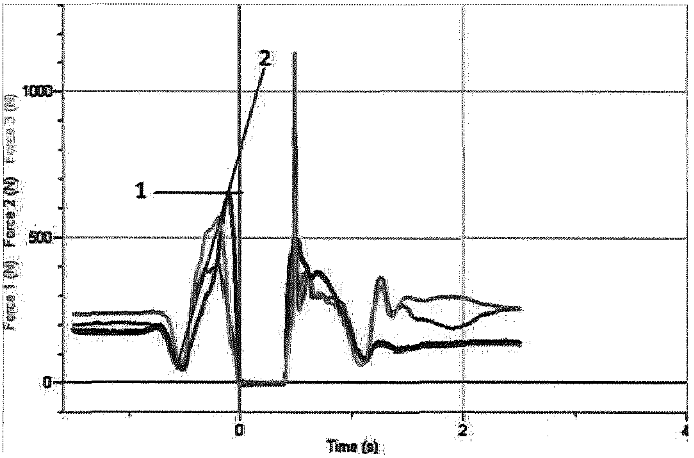

Figure 3. A typical trace for the calculation of the jump parameters based on 3 jumps. 1 = maximum value is peak jump force (JF); 2 = by this line jump rate of force development (JRFD) is calculated.

Statistical analysis

Analysis of variance (ANOVA) was used to compare devices for effects on JF and JRFD. In addition, paired-samples t-tests were used to compare JF and JRFD measurements from before the WBV intervention with data acquired a) immediately after WBV and b) after 5 min of rest after WBV. In all statistical analyses, we considered the average of three jumps in each set. Two-tailed p-values ≤ 0.05 were taken as significant. Data were analyzed with SPSS 16.0.1 for Windows.

Results

All 12 participants completed the sessions successfully. There were no reports of adverse effects of exposure to WBV, although 3 of the participants declared having a temporary (10 s) tingling sensation in their toes following the WBV intervention.

Table 3 compares the JF and JRFD data gathered prior to and immediately after exposure to WBV, stratified by device and duration of exposure. ANOVA showed no significant differences between the three devices for both JF and JRFD. In general, JF tended to be lower after the intervention, but only the decrease after 40 s of vibration with Galileo was significant. JRFD tended to increase immediately after the intervention, but the effects were not significant. The coefficient of variation for JF was 5.93% and for JRFD it was 21.88%.

Table 3. Comparison of jump values measured before and immediately after exposure to whole-body vibration for different devices and exposure durations in 12 healthy subjects. Results are expressed as the mean of the 3 jump measurements ± SD.

	WBV (15 s)			WBV (40 s)		
	Pre	Post	p-value	Pre	Post	p-value
PowerMaxx						
JF	1.92 ± 0.28	1.88 ± 0.32	0.16	1.92 ± 0.28	1.90 ± 0.31	0.24
JRFD	9.38 ± 4.52	10.70 ± 6.71	0.21	10.57 ± 4.61	11.39 ± 4.61	0.21
PowerPlate						
JF	1.85 ± 0.26	1.89 ± 0.31	0.68	1.91 ± 0.28	1.83 ± 0.26	0.23
JRFD	9.68 ± 4.35	11.26 ± 6.21	0.11	10.32 ± 4.91	10.52 ± 5.61	0.83
Galileo						
JF	1.94 ± 0.25	1.91 ± 0.25	0.07	1.95 ± 0.27	1.90 ± 0.32	0.05
JRFD	10.22 ± 4.61	10.37 ± 4.71	0.82	10.26 ± 4.81	11.02 ± 5.51	0.25

WBV: Whole-body vibration; JF: Jump force (kN); JRFD: Jump rate of force development (kN/s)

Table 4 compares the JF and JRFD data collected prior to exposure and after 5 min of rest following exposure to WBV. No significant differences were found between the devices in terms of effects on JF and JRFD. JF tended to be lower after exposure to WBV plus 5 min rest, but none of the differences were significant. After 40 s of vibration, a significant effect on JRFD after 5 min of rest was obtained with the PowerMaxx device (a reduction of 12%, $p<0.05$).

Table 4. Comparison of jump values measured before and 5 minutes after the exposure to WBV for different devices and exposure durations in 12 healthy subjects. Results are expressed as the mean of the 3 jump measurements ± SD.

	WBV (15 s)			WBV (40 s)		
	Pre	**Post**	**p-value**	**Pre**	**Post**	**p-value**
PowerMaxx						
JF	1.92 ± 0.28	1.91 ± 0.25	0.95	1.92 ± 0.28	1.91 ± 0.28	0.88
JRFD	9.38 ± 4.52	9.93 ± 5.21	0.19	10.57 ± 4.61	9.31 ± 4.42	**0.03**
PowerPlate						
JF	1.85 ± 0.26	1.83 ± 0.29	0.48	1.91 ± 0.28	1.90 ± 0.24	0.62
JRFD	9.68 ± 4.35	9.86 ± 0.44	0.72	10.32 ± 4.91	10.19 ± 4.71	0.81
Galileo						
JF	1.94 ± 0.25	1.88 ± 0.25	0.09	1.95 ± 0.27	1.91 ± 0.25	0.28
JFRD	10.22 ± 4.61	9.52 ± 4.62	0.06	10.26 ± 4.81	10.13 ± 5.34	0.75

WBV: Whole-body vibration; JF: Jump force (kN); JRFD: Jump rate of force development (kN/s)

Discussion

To our knowledge, this is the first study to compare the acute effects of different WBV devices on muscle performance. Because the devices generate vibration in different directions (Figure 2), we expected that they would exert different effects on muscle performance[31]. However, we found that exposure to WBV produced by these different devices did not have significantly different acute effects on JF and JRFD. Therefore, our hypothesis was not confirmed.

Exposure durations in the present study (15 and 40 s) were short compared to exposure durations reported in previous studies (4-10 min)[10,19-20]. Therefore, it is difficult to compare our results with those of the earlier studies. Because it is reported that short exposures to vibration can activate the tonic vibration reflex[32], we chose relatively short exposures to avoid excessive muscle fatigue. In the present study, compared to pre-WBV values, JF tended to be lower immediately following exposure to WBV and JRFD tended to be higher. It is interesting to know why short exposure to a single bout of WBV affected JF and JRFD in opposite directions. Reduction of JF might be related to inhibitory effects of vibration on recruitment of motor units. In this context, electromyography studies of leg muscle have shown increased signals following exposure to WBV of only 10-20% of maximal values, which is not adequate to recruit additional muscle fibers during WBV[5]. The increase in JRFD was probably due to the firing rate of motor units in the initial few seconds of exposure to WBV.

In line with our findings on JF, de Ruiter et al.[19] found reduced jump height 10 s following vibration, which returned to baseline values within 15 min. In contrast, Bosco et al.[17] found increased leg-extension power and jump height immediately after a single WBV training session. However, in those studies, both the subjects and the interventions were different from those in our study. Thus, there is no consensus on the effect of WBV on JF, and further research is needed.

There are a few possible explanations as to why we did not detect a clear favorable effect of WBV on JF and JRFD. First, motor neuron recruitment in response to direct muscle tendon vibration is rather limited, probably because vibration also elicits a certain level of pre-synaptic Ia inhibition, which brakes the further recruitment of motor neurons[19]. Second, during WBV the vibration is applied to the soles of the feet and each foot joint will have a dampening effect on the vibration stimulus in the distal to proximal direction of the leg[19]. Additionally, WBV causes reciprocal inhibition of antagonist muscles. During WBV, agonist and antagonist muscles are simultaneously impacted, which may further enhance the inhibitory effects of vibration[19,33].

Our study has two potential limitations. First, although we could not apply identical amplitudes and frequency settings for the three devices because of their different designs, we tried to use the most comparable settings for each device. Second, the study sample was relatively small, but the results do not suggest that a larger sample would result in different conclusions.

Practical application

In contrast to what we expected, there were no significant differences in acute effects of whole-body vibration on jump force and jump rate of force development between these devices with different mechanical behaviors. Furthermore, there were only minor acute effects. Long-term effects of training programs using vibration devices need to be evaluated in longitudinal studies. The findings of the current study imply that, in order to improve muscle performance, both professional devices and the home-use device may be used. This is an important finding, since home-use devices have the advantage that they are considerably less costly than professional ones and can be used in the natural surroundings (more time efficient). However, one should realize that loading the PowerMaxx platform can increase vertical accelerations; this makes the device less suitable for scientific purposes.

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Chapter 5

Acute effects of whole-body vibration on neuromuscular response of vastus lateralis muscle: A comparative study of different devices

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Submitted

Abstract

Whole-body vibration (WBV), a technique designed to recruit muscles, is increasingly applied in athletes and patients with chronic diseases. However, the effects of WBV on muscle force are not consistent, which might partly be explained by differences in the mechanical behavior of the WBV devices. The aim of the study was to compare the acute effects of WBV provided by three devices with different mechanical behavior on neuromuscular response of the vastus lateralis muscle. A secondary aim was to examine the magnitude of the effects for each device.

Twelve healthy persons (5 females and 7 males; age 28.1±7.8 years) were exposed to WBV for 15 and 40 seconds using two professional devices (PowerPlate and Galileo 2000), and a home-use device (PowerMaxx). Two electromyography (EMG) parameters were calculated: Integrated electromyography and root mean square electromyography. These parameters were evaluated at rest and at 40% of maximal voluntary contraction in the dominant vastus lateralis, both before and immediately following exposure to WBV.

There were no significant differences between the devices in the effects on EMG parameters. Within devices, EMG activity at rest increased by 45-62% ($p<0.05$), and at sustained contraction reduced by 11-22% ($p<0.05$) when we used the PowerMaxx. When using the Powerplate, EMG activity at sustained contraction reduced by 14% ($p=0.05$). Other within-device effects were not significant.

Our hypothesis that the WBV devices with different mechanical behaviors would result in different acute effects on neuromuscular response was not confirmed. These findings imply that to potentially improve muscle force, both the professional devices and the home-use device are comparable.

Introduction

The use of a vibrating platform as a training device for recreational athletes and patients with chronic diseases has increased. Whole-body vibration (WBV) is a relatively new method designed to recruit muscles, increase bone density, and improve balance[1-5]. WBV is performed using a machine consisting of a vibrating flat plate on which the person stands. The machine exercises the muscles that must react to keep the body in the standing position during vibration. Based on previous studies, WBV should be a safe and tolerable method for improving muscle performance[4,6-8]. However, some reports indicate that the risk of adverse health effects may be lower during radial vibration than vertical vibration and at half-squats rather than full-squats or upright stance[9].

It is suggested that WBV exercises muscles primarily through activation of the tonic vibration reflex (TVR)[6,10-11]. Applying a vibratory stimulus to the body, all sensory receptors within the epidermis, dermis, joint capsules, and muscles (Ia afferents) will be stimulated and thereby the stretch reflex will be activated[12-13]. The magnitude of muscle activation is determined by Ia-afferent sensitivity[3,6,14]. Depending on the variety of the experimental paradigm (frequency, amplitude and duration of vibration) either excitation or inhibition[15-16] of the TVR will occur. In fact, higher or lower frequencies may activate different receptors; the amplitude may also enhance the receptor responses which may lead to activation of TVR.

With respect to the effects of WBV on muscle force, contrasting results have been shown among persons with varying training levels[4,17-20]. In athletes, studies have shown effects ranging from none[18,21] to favorable effects on leg muscle power[12-13,17,22]. In the elderly, studies have shown that WBV increases muscle force[5,19, 23-24]. Furthermore, WBV training may have favorable effects on the neuromuscular system in patients with chronic diseases such as Parkinson's disease[25], multiple sclerosis[26-27], and stroke[28].

