Effects of whole-body vibration training on muscle strength and flexibility: significance of the vibration frequency

PhD thesis

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To my guardian angel Lorenzo

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Chapter 1

Introduction

1.1 Significance of the Problem

The mechanical oscillations, termed “vibrations”, was mentioned in ancient Greco-Roman as a medical technique (cited in: 50). The first application of vibration was conducted by Granville in 1881 (Cited in: 50) in the treatment of pain and subsequently employed in physical therapy to raise the excitability of the alpha and gamma motoneuron pools, thus permitting the patient to achieve greater voluntary control (52). Over the last decade the use of mechanical vibration for training purposes have begun attracting interest and many researchers have studied its effects on the physical performance of trained and untrained people (59).

Vibration is an oscillatory motion. The extent of this motion determines the amplitude of the vibration (in mm) and the repetition rate of the cycles of oscillation determines the frequency of the vibration (measured in Hz). Oscillatory motion can be produced in different forms: sinusoidal, multi-sinusoidal, random, stationary and transient. Only with sinusoidal motion it is possible to analyses the effects of different vibration frequencies due to the deterministic characteristic of this motion. Sinusoidal motion is a periodic motion, which repeats itself identically for a certain time interval termed period. The frequency of this motion is given by the reciprocal of the period and is expressed as cycles of motion per second. The S.I. unit currently utilized to define the frequency of a vibration is Hertz (Hz) (23).

There are two methods of applying vibration to the human body during exercises. In the first method, vibration is applied directly to the muscle belly or to tendon of the muscle being trained, by a vibration unit that may be held by hand or be fixed to an exterior support. In the second method, vibration is applied indirectly to the muscle being trained, that is vibration is transmitted from a vibrating source away from the target muscle, through part of the body to the target muscle. For example, vibration can be applied to the muscles of the lower extremity by a vibrating plate in a standing crouched position, so-called “whole-body vibration” or vibrating cables and dumbbells if the stimuli involves a specific muscle.

Vibrating plates currently available on the market deliver vibration to the whole body using two different systems: (1) reciprocating vertical displacements on the left and right side of a fulcrum; (2) the whole plate oscillating uniformly up and down (24).

The key difference in these methods is the magnitude of amplitude and frequency of the original vibration that reaches the target muscle. With direct vibration, the amplitude and frequency does not differ notably from the reported values measured at the vibration source. Vice-versa, with indirectly applied vibration, the amplitude and frequency may be attenuated in a non-linear manner by soft tissues during transmission of the vibration to the target muscle (59).

Vibration amplitude and frequency determine the gravitational load that vibration imposes on the neuromuscular system. In most studies, the effects of whole-body vibration have been studied using vibration frequencies from 15 to 44 Hz and displacements range from 3 to 10 mm. The acceleration values range from 3.5 to 15 g (where g is the Earth’s gravitational field or 9.81 $m \cdot s^{-2}$) (20).

In the aforementioned studies, however, the vibratory treatment used fixed pre-selected frequencies without individualizing the applied vibration frequencies to each subject.

It has been supposed that mechanical action of vibration is to produce fast and short changes in the length of muscle-tendon complex. This perturbation is detected by the sensory receptors that modulate muscle stiffness through reflex muscular activity and attempt to dampen vibratory waves (20). Wakeling et al. (97) found an elevated muscle activity and increased damping of vibration when the frequency of stimulation was close to the natural frequency of soft tissues. The latter study supports the muscle tuning paradigm and underlines the selection of the frequency as an important factor during whole-body vibration exposure.

As whole-body vibrations can produce very different responses ranging from beneficial to dangerous, it is important to define an individual frequency of vibration to activate the muscle most effectively and avoid the problems of chronic exposure to vibration stimuli highlighted in occupational medicine (23).

Therefore, the aim of this work was to analyses the effects of whole-body vibration on muscle strength and flexibility in different populations using specific frequencies of vibration.

Chapter 2

Research hypothesis

2.1 Research problem

The problem addressed in these studies was the selection of the frequency of vibration when applying whole-body vibration. Based upon the literature findings, the following research hypothesis were generated.

2.2 The effects of vibration on explosive and reactive strength when applying individualized vibration frequencies

We hypothesized that individual vibratory treatment would lead to greater explosive-reactive strength in comparison with fixed vibration treatment on trained participants and would be primarily beneficial for rebound jumps.

2.3 Effects of individualized whole-body vibration on muscle flexibility and mechanical power

We hypothesized that an individual frequency of vibration should optimize the functional activation of the primary endings of the muscle spindle which, by exerting an excitatory influence on agonist alpha motoneurones (agonist muscle contraction) and a inhibitory influence on antagonist motoneurones, would increase flexibility and reactive strength.

2.4 Low resonance frequency affects differently strength of paretic and non-paretic leg in patients with hemiplegia

We hypothesized that low frequency whole-body vibration intervention can improve muscle strength of elderly people with low physical activity level and/or neuromuscular impairment. Specifically, we hypothesized that the non-affected side is less sensitive for the low vibration frequency than the affected side and therefore the strength improvement would be greater in the paretic leg.

Chapter 3

Purpose of the studies

3.1 Effect of individualized vibration frequency

The purposes of this study were: (1) to investigate the effects of vertical whole-body vibration treatment on leg strength and power in trained male and female participants, using an individualized vibration frequency; and (2) to test whether the applied vibration intervention influences jumping ability differently when the vertical jumps are carried out with different muscle contractions and angular displacement.

3.2 Acute, acute residual and chronic effect of vibration

The aims of this study were: (1) to assess acute, residual and chronic effects of whole-body vibration on hamstring and lower back flexibility in young physically active subjects through the application of an individual frequency of stimulation; and (2) to determine whether the applied vibration intervention over time influences flexibility and reactive strength differently.

3.3 Effect of low resonance frequency

The aim of this study was to investigate the effect of low frequency, short duration whole-body vibration (WBV) on static and dynamic force production of the knee extensors.

Chapter 4

Review of the literature

4.1 Muscle Strength

Strength, or muscle strength, is the ability to generate maximum external force (73) and its measurement is used as an index of the force-generating capacity of muscle. In mechanics and physics, force is a concept that is used to describe the physical interaction of an object with its surroundings. It can be defined as an instantaneous measure of the interaction between two bodies. Force is a vector quantity characterized by magnitude, direction and point of application. Since force is an instantaneous measure and all human movements are performed over a certain span of time, the entire force-time continuum, not just the force at a given instant of time, is typically what interests coach and athletes.

The forces involved in human movement include not only the forces due to body mass and those due to the surroundings (external forces), but also the mechanical interactions within the musculoskeletal system (internal forces). Therefore, according to the aforementioned definition of strength, only external forces are regarded as a measure of an athlete's strength.

It is well-known that an active muscle exerts force on the bone while:

- shortening (concentric or miometric action),
- lengthening (eccentric or plyometric action), or
- remaining the same length (static or isometric action).

Disregarding the differences between muscle force (force developed by a muscle) and muscle strength (maximal force exerted on an external body), this classification can be used to discern variations of muscle strength. In other words, strength can be defined as the ability to overcome or counteract external resistance by muscular effort. During a concentric action, resistance forces act in the direction opposite to the motion, whereas in eccentric action, the external forces act in the same direction as the motion (100). When athletes attempt to produce maximal force, the generated force values depend on the motor task: extrinsic (external) and intrinsic (interval) factors determine these differences across tasks.

Extrinsic factors-The force exerted by an athlete on an external body depends not only on the athlete but also on external factors, in particular the type of resistance (such as elasticity, inertia, gravity force, and hydrodynamic force).

Intrinsic factors- Several intrinsic characteristic of motor tasks are important for producing maximal force. The muscle strength that an athlete can exert in the same motion depends on several variables: time available for force development, velocity, direction of movement, and body position.