Part of the variety in effects of WBV on muscle force might be explained by differences in mechanical behavior of the WBV devices[29]. The Galileo and PowerPlate are professional devices used in many studies, whereas the PowerMaxx is designed for home use (Figure 1). The Galileo creates an oscillatory motion around the horizontal axis in addition to vertical vibration, whereas PowerPlate creates only a vertical vibration, and PowerMaxx vibrates primarily in the horizontal plane[29]. We hypothesized that these technical differences between the WBV devices could influence the effects of WBV on neuromuscular response and, as a consequence, on muscle force. Effects of differences in the mechanical behaviour of the device on neuromuscular response would most likely be observable directly after vibration. Therefore, the main goal of this study was to determine whether there are differences in acute neuromuscular effects among the three vibration devices. The secondary goal was to examine the magnitude of the effects for each device.

Methods and materials

Subjects

We recruited 12 healthy volunteers (5 females and 7 males; age 28.1±7.8 years, height 175.6± 8.0 cm and body mass 72.2±8.1 kg). Four of the participants were recreationally active (participating in a variety of recreational sports/exercise for about 2 h per week) and the remainder were athletes (participating in regular sports/exercise for 8 h per week; football [n=3], volleyball [n=2], body power lifting [n=3]). All subjects gave written informed consent. The study was approved by the Medical Ethics Committee of Erasmus Medical Center.

Inclusion and exclusion criteria

Healthy adult subjects were eligible for the study. Candidates were excluded if they had recent or possible thrombosis, severe headache, a vestibular disorder, advanced arthritis, a lower limb implant, a synthetic implant (e.g. pacemaker), a lumbar disc disorder, vertebral discopathy, acute systemic infection or inflammation, medication that could interfere with postural control, pregnancy, recent fracture, gall bladder or kidney stone, or malignancy.

Procedures

WBV devices

We used three WBV devices with different mechanical behavior and settings (Figure 1) and attempted to choose the most comparable device settings for this study.

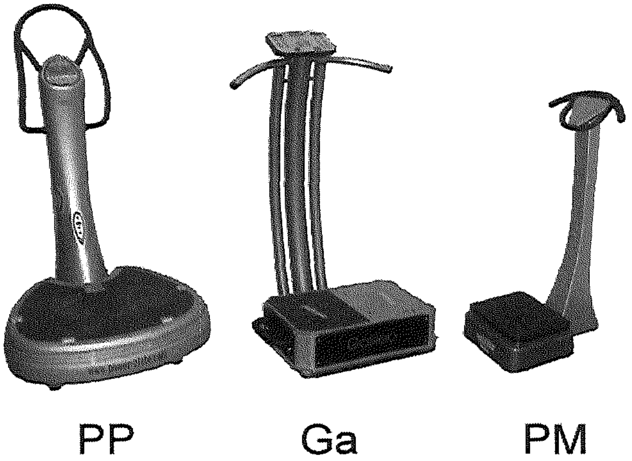

Figure 1. Whole-body vibration devices: PowerPlate (PP), Galileo (Ga) and PowerMaxx (PM).

PowerPlate and Galileo vibrate in near-perfect vertical sine waves at 25-50 Hz and 5-40 Hz frequencies, respectively. Galileo creates an oscillatory motion around the horizontal axis in addition to vertical vibration; PowerPlate creates only vertical vibration (Figure 2). For both devices, platform loading does not influence mechanical behavior[29]. The platform of the

PowerMaxx home-use device vibrates primarily in the horizontal plane at 22-34 Hz, with minimal vertical accelerations (maximum ~20 m/s^2). Loading the PowerMaxx platform can increase vertical accelerations; however, vertical accelerations are highest in the Galileo (maximum ~130 m/s^2) and PowerPlate (maximum ~70 m/s^2) devices[29].

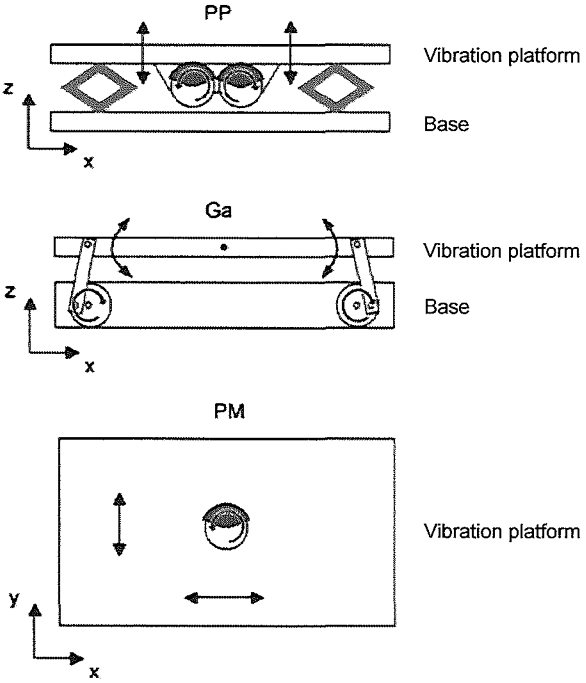

Figure 2. Different directions of vibration in whole-body vibration devices: PowerPlate (PP), Galileo (Ga), and PowerMaxx (PM).

Protocol

Within 2 weeks, each participant was exposed to 6 different WBV interventions on separate days (Table 1). All participants were instructed to avoid intensive exercise prior to the measurements. The interventions consisted of exposure to WBV provided by one of the devices for either 15 or 40 s. The order of the interventions for each participant was randomly determined. Participants stood on the platform with bare feet, with 90-degree knee flexion and a straight trunk. They kept their balance by holding the device handle with their hands. Comparable frequencies and amplitudes were chosen for all three devices (Table 1). During each session, the electromyography (EMG) activity of the vastus lateralis of the dominant leg was recorded at rest and during 40% of maximum voluntary contraction, both before and after exposure. Leg dominancy was assessed by questions regarding activities of daily living and sport).

Table 1. Whole-body vibration devices and specifications for intervention sessions. Results are expressed as mean ± SD.

Device	Frequency (Hz)	Displacement (mm)	Peak-to-peak α_{RMS} (g*)	Duration (s)
PowerMaxx	28	0.6 ± 0.02	0.4	40
	28	0.6 ± 0.02	0.4	15
PowerPlate	30	2.2 ± 0.1	3.3	40
	30	2.2 ± 0.1	3.3	15
Galileo	24	2.6 ± 0.1	5.5	40
	24	2.6 ± 0.1	5.5	15

* 1 g = 9.81 m/s^2

Measurements

Maximum Voluntary Contraction (MVC)

To determine MVC of the dominant knee extensor, we used the Biodex (Biodex Medical System, Model 900-860). Participants performed three isometric contractions at 90 degrees of knee flexion with 3 s hold times and 60 s rest between holds. The average contraction was determined and used for the present study. During the measurement, participants were instructed to build up the force gradually.

EMG

EMG signals of the vastus lateralis were recorded before and immediately (within 30 s) after exposure to WBV (EMG device: Twente Technology Transfer BV Model: 3T- PS- HDB, the Netherlands). Following skin preparation (shaving and cleansing with alcohol), a pair of surface bipolar electrodes (3M, Germany) (inter-electrode distance 10 mm) was placed on the vastus lateralis according to European surface EMG recommendations (SENIAM project). EMG of the vastus lateralis muscle was evaluated during 5 s of absolute muscle rest in a sitting position with 90-degree knee flexion, followed by 10 s at 40% of MVC. A manual dynamometer (MicroFET2, Hogan Health Industries; West Jordan, Utah, USA) was used to apply force on the lower ventral part of the shank, just above the malleoli. The contact area of the dynamometer was marked to ensure the same placement on retest. The examiner encouraged the participant to apply the amount of force needed to reach 40% of MVC. Through verbal feedback, participants were requested to maintain this level of force for 10 s. EMG measurements were performed at 40% of MVC because 40% can be sustained at a constant level.

Vastus lateralis signals were amplified (Twente Technology Transfer BV Model: Ps-800, The Netherlands). All EMG signals were sampled at 1000 Hz and band-pass filtered at 10-500 Hz using a 22-bit analog-digital converter. The digitized signals were full wave rectified and low-pass filtered using a moving average filter with a window of 50 samples. Two EMG parameters were calculated for a 10-second period using custom-made Lab View software: Integrated EMG (IEMG) and root mean square EMG (EMGrms) of the vastus lateralis. We chose both parameters because the EMGrms is a robust measure that limits the effects of movement artifacts. However, it is also less sensitive to changes in the EMG signal and may mask differences in muscle activation intensity between experimental conditions. The IEMG is more sensitive to temporal changes in onset and offset of muscle activation. However, for continuous levels of activation both outcomes will be highly correlated.

Statistical analysis

Analysis of variance (ANOVA) was used to compare differences in effects between the devices, and between athletes and recreationally trained subjects. Paired-samples t-tests were used to compare EMG measurements before the WBV intervention with data acquired immediately after WBV for each device. A two-tailed p-value of ≤ 0.05 was used to determine significance. SPSS version 20.0.1. for Windows was used for analysis.

Results

None of the subjects had any previous experience with WBV training. One of the participants complained of muscle soreness within 24 h after exposure to 40 s of Galileo vibration; no other objective or subjective side-effects were noted. For both rest and sustained force, no significant differences were found in acute effects between the PowerPlate, Galileo, and PowerMaxx devices. Table 2 show EMG parameters at rest before and after WBV, by each device and time of exposure. The EMG parameters at rest significantly increased only after using PowerMaxx: IEMG by 45% (15 s intervention) and 59% (40 s intervention); EMGrms by 62% (40 s intervention; $p<0.05$).

Table 2. Comparison of the EMG outcome parameters after recording of the vastus lateralis before (pre) and after (post) exposure to WBV by different devices and at different exposure duration at rest. Results are expressed as mean ± SD.

	WBV (15 s)			WBV (40 s)		
	Pre	Post	p-value	Pre	Post	p-value
PowerMaxx						
IEMG	0.203 ± 0.13	0.294 ± 0.15	**< 0.05**	0.181 ± 0.10	0.288 ± 0.21	**< 0.05**
EMGrms	0.082 ± 0.05	0.121 ± 0.06	0.09	0.074 ± 0.04	0.120 ± 0.08	**< 0.05**
PowerPlate						
IEMG	0.186 ± 0.14	0.165 ± 0.08	0.32	0.133 ± 0.09	0.167 ± 0.11	0.41
EMGrms	0.077 ± 0.05	0.067 ± 0.03	0.24	0.056 ± 0.04	0.073 ± 0.04	0.34
Galileo						
IEMG	0.192 ± 0.07	0.202 ± 0.10	0.75	0.169 ± 0.06	0.243 ± 0.12	0.10
EMGrms	0.077 ± 0.03	0.085 ± 0.04	0.53	0.066 ± 0.02	0.102 ± 0.05	0.60

IEMG: Integrated electromyography in µv; EMGrms: root mean square Electromyography in µv
WBV: Whole-body vibration

Table 3 shows EMG parameters during 40% of MVC before and after WBV, by each device and time of exposure. When using PowerMaxx, IEMG was significantly reduced by 11% (15 s intervention), and EMGrms by 14% (15 s intervention) and 22% (40 s intervention). Following vibration by PowerPlate, IEMG was reduced by 14% (40 s intervention). Other changes were not significant. Although the fitness levels of the participants differed, we found no significant differences in acute effects between recreationally trained subjects and the athletes following exposure to a single bout of WBV.

Table 3. Comparison of the EMG outcome parameters recording of the vastus lateralis before (pre) and after exposure to WBV by different devices and at different exposure duration at 40% of maximum voluntary contraction. Results are expressed as mean ± SD.

	WBV (15 s)			**WBV (40 s)**		
	Pre	**Post**	**p-value**	**Pre**	**Post**	**p-value**
PowerMaxx						
IEMG	2.979 ± 1.35	2.631 ± 1.09	< **0.05**	2.992 ± 1.44	2.424 ± 1.12	0.06
EMGrms	1.310 ± 0.55	1.130 ± 0.47	< **0.05**	1.255 ± 0.60	0.978 ± 0.52	< **0.05**
PowerPlate						
IEMG	2.698 ± 1.10	2.512 ± 0.66	0.40	2.720 ± 2.10	2.350 ± 1.69	**0.05**
EMGrms	1.126 ± 0.43	1.030 ± 0.27	0.24	1.093 ± 0.82	0.985 ± 0.66	0.22
Galileo						
IEMG	2.740 ± 1.18	2.296 ± 0.83	0.11	2.651 ± 1.24	2.296 ± 0.94	0.10
EMGrms	1.123 ± 0.42	0.989 ± 0.26	0.11	1.093 ± 0.50	0.997 ± 0.41	0.14

IEMG: Integrated electromyography in µv; EMGrms: root mean square Electromyography in µv
WBV: Whole-body vibration

Discussion

To our knowledge, this is the first study to compare the acute effects on neuromuscular response between WBV devices with different mechanical behavior. We have also compared the devices to evaluate their effects on explosive muscle force (Jump Force and Jump Rate Force of development)[30]. In agreement with the results on muscle force, we found no differences in effects on IEMG and EMGrms between the PowerPlate, Galileo, and PowerMaxx. Apparently, the differences in mechanical behavior do not result in different acute effects on EMG parameters recording from the vastus lateralis.

Although only significant in some interventions while using the PowerMaxx, the vibration interventions tended to result in an increased EMG during rest and a decreased EMG during

40% of MVC. Because of the primarily horizontal vibration, we did not expect the PowerMaxx to affect the neuromuscular response. However, almost all significant effects were found after vibration provided by the PowerMaxx. This may partly be explained by our earlier finding that loading the PowerMaxx platform increases vertical accelerations[29]. Future longitudinal studies are required to investigate differences in training effects between the different devices.

The increased neuromuscular response we found at rest following vibration may indicate increased excitability of the vastus lateralis. Neuromuscular excitability following WBV exposure has been reported previously[3,14,31-32]. To date, we are not aware of any study reporting on EMG activity of muscles at rest immediately following vibration. The reduced neuromuscular response as we found during 40% of MVC following exposure to vibration, could be related to non-synchronized motor unit firing. Similar to our findings, Bosco et al.[31] reported a reduction of EMGrms in vastus lateralis during MVC following 5 min of vibration. In contrast to our findings and those of Bosco et al.[31], in the study of Torvinen et al.[20] the EMGrms of the soleus muscle, vastus lateralis and paravertebrae muscles showed no significant change during 4-min vibration interventions. However, they measured EMG during vibration exposure and with different settings. Bongiovanni et al.[33] also found no significant changes in EMGrms following vibration.

Exposure times in the present study (15 and 40 s) were short compared to exposure times reported in previous studies (4-10 min)[15,20,31]. We chose this duration of exposure to avoid muscle fatigue, and because this duration would be long enough to activate the tonic vibration reflex (TVR) physiologically. A study by Dolny and Reyes[7] indicated that short exposures to vibration (as short as 30 s) could activate TVR physiologically. Da Silva et al.[34] also determined 30 and 60 s as the most appropriate duration of vibratory stimuli (frequency 30 Hz and amplitude 4 mm), to improve jump ability and power generated by the lower limb muscles. They reported that exposure to 90 s of WBV resulted in reduction of muscle performance. In our experiments, exposure to either 15 s or 40 s did not influence the acute effects of WBV on jump force and jump rate of force development[30].

Our study has some limitations. First, we could not apply the same amplitude and frequency for the three devices due to differences in their design. For instance, the PowerPlate had only two amplitude options (low and high), whereas the Galileo had four options, dependent on the distance from the centre of oscillation, and the PowerMaxx had three options. However, we attempted to choose the most comparable device settings for this study. Second, although the study sample might have been too small to detect effects, the results do not suggest that a larger sample would have influenced the main conclusions of our study. Third, inter-day variability might have influenced data outcomes. However, we followed exact anatomical landmarks on the skin to ensure the same placement for the electrodes, and all measurements were made under constant laboratory conditions. Fourth, because the measurements had to be performed immediately after the vibration (within 30 s), we could not consider other muscles, such as the calf muscles. Future research could also focus on the effects of different vibration devices on other muscles. Finally, adding a control intervention to the current study in which the participants stand on the platform without vibration might have discriminated between the effect of the vibration and the effect of the standing position. However, the aim of our study was to assess differences in acute effects between the devices, not to assess differences in effects between standing with and without vibration.

Conclusion

The results of the study imply that there were no differences in acute neuromuscular responses between the whole-body vibration devices with different mechanical behaviors. Furthermore, there were only minor acute effects at the level of each device. The findings of the current study imply that, as yet, to potentially improve muscle performance both the professional devices and the home-use device are comparable. This is an important finding, since home-use devices have the advantage that they are considerably less costly than professional devices and can be used in the natural surroundings, and therefore more time efficient.

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Chapter 6

Immediate effects of two-minutes whole-body vibration on postural stability and motor neuron excitability in older adults

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Submitted

Abstract

This study aimed to determine the immediate effects of WBV on postural stability and motor neuron excitability in healthy older adults.

Ten volunteers (4 men, 6 women; mean age 58.2 years) participated. In a crossover study, participants were examined in two sessions. In one session they stood on a WBV device for 2 min while the device was switched on (30 Hz, 2 mm: vibration condition) and in the other session it was switched off (control condition). Measurements were done before and immediately after each condition. Postural stability was measured with a force plate (range, mean displacement, and mean velocity of the center of pressure). Motor neuron excitability was measured by recording the soleus H-reflex (amplitude of the H-reflex and M-wave, H/M ratio).

For the force plate and H-reflex parameters no significant differences were found between change scores of the vibration and control condition. The only significant finding was a reduction in the amplitude of the H-reflex within the vibration condition (-26%; $p<05$). No relationship was found between the effects on postural stability and motor neuron excitability.

We conclude that a single bout of WBV has no immediate effect on postural stability and motor neuron excitability when compared to the control condition. Future studies should focus on the role of the device settings and on the effects of a prolonged vibration training program.

Introduction

Fall-related injuries, including head injuries and fractures, are common problems in the elderly as they often lead to prolonged disability[1-2]. Reduced muscle strength and balance control are considered to contribute to postural instability and are therefore important risk factors for falls[3-4]. Prevention of falls and their associated injuries might reduce disability, improve quality of life, and lower the costs of health care[5-6].

Studies have shown the positive effect of physical exercise on postural stability in healthy elderly persons. For example, conventional methods such as balance training[7], progressive resistive exercise[8], agility exercise[9], cycling and walking[10] are effective. Whole-body vibration (WBV) is also reported to be an effective modality to improve balance[11] or postural control[12], walking ability[13], muscle strength[14] and proprioception[15] in the elderly.

Although some studies of prolonged vibration training ($\geq$ 6 weeks) have shown some positive effects on postural stability in the elderly[12-14,16-17], there is no consensus and the results are not conclusive. Studies focusing on the immediate effects of vibration on postural stability also report conflicting results. For instance, Priplata et al.[18] showed that vibrating insoles caused an immediate reduction in postural sway of elderly persons during quiet standing. Van Nes et al.[19] studied the immediate effects of WBV on postural stability in stroke patients and concluded that WBV might be a promising modality to improve proprioceptive control of posture in these patients. However, Torvinen et al.[20] and Carlucci et al.[21] found no immediate effects of WBV on muscle performance and postural stability in healthy subjects. Thus, the acute effects of WBV on postural stability remain a topic of debate.

Besides the uncertainty regarding the effects of WBV on postural stability, the underlying mechanisms are also unclear. The prevailing hypothesis is that the effects of WBV on postural stability are mainly due to stimulation of mechanoreceptors such as joint receptors and muscle spindles. These mechanoreceptors stimulate the Ia afferent fibers which, in turn, activate alpha-motor neurons, resulting in muscle contractions[22]. This excitation of monosynaptic reflex activity and the resulting muscle contractions can support stability across a joint and increase balance[23]. However, inhibitory effects of WBV on monosynaptic reflex activity have also been reported[24], probably due to pre-synaptic inhibition[25] and reciprocal inhibition. Whether WBV stimulates or inhibits motor unit excitability may depend on the exposure time and vibration settings used[26-27].

One way to identify motor neuron excitability and related mechanisms of WBV is to measure the Hoffman reflex (H-reflex). The H-reflex is an electrical equivalent of the mechanically induced stretch reflex; in both reflexes afferent Ia-fibers are activated[28]. Since the H-reflex bypasses the muscle spindle, it is a valuable tool to assess modulation of monosynaptic reflex activity (Figure 1). Based on the idea that WBV (as a kind of somatosensory stimulation) leads to increased motor unit excitability, an increased amplitude of the H-reflex can be expected. However, Armstrong et al.[29] reported a significant suppression of the H-reflex during the first minute after WBV in healthy and young subjects. Also, McBride et al.[30] found no significant change in the ratio between amplitudes of the H-reflex and the M-wave (H/M) or muscle activity in either the WBV or control group. Therefore, here again, the results remain inconclusive.

To our knowledge, no study has focused on the immediate effects of a single bout of WBV on both objectively measured postural stability and motor neuron excitability. Therefore, the present study investigates whether WBV leads to immediate effects on postural stability (measured by force plate) and motor neuron excitability (measured by recording soleus muscle H-reflex). We hypothesize that WBV will lead to excitation of monosynaptic reflex activity and, as a result, postural stability will be improved without any adverse effects.

The research questions were:

1) Does a single bout of WBV lead to a decreased sway of the center of pressure (CoP) compared to a control session?
2) Does a single bout of WBV lead to an increase in amplitude of the H-reflex, M-wave and H/M ratio?
3) Is there a relationship between CoP sway and the H-reflex parameters?

Methods and materials

Subjects

Ten healthy volunteers (4 male, 6 female) participated in the study (Table 1). Inclusion criterion was age over 55 years. Exclusion criteria were inflammatory diseases, regular participation in high-intensity exercise (≥ 3 times/week), medication use that might affect the musculoskeletal system, and general contra-indications of WBV (such as endoprostheses). All participants provided informed consent. The study was approved by the Medical Ethics Committee of the Erasmus MC.

Table 1. General information on the 10 study participants (4 men and 6 women).

Items	Mean (SD)	Range
Age (years)	58.2 (2.5)	[54 – 60]
Height (m)	1.77 (0.12)	[1.60 – 1.96]
Weight (kg)	81.1 (12.9)	[59.2 – 100.5]
Foot length (m)	0.38 (0.05)	[0.30 – 0.47]
Foot width (m)	0.18 (0.01)	[0.16 – 0.21]

Protocol

Each participant was measured on two occasions (with a 1-week interval in between) and served as his/her own control. Participants were instructed to stand on the vibration platform (PowerPlate International, Model: Next Generation, Irvine, CA, USA) with 15 degrees of knee flexion while grasping the handle of the device and keeping their feet parallel to each other. In one session participants stood on the device for 2 min while the device was turned on (30 Hz and 2 mm); for the other session, they stood on the device for 2 min while it was switched off. The sequence of the two conditions was determined in random order. Measurements of the H-reflex and force plate were done before and immediately after the intervention (within 30 s).

The H-reflex was always measured first. The average time interval between measurements of the H-reflex and force plate was about 1 min.

Measurements

Postural stability

Subjects stood barefoot on a strain gauge force plate (AMTI, BP400600) with the feet together in a stride stance, the heel of the non-dominant foot positioned at the middle of the dominant foot. The placement of the feet between sessions was standardized by drawing the circumferences of both feet on a paper sheet that was placed on the force plate. Participants were instructed to cross their arms over the chest and to grasp the contra-lateral shoulders. They were asked to stand as still as possible with eyes closed for 20 s. A second trial was performed after a 30-s interval. The average of these two trials was used for analyses. During the 20 s of each trial, the position of the CoP in the anterior-posterior (AP) and in the medio-lateral (ML) directions was recorded (600 Hz).

Outcome measures for postural sway in both the AP and ML directions were:

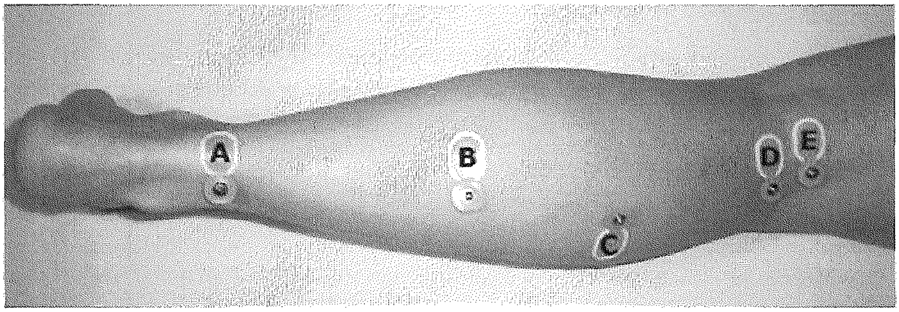
- Range: difference between the maximum and minimum value of the CoP position.
- Mean displacement: the average of the absolute distance between the actual CoP position and the mean CoP position, calculated over all samples.
- Mean velocity: the average of the displacement of the CoP position per second (m/s).

Range and displacement were normalized to the maximal width and length derived from the circumference drawing of both feet.

Motor neuron excitability

The H-reflex response of the soleus muscle of the dominant leg was recorded with a Viking IV select device (Nicolet Biomedical, Madison, WI, USA). Before measurements, the areas of the popliteal fossa and soleus muscle of the left leg were prepared. The recording electrode (Noraxon USA, Inc., Scottsdale, AZ, USA; 2-cm inter-electrode distance, 1 cm^2 circular conductive area) was positioned on the soleus muscle about 13 cm above the superior portion of the calcaneus and below the fibers of the gastrocnemius muscle. Then a stimulus device (Nicolet Viking II; Nicolet Biomedical, Madison, WI) was used to locate the optimal site for stimulation of the tibial nerve.

When the optimal site was determined, a bipolar stimulating electrode (1-cm conduction area and 3-cm inter-electrode distance) was secured in the same area using adhesive tape. The test was completed with subjects in a prone position. The stimuli were delivered as one millisecond square pulses without simultaneous contraction of the triceps surae complex. Starting at a stimulus of 3 V, the stimuli were administered in 3-V increments at a rate of 0.1 Hz until no further visual increase in the peak-to-peak M-wave amplitude was detected (the intensity was adjusted to obtain the largest H reflex response). The stimulations elicited both H-wave and M-wave responses in the soleus muscle. After the pre-intervention measurement, a tube grip bandage was used to keep the electrodes in the same position for the post-intervention measurement (Figure 1). After the first session the examiner marked the location of the electrodes on the skin and determined the anatomical location in each participant to enable optimal reproduction of the electrode positions for measurement in the second session.



Place of electrodes to record H-reflex. A and B; recording electrodes over soleus muscle, C; ground electrode, D and E; stimulating electrodes over tibial nerve.

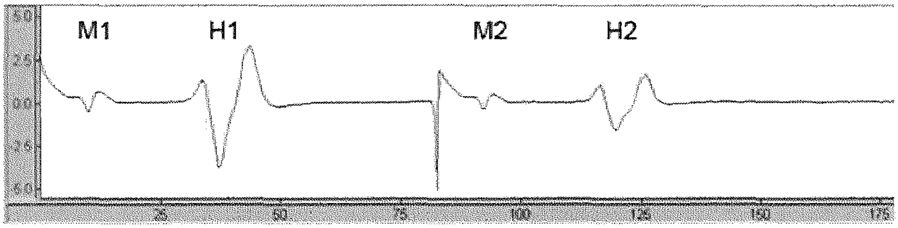


Figure 1. Recording Hoffmann (H) reflex and M wave from soleus muscle[33]. The maximum amplitude of the H-reflex is determined by using as many as stimuli as needed to record the largest amplitude of the reflex. Two stimulations in one trace are shown here[33].

Outcome measures for motor neuron excitability were:

- Amplitude of the H-reflex: peak-to-peak amplitude of the H-reflex.
- Amplitude of the M-wave: baseline-to-peak amplitude of the M-wave.
- H/M ratio: ratio between the amplitude of the H-reflex and the amplitude of M-wave.

Statistical analysis

Changes (differences between pre- and post-intervention) were non-parametrically compared between the WBV and control conditions (Wilcoxon test). The same test was used to examine differences in post- and pre-intervention data for each condition. The absolute values of Pearson's correlation were used to assess the relationships between the individual changes in force plate parameters and H-reflex parameters. All analyses were performed with SPSS (16.0.01). A p-value <0.05 was considered statistically significant.

Results

No participant reported any complaints or experienced any adverse effects related to WBV. Data related to the H-reflex of two participants were excluded; in one the H-reflex could not be recorded and in another participant the amplitude of the H-reflex was too low to be considered valid. There were no differences in the pre-intervention data of the force plate and H-reflex between the two conditions.

Postural stability

There were no significant differences in the change in range, mean distance and mean velocity of CoP sway between the WBV and control conditions (Table 2).

Table 2. Comparison of the change in postural stability parameters between the two conditions. Data are presented as mean ± SD.

Parameters	WBV condition	Control condition	p-value
Range ML (%)	- 1.49 ± 3.89	- 0.78 ± 7.12	0.72
Range AP (%)	+ 0.44 ± 2.13	- 0.65 ± 2.34	0.24
Mean distance ML (%)	- 0.24 ± 0.80	- 0.13 ± 0.89	0.76
Mean distance AP (%)	- 0.05 ± 0.30	- 0.08 ± 0.30	0.84
Mean velocity ML (m/s)	+ 0.007 ± 0.028	- 0.004 ± 0.038	0.65
Mean velocity AP (m/s)	- 0.006 ± 0.019	- 0.006 ± 0.017	0.89

WBV: Whole-body vibration; ML: Mediolateral; AP: Anteroposterior.

Similarly, there were no significant differences between the pre- and post-intervention scores within the two conditions (Table 3).

Table 3. Comparison of the postural stability parameters before and after intervention within the two conditions. Data are presented as mean ± SD.

Parameters	WBV condition			Control condition		
	Before	After	p-value	Before	After	p-value
Range ML (%)	28.89 ± 6.62	27.39 ± 5.15	0.14	28.06 ± 8.66	27.28 ± 6.93	0.51
Range AP (%)	9.51 ± 3.45	9.95 ± 2.80	0.58	10.22 ± 2.88	9.57 ± 2.33	0.24
Mean distance ML (%)	4.45 ± 1.31	4.21 ± 1.11	0.29	4.48 ± 1.47	4.35 ± 1.38	0.58
Mean distance AP (%)	1.44 ± 0.52	1.39 ± 0.34	0.60	1.44 ± 0.33	1.36 ± 0.35	0.33
Mean velocity ML (m/s)	0.195 ± 0.057	0.202 ± 0.061	0.33	0.201 ± .084	0.197 ± 0.070	0.80
Mean velocity AP (m/s)	0.090 ± 0.039	0.084 ± 0.026	0.72	0.087 ± 0.031	0.081 ± 0.027	0.45

WBV: Whole-body vibration; ML: Mediolateral; AP: Anteroposterior.

Motor neuron excitability

There was no significant difference in the change of the H-reflex parameters between the WBV and control condition (Table 4).

Table 4. Comparison of changes (post- minus pre-intervention) in H-reflex parameters between the two conditions. Data are presented as mean ± SD.

Parameters		WBV condition	Control condition	p-value
Amplitude (μV)	H-reflex	- 0.85 ± 0.88	- 0.42 ± 1.29	0.26
	M-wave	- 0.05 ± 1.42	- 0.32 ± 1.36	0.79
H / M ratio		- 0.075 ± 0.10	+ 0.006 ± 0.17	0.17

WBV: Whole-body vibration

Within the WBV condition, the amplitude of the H-reflex showed a significant decrease after the intervention ($p<0.05$), and there was a tendency toward a significant decrease in the H/M ratio ($p=0.08$) (Table 5).

Table 5. Comparison of H-reflex parameters before and after intervention within the two conditions. Data are presented as mean ± SD.

Parameters	WBV condition			Control condition		
	Before	After	p-value	Before	After	p-value
Amplitude H-reflex (μV)	3.22 ± 1.62	2.37 ± 1.35	**< 0.05**	3.58 ± 1.54	3.16 ± .90	0.37
Amplitude M-wave (μV)	13.03 ± 4.86	12.98 ± 5.09	0.64	13.82 ± 4.98	13.50 ± 4.52	0.30
H / M ratio	0.267 ± 0.16	0.192 ± 0.08	0.08	0.264 ± 0.06	0.270 ± 0.16	0.51

WBV: Whole-body vibration

Relationships in the WBV condition

None of the correlation coefficients between the change of postural stability and motor neuron excitability parameters were significant; the absolute values of the coefficients ranged from 0.00 to 0.40 ($0.22<p<0.99$).

Discussion

To our knowledge, this is the first study to examine the immediate effects of a single bout of WBV on both objectively measured postural stability and motor neuron excitability. Other studies on the effects of WBV did not include postural stability and motor neuron excitability, and mainly focused on long-term effects or assessed postural stability subjectively.

In the present study there were no significant immediate effects of WBV on postural stability parameters. This is in contrast to our expectation that WBV would lead to improved postural stability expressed by less sway of the CoP. This expectation was based on, for example, the study of Priplata et al.[18] who found that application of vibration resulted in a reduction of sway parameters in both young and elderly participants. However, we should mention that these authors used a different method of vibration, i.e. their subjects were fitted with a pair of vibrating sandals. Thus, use of a different method of vibration and a different frequency (90 Hz compared to our 30 Hz) might explain the difference in results. In line with Priplata et al., Van Nes et al.[19] concluded that WBV might be a promising candidate to improve proprioceptive control of posture. However, their results were not significant, and their study population consisted of stroke patients rather than healthy elderly subjects.

Our results are in agreement with those of Torvinen et al.[20] and Carlucci et al.[21] who objectively explored the acute effects of WBV on postural stability in healthy subjects. They concluded that a single bout of WBV (of 4 or 9.5 min duration) does not induce changes in postural stability and muscle performance, such as isometric lower limb extension strength, jump height, and EMG activity of some muscles. Despite the similarity between their results and ours, it should be noted that they also used a different device, different settings, and a different exercise protocol. Therefore, we feel this precludes a direct comparison between those studies and ours. In future research, standardization of the device settings and of the training protocol will help facilitate comparison of data.

The original hypotheses of our study were based on the results of studies that focused on the long-term effects of WBV-based training programs (≥ 6 weeks). As most of those studies reported improvements in postural stability[13,16-17,31], we assumed that beneficial short-term effects would also be found. There are several possibilities for the discrepancy between the results of those studies and ours. First, in the training studies the effects were assessed by clinical tests such as the Tinetti and the Blind Flamingo test, and not by posturography based instruments such as force plates. Moreover, in those studies the interventions differed regarding the type of device, the settings (e.g. of frequency and amplitude), duration of exposure to vibrations, and the posture of the subject involved. The influence of these factors has been reported by, for example, Abercromby et al.[32], that reported that the neuromuscular responses of the vastus lateralis, gastrocnemius, and tibialis anterior muscles toward vibration depend on the knee angle. In earlier studies, the effects of WBV were examined in both training studies (consisting of several sessions of WBV and focusing on the long-term effects), and in short-term studies focusing on the immediate effects of one session. In our study we decided to determine the acute effects (instead of the training effects) of WBV on postural stability for several reasons. First (as described above), we assumed that the long-term effects would also be found in the acute effects. Also, due to the uncertainty about the effects of WBV, a training study was not considered to be the most efficient approach. Second, an important characteristic of our study was its focus not only on the effects of WBV on postural control, but also on its mechanism of action. For this, we felt that a single-bout intervention would be the most appropriate.

Besides immediate effects on postural stability, we also expected to detect a significant effect of WBV on the H-reflex parameters, such as the amplitude of the H-reflex and the M-wave, and the H/M ratio. Increasing the excitability of the monosynaptic reflex should lead to an increase in the amplitude of the H-reflex and a higher value for the H/M ratio. However, our results showed no significant differences between the control and vibration conditions. Nevertheless, an interesting finding of our study might be that, following exposure to WBV, the amplitude of the H-reflex showed a significant reduction of about 26%. Accordingly, the H/M ratio also showed a tendency to decrease (-28%; p=0.08). This may suggest some inhibitory effects of WBV instead of activation of the monosynaptic reflex; this is in line with Armstrong et al.[29] who also found suppression of the H-reflex following exposure to WBV.

We also assumed that the effects on postural stability would be related to changes in motor neuron excitability. However, we found no relationship between the force plate and H-reflex parameters. This might indicate that no relationship exists between these two constructs. Nonetheless, we feel that such a putative relationship is worth investigating in the future.

There are numerous ongoing discussions about the efficacy and working mechanisms of WBV. We assumed that WBV, as the primary candidate for somatosensory stimulation, exerts its effect through the following sequence of events: 1) stimulation of muscle spindles; 2) activation of the tonic vibration reflex; and 3) involuntary contraction of muscles resulting in increased postural stability. However, the present results do not support such a scenario and, as discussed above, there is even a tendency for suppression of the H-reflex. The physiological mechanisms that might be responsible for that effect are reciprocal inhibition and pre-synaptic inhibition. Some studies showed that exposure to WBV can elicit a certain level of pre-synaptic Ia inhibition[24-25], which breaks the further recruitment of motorneurons. Moreover, Shinohara et al.[26] reported that prolonged vibration modulates Ia feedback and motor unit activity, which leads to reduced peak force during maximal contractions. Many factors may influence the direction and magnitude of the effects of WBV (e.g. the duration of exposure to WBV) and additional studies are needed to elucidate the precise mechanisms of WBV.

The present study has some limitations. First, although we tried to assess H-reflex and postural stability as quickly as possible after the intervention, it necessarily took some time before postural stability could be assessed. Therefore, a short-term effect of WBV on postural stability could have been missed; however, such a timing effect on postural stability could not have been large. Second, although the study sample might have been too small to detect effects, the data do not suggest that a larger sample would have changed the main conclusions of our study. Third, we used only one setting (30 Hz and 2 mm) and did not try another paradigm (such as a high amplitude combined with the same frequency); it is possible that different settings will produce different results. Finally, fatigue may influence both postural stability and motor neuron excitability parameters. However, we feel that in our study the inhibition was not due to fatigue, because the amplitude of the M-response was not changed. If inhibition is due to fatigue, one would expect a reduction in the amplitude of the M-response in the same direction as the H-reflex[33].

Practical applications

The results of this study do not support the hypothesis that a 2-min period of exposure to whole-body vibration has immediate beneficial effects, i.e. an improvement of postural stability and an increase of motor neuron excitability. Additionally, a relationship between the effects on postural stability and motor neuron excitability could not be supported. Future research should focus on the role of settings, such as high amplitude combined with low frequency, and on the effects of a vibration training program on postural stability and motor neuron excitability.

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Chapter 7

Acute effects of whole-body vibration on spasticity of calf muscles in chronic stroke patients

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Submitted

Abstract

To investigate the acute effects of a single bout of whole-body vibration (WBV) on spasticity of the calf muscles, assessed by clinical and electrophysiological measurements in patients in the chronic phase after stroke.

Twenty one patients with chronic stroke (7 females and 14 males; age 60.6±10.8 years) in a single blind crossover study were included.

Measurements were made for each patient on two separate days with a one-week interval. Patients were exposed to a vibration platform (PowerPlate). For the first session, patients stood on the device for 3 min while the device was turned on ('Standing with WBV' intervention; 30 Hz and 2-mm amplitude). The second session included two interventions with a 1-h interval: first, the patient stood on the device for 3 min while it was switched off ('Standing without WBV' control intervention). After a 1-h rest, patients sat on the table with their feet on the platform while the device was turned on with the same settings as used previously ('Sitting with WBV' intervention). The order of the sessions/days was randomly determined. Clinical assessments (including passive ankle dorsiflexion, Tardieu test with knee extended and flexed), and an electrophysiological test (including Hoffmann's reflex recording of the soleus muscle) were made as quickly as possible before and immediately after each intervention.

Ankle dorsiflexion improved and one of Tardieu values - with knee extension - showed a significant increase in the Sitting with WBV intervention compared with the control intervention. No difference was found between the Standing with WBV intervention and the control intervention. In none of the interventions an effect was found on the electrophysiological parameters.

In the patients with chronic stroke, sitting with the feet on a vibrating platform improved ankle dorsiflexion and Tardieu score compared to standing without vibration. These clinical effects were not supported by electrophysiological measurements.

Introduction

Stroke is one of the most common causes of complex disability[1-4]. It is reported that (in both genders) the incidence of stroke increases with each decade of life[5]. Each year in the Netherlands, about 41,000 people have a first stroke[6]. After stroke, many patients have difficulty with walking because of less effective dorsiflexion in the ankle during gait. This problem can be due to an inability to activate the ankle dorsiflexors, and/or to spasticity in the calf muscles[7-8]. Prevalence of spasticity in stroke patients is 19-38%[9-10], and it is estimated that about 20% of stroke survivors have a spastic drop foot[11].

Reduction of spasticity to restore normal gait is a common and important treatment goal in stroke patients suffering from a spastic drop foot. Various types of treatments such as spasmolytic drugs[7,12], electrical stimulation[13-16], ultrasonic therapy[17-18], and surgical procedures[19-20] are reported. However, some current treatments have not been proven effective and/or show many complications[21]. Therefore, there is still need for a clinically applicable, non-invasive and effective treatment of spasticity.

Whole-body vibration (WBV) might be an option in spasticity treatment. WBV has become popular in clinics and fitness centers due to several benefits ascribed to its use. Although the results of WBV studies are not unequivocal, positive effects on muscle strength[22-23], flexibility[24], and performance measures such as jump ability[25-26] have been reported. To date only a few studies have focused on the effects of WBV on spasticity. One study showed a significant reduction in quadriceps spasticity in patients with spinal cord injury after participation in a WBV intervention that lasted for at least 8 days[27]. In another study with adults with spastic diplegia, WBV was associated with improvements in muscle strength without adverse effects on spasticity of the knee extensor muscles[28]. However, a study on patients with multiple sclerosis showed that muscle tone (measured by the Modified Ashworth Scale; MAS) was generally unaffected by training with WBV[29]. Therefore, there is lacking evidence of the effects of WBV on spasticity. Additionally, effects of WBV in stroke patients to reduce spasticity have not been studied.

Besides the clinical outcome measures, such as passive range of motion and spasticity tests such as the Tardieu test, measurement of the soleus Hoffmann's reflex (H-reflex) can be done to assess spasticity. The H-reflex measurement is a reliable and accepted way to evaluate the excitability of alpha motoneuron electrophysiologically[30-31]. Physiologically, spasticity is caused by an exaggerated monosynaptic stretch reflex[32-33]; therefore, inhibition of the reflex is a priority in the treatment of spasticity. In WBV, it is assumed that vibration leads to inhibition of Ia afferent fibers via mechanisms of both pre-synaptic inhibition and reciprocal inhibition[34-35]. This inhibiting effect of vibration is supported by some data. For example, Ashby et al.[36] concluded that local vibration leads to pre-synaptic inhibition of Ia afferents. Schieppati and Crenna[37] also found that the H-reflex during induction of tonic vibration reflex unloaded in muscles was lower than control values. In a previous study of our group *(Chapter 6)*, exposure to a single bout of WBV in older individuals showed a tendency to lower H-reflex amplitude in the soleus muscle. Therefore, WBV might be an effective therapeutic intervention to inhibit the stretch reflex and, in this way, to decrease spasticity.

One of the issues in WBV is the question of using a loaded or unloaded posture in persons who might benefit from this intervention. However, especially among stroke patients, a loaded posture might be difficult to achieve or may cause them to feel insecure or uncomfortable. Furthermore, it is assumed that somato sensory stimulation of receptors via the feet in spastic stroke patients may be enough to reduce spasticity. WBV is suggested to be an appropriate modality to generate effective somato sensory stimulation, so it can potentially reduce spasticity of lower limbs in stroke patients without loading. Therefore, it is relevant to obtain knowledge on the difference in effects between a loaded and unloaded position.

The research questions of the present study are:

1) Does a single bout of WBV reduce spasticity of calf muscle in stroke patients?
2) Is there a difference between loaded and unloaded WBV in effects on spasticity of calf muscle in stroke patients?

Methods and materials

Subjects

In a single-blind cross-over study, 21 subjects [7 females and 14 males; age 60.6±10.8 years; height 171.9±7.9 cm; weight 75.1±12.2 kg; Modified Ashworth Scale (MAS) 2.9±0.4)] with diagnosis of stroke were included. Of the 21 patients, 18 were right handed and 10 suffered from paralysis of the left side. Inclusion criteria were single stroke (at least 9 months previously), ability to stand on the vibration platform whilst grasping the handles of the device with two hands, and having a MAS score of 2-4 in the ankle plantar flexors. Exclusion criteria were: 1) non-stroke-related sensory or motor impairments, 2) concomitant cognitive problems that impaired the ability to follow simple verbal instructions, and 3) contraindications for WBV such as discopathy, recent fractures, gallbladder or kidney stones, malignancies, acute systemic infection, and cardiac pacemaker. Before the first session, the subjects were informed about the study and provided informed consent. The study was approved by the Medical Ethics Committee of the Erasmus MC.

Protocol

Each patient was measured on two separate days with a one-week interval in between and served as his/her own control. Patients were instructed on how to use the vibration platform (PowerPlate international, Model: Next Generation, USA). For the first session, patients stood on the device with 15 degrees of knee flexion whilst grasping the handle of the device and keeping the feet parallel to each other. Vibration was given for 3 min at 30 Hz with a 2-mm amplitude (Standing with WBV intervention). During the Standing interventions, two persons were standing on either side of the patients to protect him/her and to avoid the risk of falling. The second session comprised two interventions performed with a 1-h interval in between. First, the patient stood on the device in the above-described posture for 3 min while it was switched off (Standing without WBV; control intervention). After a 1-h rest, patients were asked to sit on the edge of the table in front of the WBV device and put their feet on the platform while the device was turned on with the same settings and for the same duration as standing position (Sitting with WBV intervention). We adjusted the height of the table to have 90 degree flexion in knee and hip during exposure to WBV. The sequence of the days was determined in random order (Figure 1). The examiner who performed the measurements was blinded for the intervention.

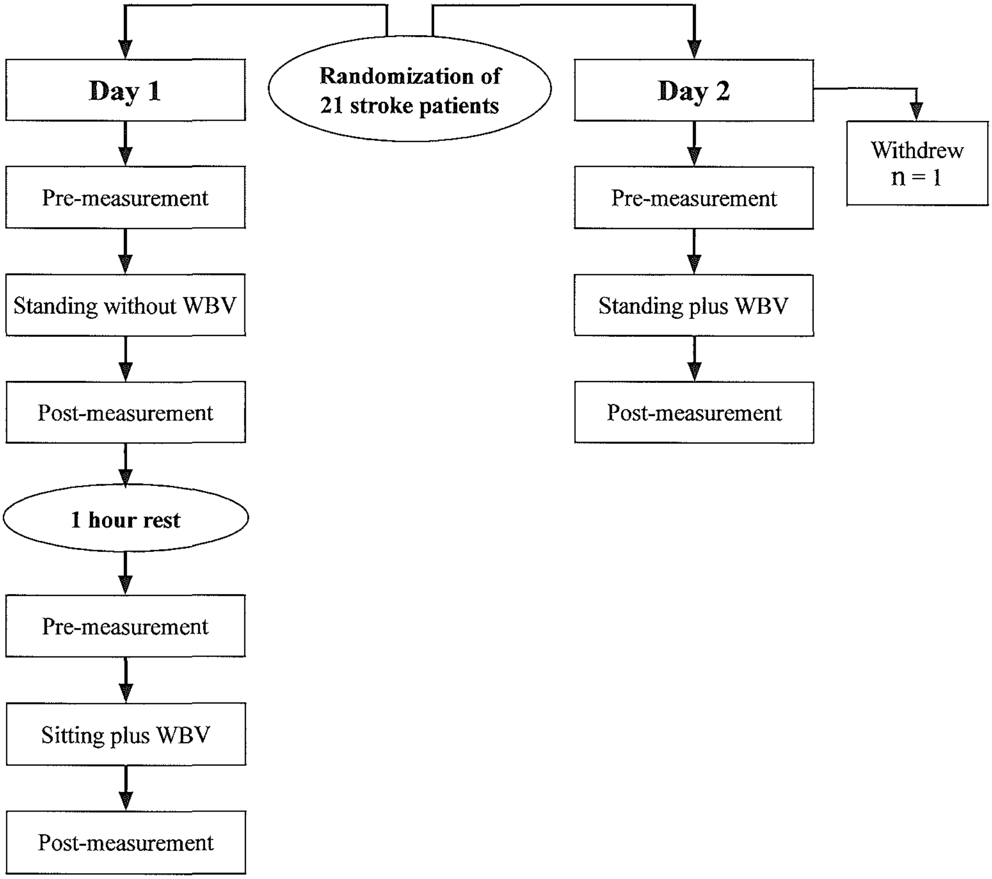

Figure 1. Sequence of the treatment sessions on two separate days with a one-week interval.

Measurements

The pre-measurements were done as quickly as possible before the intervention and the post-measurements were done immediately after each intervention. Clinical measurements were always done after the electrophysiological measurements.

Electrophysiological measurement

A two-channel EMG device was used for the electrophysiological measurements. All measurements were done with the subject in prone position. If subjects could not lie in the prone lying position, the measurement was done in the side lying position. Standard 11-mm stainless steel surface-electrodes covered with conductive paste were used for all recordings. The active electrode was placed over the belly of the soleus muscle; on the midpoint between the popliteal crest and medial malleolus, and the reference electrode was over the Achilles tendon. A ground electrode was placed over the upper gastrocnemius muscle. Electrical stimuli were applied with bipolar surface-electrodes. H-reflex was evoked from the soleus muscle, by stimulating the posterior tibial nerve at the popliteal fossa. Rectangular electrical shocks with 1-ms duration were applied, and the intensity was adjusted to obtain the largest H-reflex response. Peak-to-peak amplitude of the H-reflex and peak-to-peak amplitude of the M-wave were recorded. The following outcome measures were calculated:

- The peak-to-peak amplitude of the H-reflex (H-amplitude)
- The peak-to-peak amplitude of the M-wave (M-amplitude)
- The ratio of H-amplitude to M-amplitude (H/M ratio)

Clinical measurements

Passive ankle dorsiflexion

Passive dorsiflexion of ankle was assessed before and after each intervention by goniometry (Lafayette instrument, model 01135). Examination was done while the subject was lying in supine position, while their hips and knees were positioned in 90 degree flexion. This position was supported by an adjustable stool, which was placed under the legs of the patient. The degrees the ankle joint could be moved passively into dorsiflexion from neutral position was measured.

Tardieu test

The second clinical outcome measure was derived from the Tardieu test. The test was done twice in the supine position, head in midline; once with the hip and knee in 90 degree flexion and once with the hip and knee extended. The test was only done in the affected leg. The examiner tried to move the ankle as fast as possible and then record the catching angle by the goniometry.

Statistical analysis

Differences in change scores between interventions were non-parametrically tested (Wilcoxon Test). The same test was also used to examine differences in pre- and post-intervention data for each intervention. All analyses were performed with SPSS (17.0.01). A result was considered statistically significant when the p-value was ≤ 0.05.

Results

Of the 21 included participants, one patient was excluded because of discomfort and fear related to the vibration. The remainder of the participants completed the measurements successfully. However, in four patients the response of H-reflex was lacking. There were no reports of any adverse side-effects of exposure to WBV.

Clinical outcome measures

Table 1 shows the change scores and the comparison between interventions. Ankle dorsiflexion improved and Tardieu values with knee extension increased significantly more in the Sitting with WBV intervention than in the control intervention (Standing without WBV) ($p<0.05$). Other data showed no significant differences between interventions.

Table 1. Change scores (post- minus pre-intervention) of clinical parameters within the interventions and the comparison between interventions. Data are expressed as mean ± SD; p-values are given between brackets.

Parameters	Difference within interventions			Difference between interventions		
	Standing - WBV	Sitting +WBV	Standing +WBV	Standing-WBV vs. Sitting+WBV	Sitting+WBV vs. Standing+WBV	Standing-WBV vs. Standing+WBV
Ankle dorsiflexion (°)	0.0 ± 1.7	1.4 ± 1.2	0.8 ± 2.4	-1.4 ± 2.2 **(0.007)**	0.6 ± 3.1 (0.36)	-0.8 ± 2.4 (0.13)
Tardieu Ext. (°)	1.2 ± 2.5	1.7 ± 2.2	1.2 ± 2.7	-0.5 ± 1.7 **(0.03)**	0.5 ± 3.4 (0.28)	0.0 ± 3.8 (0.95)
Tardieu Flx. (°)	0.9 ± 2.9	1.7 ± 1.9	1.8 ± 4.0	-0.8 ± 2.8 (0.15)	- 0.1 ± 4.2 (1.00)	-0.9 ± 4.1 (0.32)

WBV: Whole-body vibration; Tardieu Ext: Tardieu test with knee extension; Tardieu Flx: Tardieu test with knee flexion.

Table 2 shows the pre-post data of the clinical parameters of each intervention. Within the Sitting with WBV intervention all clinical parameters showed a significant change. The Tardieu score with knee extension also showed a significant increase within the other two interventions. Other data showed no significant pre-post effects.

Table 2. Comparison of clinical parameters before (Pre) and immediately after (Post) each intervention. Data are expressed as mean ± SD.

Intervention	Ankle dorsiflexion (°)			Tardieu (knee extended) (°)			Tardieu (knee flexed) (°)		
	Pre	Post	p-value	Pre	Post	p-value	Pre	Post	p-value
Standing -WBV	8.3 ± 3.1	8.3 ± 2.8	1.00	22.4 ± 8.6	23.6 ± 7.9	**0.047**	29.4 ± 6.1	30.3 ± 5.5	0.20
Sitting +WBV	8.0 ± 3.3	9.4 ± 3.5	**<0.001**	23.4 ± 7.1	25.1 ± 6.7	**<0.001**	29.7 ±6.5	31.4 ± 6.7	**<0.001**
Standing +WBV	8.6 ± 4.0	9.4 ± 3.6	0.13	20.6 ± 7.1	21.8 ± 6.7	**0.049**	27.7 ± 7.2	29.5 ± 8.0	0.06

WBV: Whole-body vibration

Electrophysiological outcome measures

The change scores of H-amplitude, M-amplitude and H/M ratio showed no significant difference between the interventions (Table 3). The pre-post differences of these parameters within each intervention were not significant too (Table 4).

Table 3. Change scores (post- minus pre-intervention) of electrophysiological parameters of the interventions and the comparison between interventions. Data are expressed as mean ± SD; p-values are given between brackets.

Parameters	Difference within Interventions			Difference between interventions		
	Standing - WBV	Sitting +WBV	Standing +WBV	Standing-WBV vs. Sitting+WBV	Sitting+WBV vs. Standing+WBV	Standing-WBV vs. Standing+WBV
H-Amplitude (μV)	- 0.12 ± 1.24	- 0.08 ± 1.02	- 0.10 ± 1.02	0.04 ± 1.59 (0.91)	- 0.02 ± 1.42 (0.95)	- 0.02 ± 1.54 (0.94)
M-Amplitude (μV)	- 0.15 ± 2.58	- 0.48 ± 2.26	- 0.23 ± 2.43	- 0.33 ± 3.44 (0.56)	0.25 ± 3.03 (0.57)	- 0.08 ± 3.09 (0.92)
H/M ratio	- 0.002 ± 0.14	0.059 ± 0.09	0.005 ± 0.12	0.061 ± 0.13 (0.83)	- 0.054 ± 0.14 (0.40)	0.007 ± 0.12 (0.43)

WBV: Whole-body vibration

Table 4. Comparison of electrophysiological parameters before (Pre) and immediately after (Post) each intervention. Data are expressed as mean ± SD.

Interventions	H-Amplitude (µV)			M-Amplitude (µV)			H / M ratio		
	Pre	Post	P-value	Pre	Post	P-value	Pre	Post	P-value
Standing -WBV	3.77 ± 3.05	3.65 ± 3.02	0.67	13.13 ± 5.42	12.98 ± 4.83	0.80	0.307 ± 0.251	0.305 ± 0.267	0.95
Sitting +WBV	3.38 ± 2.71	3.30 ± 2.52	0.72	13.09 ± 4.50	12.61 ± 5.65	0.37	0.254 ± 0.180	0.313 ± 0.276	0.31
Standing +WBV	3.54 ± 2.60	3.44 ± 2.62	0.68	12.84 ± 5.30	12.61 ± 4.15	0.68	0.271 ± 0.189	0.276 ± 0.196	0.88

WBV: Whole-body vibration

Discussion

To our knowledge this is the first study to investigate the immediate effects of short-term WBV on spasticity of the calf muscle, assessed by clinical and electrophysiological measurements in patients in the chronic phase after stroke. Application of WBV in a sitting position resulted in a significant improvement in the dorsiflexion and an increase in one Tardieu score of the ankle. With the exception of the Tardieu score with knee flexed, the change scores of this intervention were different from the control intervention with WBV in the standing position. Other change scores (for clinical and electrophysiological parameters) did not differ between the interventions.

Electrophysiological measurements showed that exposure to a single bout of WBV had no significant effect on the amplitude of the H-reflex and M-response in any intervention session. Although a few studies investigated the effectiveness of WBV on H-amplitude, these studies were performed in healthy subjects. For instance, Kipp et al.[38] observed reduction of H-amplitude, 1 min after exposure to a single bout of WBV. Similarly, Armstrong et al.[39] showed that subjects had a significant suppression of the H-reflex during the first minute after WBV. The difference between healthy subjects and those with stroke might be caused by physiological and morphological differences between intact and spastic muscles. In contrast to studies[38-39] reporting a depression of the H-reflex immediately after WBV, we found no suppression of the H-reflex in our study. It is assumed that the main mechanism responsible for the suppression of the H-reflex (post-activation depression) depends on the vibration frequency and, as a result, on the number of muscle contractions per second[40]. It might be that the results of our study are influenced by the selected vibration frequency of 30 Hz. Additionally the difference in sensitivity of the muscle spindle between stroke patients and healthy subjects might be another reason that we did not find the same results. Further studies need to focus on identifying the optimal frequency and amplitude of WBV in patients with upper motor neuron lesions who are suffering from spasticity.

The only study aiming at spasticity was done by Sayenco et al[41], and included persons with spinal cord injury (SCI). That study revealed that WBV during passive standing caused significant inhibition of the soleus H-reflex in male participants both with and without SCI[40]. The potential reasons of these different results compared to our study might be that in that study the H-reflex was measured during, and not after vibration. Additionally, the physiological responses on WBV may differ because of the different pathology between SCI and stroke patients. Future research may include H-reflex measurements both during and after exposure to WBV, and will thus elucidate whether or not this timing issue plays a role.

A novel aspect of our study is comparison of the acute effects of WBV on spasticity of calf muscles between a loaded and an unloaded position. Since unloaded position is safer and more comfortable for disabled people, such as stroke patients, it could be more practical to use WBV training in this way. The interesting finding of our study was that in the unloaded condition with WBV the effects were significantly larger than in the loaded condition without WBV. In the literature, we have found no studies about the effects of WBV in different positions related to spasticity in neurologic disease. Although our results show effectiveness of WBV in the unloaded position on spasticity of calf muscles in terms of clinical assessment, the results were not supported by the electrophysiological measurements. Additionally, we found no difference in electrophysiological outcomes between the Sitting with WBV intervention and the Standing with WBV intervention. The positive effects on the clinical outcomes might be explained by the effect that in the standing position with WBV the subjects lean more on their intact leg and subsequently there is less somatosensory stimulation and less orientation of the brain towards the affected leg. As a result, the modulation of postural reflexes in standing position might be less than in sitting position.

The present study has some limitations. Firstly, although we tried to assess H-reflex immediately after exposure to vibration, there was a time gap between the end of the exposure and the post-measurements. For the clinical measurements this was even more present; we did the clinical measurements as quick as possible after the H-reflex measurements, but some delay was unavoidable. This might have affected the results. Secondly, we are aware that manual measurement of the ankle joint (dorsiflexion and Tardieu test) by goniometry may not be responsive enough. However, we performed these measurements in such a way that reliability was optimized as much as possible. Finally, the sample size was not very large. However, our sample size is similar to that of comparable studies and a larger sample size would probably not have influenced the main conclusions of our study.

Conclusion

Exposure to a single bout of whole-body vibration in a sitting position has a beneficial effect on clinical outcomes, also when compared to a control intervention with standing without whole body vibration. However, electrophysiologically no effects of and differences between interventions were found.

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Chapter 8

General discussion

Main findings

Whole-body vibration (WBV) is a therapeutic and training method that is increasingly used in physical therapy and rehabilitation departments. However, the effectiveness and the underlying mechanisms of WBV are still frequently debated, despite the studies that have already investigated these issues. This thesis aims to add new knowledge to the controversial topic of WBV. To this end we have performed a systematic literature review, compared different WBV devices, and examined the acute effects of WBV on neuromuscular performance and balance in both healthy subjects and stroke patients.

The literature review in *Chapter 2* explores the effectiveness of WBV training on neuromuscular performance in patients with neurologic disorders. Based on this review we concluded that there is no evidence, or only conflicting evidence, for the effectiveness of WBV. The review also indicates that the number of studies (RCTs and CCTs) is relatively small, and that the populations and outcomes were diverse, as were the interventions and control conditions. Moreover, although the methodological quality was high according to Furlan's criteria, they generally had some methodological and/or statistical flaws. Well-designed studies are needed to allow final conclusions to be drawn about the effectiveness of WBV training in neurologic patients.

Chapter 3 focuses on the technical differences between currently available vibration platforms and their technical characteristics. We showed that in the preset frequency (25 Hz), two professional devices (PowerPlate and Galileo) evoked the highest accelerations compared to a home-use device (PowerMaxx). Furthermore, this study showed that in the professional devices loading does not affect their mechanical behavior, such as amplitudes of accelerations.

In *Chapter 4* we focused on differences between these devices in the acute effects on jump force and in *Chapter 5* we compared them with regard to their acute effects on neuromuscular response of vastus lateralis muscle. From these studies it was concluded that the different devices do not result in significantly different effects following exposure to vibration for 15 seconds and for 40 seconds.

One of the reported effects of WBV is related to postural stability and motor neuron excitability in older individuals. In the study presented in *Chapter 6* we examined the immediate effects of a single bout of WBV on these parameters, measured with a force plate and with electromyography. However, we found no significant effects on postural stability and motor neuron excitability. Finally, *Chapter 7* describes the effectiveness of a single bout of WBV on spasticity of the calf muscle in patients with chronic stroke. Again, there were no significant differences in the electrophysiological parameters between the three interventions, i.e. either standing or sitting with WBV, and standing without WBV as control condition.

Overall, the experimental studies included in this thesis (focusing on the immediate effects of WBV) do not show any significant effects of WBV. As a result, we have to conclude that these results do not support the application of WBV when improvement of neuromuscular performance, balance or reduction in spasticity is the aim of treatment. An important problem related to WBV is the large number of factors that might influence its effectiveness, such as therapeutic goal, characteristics of WBV, clinical outcomes, target population, acute or training effects, and treatment protocols. Although unequivocal and positive results would have made general discussion of the studies easier, we present our thoughts about the relevant items and results in the following sections.

Characteristics of whole-body vibration

WBV is in fact a periodic change in displacement of the body (or parts of the body) with respect to a fixed reference point of the body position. Treatment generally consists of static or dynamic exercise on a vibrating platform; however, the vibration characteristics differ considerably because the various devices have different characteristics. Therefore, differences in the devices settings (frequency, amplitude and type of vibration), interventions (differences in duration of exposure and loaded or unloaded condition) may, to some extent, explain the conflicting results associated with WBV. Table 1 lists the characteristics of the most commonly-used devices· They differ in frequency range, maximal acceleration, vertical displacement (amplitude), and type of vibration. It is possible that the mechanical behaviour of the devices affects the physiological changes occurring in the human body. In our technical study (*Chapter 3*) we aimed to identify the mechanical characteristics of each device.

Table 1. Characteristics of the whole-body vibration devices used in the studies.

Device	Frequency (Hz)	Maximal acceleration (m/s^2)	Vertical displacement (mm)	Type of vibration
PowerMaxx	22 – 34	~20	0 – 2	Horizontal vibration
Galileo	5 – 40	~130	0 – 6	Radial vibration
PowerPlate	25 – 50	~70	0 – 4	Vertical vibration

Setting of devices

Frequency

It is suggested that application of WBV at various frequency ranges may achieve different therapeutic goals. A wide range of frequencies (15-50 Hz) has been used in studies on WBV[1-5], and different results have been reported. For instance, Cardinale and Bosco[6] suggested that beneficial effects could be obtained using moderate frequencies (15-44 Hz). However, this suggestion is questionable because the use of WBV at 6 Hz[1] and also at 50 Hz[3] has shown to be effective on neuromuscular performance. In our experiments, designed to examine the acute effects of WBV on jump force *(Chapter 4)* and EMG activity of vastus lateralis *(Chapter 5)*, frequencies of 22 to 26 Hz were used. Although we did not aim to determine optimal frequencies the findings were similar in their effects where frequencies ranged from 22 to 30 Hz. Some researchers believe that the combination of frequency and amplitude plays an important role in the effectiveness of WBV; for example, it is reported that the combination of high frequency with low amplitude has the same effect as high amplitude with low frequency[7]. Nevertheless, there is no consensus about which frequency is optimal and therefore which would be more effective as therapy for the neuromuscular system.

Amplitude

Although the effectiveness of WBV seems to depend more on the amplitude of vibration than on other parameters, it is only an assumption that is still not strongly supported by scientific evidence. To date, the optimal range of amplitude to improve neuromuscular function has not been determined and a wide range of amplitude settings have been used and reported[8]. One hypothesis is that the higher the amplitude the greater the muscular activity; however, this is not widely accepted and supported, and literature is inconclusive. For example, some studies[9-11] reported that EMG activity of leg muscles during WBV is higher when a higher-amplitude is used rather than a lower-amplitude. In contrast, other studies[5,7,12-13] reported that the combination of a low-amplitude and a high-frequency (or vice versa) had maximum effects on neuromuscular performance.

Type of vibration

There are three types of vibration (Table 1): vertical vibration, radial vibration, and horizontal vibration. Although other types of vibration, such as 3-dimensional vibration are also available, our studies were performed with common types of vibration. One of our goals was to establish whether the type of vibration affects muscle performance. In two experiments, we compared WBV devices that provide different types of vibration on their effects on jump force (*Chapter 4*) and on neuromuscular response (*Chapter 5*). In those studies we found no differences in effect between the three devices, thus no effect of type of vibration. A few studies are available that focus on the comparison of vertical and radial vibration. Klarner et al.[7] compared effects of different types of WBV training on neuromuscular performance; they reported that the muscle strength of leg and trunk muscles was significantly increased in both vibration groups in comparison with the control group. A similar result was reported by Von Stengel et al.[14] who also found effects of WBV on the muscle strength of the leg irrespective of the type of vibration. However, Abercromby et al.[15] indicated that the risk of adverse health effects may be lower during radial vibration than vertical vibration. In general, more research is needed to explore the possible long-term health hazards associated with WBV.

Interventions

Duration of exposure

The duration of exposure is another parameter to be considered when the vibration is applied to improve neuromuscular performance. When the duration of exposure is excessive, muscle fatigue occurs. In their studies, Bongiovannie et al.[16] and Rittweger et al.[17] observed increased muscular fatigue when the exposure to vibration is prolonged, thus confirming this phenomenon by showing a decrease in EMG activity of the dorsiflexor muscles. Most researchers assume that positive effects of vibration can be detected if the duration does not exceed 10 minutes of total exposure in one session, with 30-90 seconds per bout. In our studies we found no effects of duration of vibration exposure. We observed that application of WBV in bouts lasting 15 and 40 seconds showed no difference in their effects on jump force and EMG activity of the vastus lateralis.

Loaded or unloaded condition

One of the important questions about the application of WBV is whether loading can influence the vibration and its effectiveness. Loading is generally created by a person's body weight whilst doing an exercise, or maintaining a body posture on the platform during vibration. In *Chapter 3*, we conducted a technical experiment to identify the role of loading on the magnitude of vibration. We measured 3-dimensional platform accelerations of three different WBV devices without loading and with volunteers of different weight in a squat position. In case of the professional devices (PowerPlate and Galileo) platform accelerations were slightly influenced by body weight, whereas the weight of the volunteers reduced the platform accelerations significantly in the home-use device (PowerMaxx). However, this study shows that conversion of horizontal vibration to vertical vibration occurs when the platform of PowerMaxx is used in a loaded condition. According to these findings, each of the investigated devices seems equally appropriate to use, although this statement may depend on the goal of treatment. For instance, to increase or maintain bone density, low acceleration is needed and then a device such as the PowerMaxx - which allows low acceleration settings - may be more suitable. In contrast, when the aim is to improve muscle strength in athletes the PowerMaxx is probably not the best choice, because the maximal acceleration is too low.

In the previous paragraph loading is discussed from the perspective of the platform. However, in addition to body mass, the load on the platform and the human body is also determined by additional weights, body postures and exercises during vibration. Here again, literature is not unambiguous. For example, Lamont et al.[18] and Preatoni et al.[19] showed that WBV exercising with additional weights do not results in additional effects on muscle force and power compared to WBV exercising without weights. Kvorning et al.[20] reported that combining WBV with conventional loaded resistance exercise for a 9-week training period in young men did not improve maximal voluntary contraction and vertical jumping ability more than either resistance training or vibration only. In contrast of the aforementioned studies, Hazell et al[21]. evaluated and reported that the detected results demonstrate the potential effectiveness of using external loads with exposure to WBV.

A novel aspect of the present thesis is the comparison of loaded (standing with WBV) and unloaded WBV (sitting with WBV) in stroke patients to show which condition is more effective on spasticity of the calf muscle. Although we found no beneficial effects of WBV (either loaded or unloaded) on spasticity of the calf muscles, the unloaded condition was effective on spasticity of calf muscles in terms of clinical measures (*Chapter 7*). Therefore, further studies should be focused on therapeutic effects of the unloaded WBV to reduce spasticity in patients with neurologic disorders.

Vibration transmission to the body

Another important issue related to WBV is understanding the vibration transmission to the body: how are the accelerations provided by the devices transmitted to the different parts of the body? Therefore, the second part of our technical study (*Chapter 3*) focused on the transmission of vibration to parts of the body close to the vibrating platform (ankle joints) and to the more proximal joints such as knee and hip. In that study, subjects were standing in squat position. We found that vertical vibrations at 25 Hz resulted in the largest accelerations in the ankle (1.8-4.2 units of g) while they were reduced 6-10 times at the knee and hip (about 0.45 unit of g). From a clinical point of view, it is important to know which part of the body is the target of treatment; too much storage of vibration energy in body parts between the platform and target should be avoided. For example, when enhancement of muscle strength in the upper body is the aim of WBV, damping may counteract the transmission of accelerations and the potential effect on muscle strength. Changing the posture to half squat, sitting, or another position may also affect the transmission. For instance, Berschin et al.[22] concluded that different postures in bipedal standing imply not only different degress of energy absorption, but also different effects on muscle performance. The degree of transmission (or damping) is also related to age. In a study by Bressel et al.[23], focusing on transmissibility of vibration in children and adults, it was shown that transmissibility in children was 42% and 62% greater than in adults for the ankle and hip, respectively.

Target population

Since the introduction of WBV, various groups of people have been studied to show the effects of this modality; these persons ranged from astronauts to athletes, young to old, healthy persons to patients, and included obese people who wanted to loose weight. Different settings and protocols were used and different results were obtained. The most important and more clinical comparisons were made between younger and older people.

Young versus older individuals

Importantly, the acute physiologic responses to WBV have been investigated more extensively in younger persons than in older people. One might speculate that the responses to WBV are mitigated in older people. There are two hypotheses about the physiologic response of the young towards WBV in comparison to older people. One hypothesis states that aging is associated with a reduction of motor neuron excitability and structural changes of the muscle spindle. These changes lead to less sensitivity to vibration because of the fiber composition and reflex deterioration in older individuals[24-25]. The other hypothesis is related to the finding that comparisons between the older and younger population consistently demonstrate that balance and other neuromuscular aspects decrease with aging. As such, the older population should have a greater potential to improve balance than young people. This analogy was proposed by Torvinen et al.[26] who reported that 8-months vibration training did not have an effect on postural sway in young adults. This paradoxical theory about the effects of vibration on muscular performance in the young compared with the elderly is still under debate and should be examined by further. Nevertheless, based on a recent systematic review in older individuals[27], vibration training appeared to improve strength, power and balance.

Acute effects vs. training effects

Another important issue is the relationship between acute and training effects. There are two main kinds of vibration studies: those focusing on the immediate effects generally following short-term exposure to WBV, and those focusing on the training effects of WBV generally following several sessions of WBV.

All the experiments presented in this thesis were aimed at determining the acute effects of WBV on neuromuscular performance (such as muscle force, postural stability, and motor unit excitability) in healthy subjects, and reduction of spasticity in stroke patients. We performed studies using short-term exposure because we were interested in the working mechanisms and because this type of study is more time and cost-effective. A third argument was that, if WBV is effective as an exercise modality, effects after short-term exposure have to be expected. However, we realize that this latter assumption remains questionable. It is possible that long-term WBV training leads to significant effects, but without immediate effects after (a few bouts in) one session. Until now no studies have explored the relationship between immediate and long-term effects of WBV.

Conclusion

Although there are indications that whole body vibration may be a potent stimulus for the neuromuscular system, the results of our studies do not indicate that short bouts of vibration result in immediate improvement of postural stability in older individuals or in a reduction of spasticity in stroke patients. Also, our literature review provided no evidence for the effectiveness of training studies in patients with a neurological disease. As a result, the work in this thesis does not support the use of vibration as an effective modality to improve neuromuscular performance in healthy persons and in people with neuromuscular disorders. However, the research field of WBV, a modality whose effects possible depend on several parameters, is still young and warrants more comprehensive and long-term research.

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Summary

Summary

Whole-body vibration (WBV) refers to mechanical energy oscillations which are transferred to the body as a whole (in contrast to specific body regions), usually through a supporting system such as a seat or platform. This modality is applied to improve muscle strength, balance, and to increase bone density and functional ability in people from different groups, including athletes and patients.

The General Introduction *(Chapter 1)* introduces WBV with a brief description of its history and development, its basic physical principles and physiological mechanisms. The Tonic Vibration Reflex (TVR) is also described, which is assumed to be the main working mechanism of WBV. Some of the conflicting results and controversies around WBV are discussed, as well as some possible explanations for them.

Chapter 2 presents a systematic review of all studies performed in recent years on the training effects of WBV on neuromuscular function in neurological patients. Although different neurological diseases are investigated in these studies, the common therapeutic goals such as muscle strength, balance ability and spasticity are common in this group of patients. Nine studies (1 CCT and 8 RCTs) on stroke (2 studies), multiple sclerosis (3 studies), Parkinson (2 studies) and cerebral palsy (2 studies) were reviewed. The results of our review do not support the effectiveness of WBV in neurological disease such as Parkinson, multiple sclerosis, stroke and cerebral palsy. For most diseases and outcomes we found either no evidence, or no studies were available. Conflicting evidence was found only for muscle strength in multiple sclerosis. However, these results should be interpreted with caution because of the small number of studies involved and the considerable heterogeneity between them.

Chapter 3 reports the findings of a technical study on healthy subjects to explore the mechanical behavior of three conventional devices of WBV: two professional devices (PowerPlate and Galileo), and one home-use device, the PowerMaxx. The first aim was to determine platform accelerations of the devices with and without loading. The measurements showed that the professional platforms vibrated in an almost perfect vertical sine wave at frequencies of 25-50 Hz (PowerPlate) and 5-40 Hz (Galileo). The platform accelerations were only slightly influenced by body weight. In case of the PowerMaxx, the platform mainly vibrated in the horizontal plane at frequencies of 22-32 Hz, with minimal accelerations in the vertical direction. The weight of the volunteers reduced the platform accelerations in the horizontal plane but amplified those in the vertical direction about eight times.

The second goal of the experiment was to determine the transmission of vertical platform accelerations of each device to the lower limbs. Therefore, eight healthy volunteers were tested in squat position. Data showed that the vertical accelerations at a preset frequency of 25 Hz was largest in the ankle, and that they were about 10 times smaller at the knee and hip. We concluded that large variations in 3-dimensional accelerations exist in the commercially available devices, that the home-used device was more sensitive to loading, and that a considerable damping of accelerations occurs within the human body.

In *Chapter 4* we studied and compared the acute effects of the three WBV devices on explosive muscle force in healthy subjects. The study aimed to examine whether or not differences in the mechanical behavior of the devices will result in different effects on jump force. In a randomized crossover study, 12 healthy subjects were included. Jump force and jump rate of force development were measured before, immediately after, and 5 minutes after finishing the intervention, i.e. exposure to WBV of 15 and 40 seconds. We found no significant differences between the devices. In conclusion, our hypothesis that WBV devices with different mechanical behaviors would lead to different acute effects on explosive muscle force was not confirmed.

Chapter 5 reports the findings of a similar experiment. Twelve healthy subjects were included to explore the acute effects of the different WBV devices on neuromuscular response of the dominant vastus lateralis muscle. We hypothesized that the different mechanical behaviors of the devices will affect the electromyography (EMG) activity of the muscle. Therefore, we used surface EMG recordings during muscle rest and at 40% of maximal voluntary contraction. The EMG measurement was done before and immediately after 15 and 40 seconds exposure to WBV. For both rest and sustained contraction measured by surface EMG, we found no significant differences in acute effects between the three devices. In conclusion, the findings of this study suggest that, when aiming to improve muscle performance following exposure to a single bout WBV, there are no differences between the professional and the home-use devices.

In *Chapter 6* we studied the immediate effects of a single bout of WBV on postural stability and motor neuron excitability in 10 healthy elderly people. In a crossover study participants were examined in two sessions; in one session they were asked to stand on a WBV device for 2 minutes whilst the device was switched on (vibration condition) and in another session it was switched off (control condition). Postural stability and motor unit excitability were evaluated before and immediately after intervention. No significant differences were found for either the force plate or H-reflex parameters between the two conditions. The only significant finding was a reduction in the amplitude of the H-reflex within the vibration condition (-26%; $p<0.05$). It was concluded that WBV does not have immediate effects on postural stability and motor neuron excitability.

Based on theory and literature, it can be hypothesized that WBV has a positive effect on spasticity. Therefore, *Chapter 7* investigated the acute effects of WBV on spasticity of calf muscles in stroke patients. A total of 21 stroke patients with calf muscle spasticity were recruited. In a crossover study, two categories of outcome measurements (clinical and electrophysiological parameters) were examined before and immediately after the intervention. Loaded (Standing with WBV) and unloaded (Sitting with WBV) interventions were compared with the control intervention (Standing without WBV). In conclusion, electrophysiological outcomes showed no significant differences between the interventions. However, ankle dorsiflexion improved and one of Tardieu values - with knee extension - showed a significant increase in the unloaded WBV intervention compared to the control intervention.

Chapter 8 presents a general discussion and the overall conclusions. Although there are indications that WBV may be a potent stimulus for the neuromuscular system, the results of our studies indicate that short bouts of vibration do not result in immediate improvement of postural stability in older individuals or in reduction of spasticity in stroke patients. In addition, the literature review does not provide any evidence for the effectiveness of training studies in patients with neurological diseases. As a result, the use of vibration as an effective modality to improve neuromuscular performance in different groups of people is not supported by this thesis. However, the field of WBV, a modality that depends on several parameters, is relatively young and warrants further comprehensive research.

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About the author

Javad Bagheri was born in Lahr in the south of Iran on 21st March 1966. After finishing high school in 1984, he entered the Shiraz University of Medical Sciences after successfully competing in an annual national examination. He started studying Physical Therapy in the rehabilitation faculty and his first BSc research project was '*The effects of needle acupuncture in patients with chronic sciatica*', under the supervision of Professor. Behruz Kazemi. In 1988 he entered Tehran University of Medical Sciences to continue his studies in the rehabilitation faculty. The author completed his studies with a Master's thesis on '*Electrophysiological studies in the normal range compared with patients with cervical spinal compression syndrome*'. In 1991 he started work at the Shiraz University of Medical Sciences teaching medical students, and in 1995 was appointed a research director and university lecturer in the Isfahan University of Medical Sciences.

In 2005 he was awarded a scholarship by the Iranian Ministry of Health to continue his studies abroad to obtain a PhD degree. To achieve this he joined the team of Professor H.J. Stam at the department of Rehabilitation Medicine & Physical Therapy, Erasmus Medical Center (Rotterdam, the Netherlands). In 2007 he started the research project '*Whole-Body Vibration*' in which several technical experiments and clinical studies were performed to establish the effect of whole-body vibration on neuromuscular performance in healthy persons and in neurological patients. These studies have led to the production of this PhD thesis.