Time available for force development is a crucial factor in many sport events. The time to peak force varies with each subject and with different motion; on average if measured isometrically, it is approximately 0.3 to 0.4 s. The time required to produce maximal force is typically longer than the time available for the manifestation of strength in real sport movement. The relative contribution of the maximal force in sport movement is termed the explosive-strength deficit (ESD). By definition:

$$ESD = 100(Fmax - Fd)/Fmax$$

Where Fmax is the maximal force, and Fd is the highest among the maximal forces attained in the most beneficial condition.

By definition, explosive strength is the ability to exert maximal forces in minimal time. When sport performance improves, the time of motion turns out to be shorter. The better an athlete's qualifications, the greater the role of the rate of force development in the achievement of high-level performance. Several indices are used to estimate explosive strength and the rate of force development (101).

a) Index of explosive strength (IES):

$$IES = Fm / Tm,$$

where Fm is the peak force and Tm the time to peak force.

b) Reactivity coefficient (RC):

$$RC = Fm / (Tm\ W),$$

where W is an athlete's weight. RC is highly correlated with jump jumping performance.

c) Force gradient, also called the S-gradient (S; start):

$$\text{S-gradient} = F_{0.5} / T_{0.5},$$

where $F_{0.5}$ is one half of the maximal force Fm and $T_{0.5}$ is the time to obtain it. S-gradient characterizes the rate of force development at the beginning phase of a muscular effort.

d) A-gradient (A; acceleration):

$$\text{A-gradient} = F_{0.5} / (T_{max} - T_{0.5}).$$

A-gradient is used to quantify the rate of force development in the late stages of explosive muscular efforts.

An alternative approach, is the use of vertical jump performance as expression of explosive leg strength. The vertical jump performance can be assessed measuring the vertical ground reaction forces during a jump performed on a force platform, and the entire force-time continuum (impulse) is calculated by the integral of force with respect to time as follow:

$$\text{Impulse} = \int_{t1}^{t2} F dt, \ \ [\text{N·s}],$$

where t_1 and t_2 define the beginning and end of the force application. During a vertical jump, the impulse divided by subject's body weight gives the vertical velocity of the centre of mass (COM) of the subject at take off phase (v). The vertical displacement of the COM (h) can be obtained with the following equation:

$$h = v^2 / 2g \ \ [\text{m}],$$

where g is gravity constant of 9.81 m/s^2. Alternatively, the jump height can be calculated measuring the flight time with the following equation (2):

$$h = t_f^2 \cdot 1.226, \ \ [\text{m}]$$

where time flight (t_f) is measured as the time interval between the take off phase and the toe touch on a contact mat (17).

Movement velocity influences the magnitude of the force that can be produced; the higher the velocity, the smaller the force. The force-velocity relation carried out on single muscles in laboratory conditions can be described by the hyperbolic equation known as Hill's equation (44):

$$(F + a)(V + b) = (Fmax + a)b = C,$$

where, F is force; V, velocity of muscle shortening; Fmax maximal isometric tension of that muscle; a a constant with dimensions of force; b a constant with dimensions of velocity; C, a constant with dimensions of power. Hill's equation can be rearranged to determine muscle power explicitly:

$$Fmax \cdot V = \frac{V(bFmax - aV)}{V + b}$$

On the base of the latter equation it is possible to demonstrate that power is maximum when the muscle shortens at one third of V and about one half of maximal force Fmax. The force-velocity curve can be considered part of a hyperbolic curve with the axis translate. The curvature of the force-velocity graph is determined by the ratio a:Fmax. The lower the ratio, the greater the curvature. The ratio a:Fmax varies from 0.10 to 0.60. Athletes in power sports usually have a ratio higher than 0.30, while endurance athletes and beginners have a ratio that is lower (100). Force-velocity relations in human movements are not identical to analogous curves of single muscles because they are a result of the superposition of the force outcome of several muscles possessing different features (15).

Force in the yielding phases of a motion, under conditions of imposed muscle lengthening (eccentric or plyometric muscle action), can easily exceed the maximal isometric strength of an athlete by 50 to 100%. A typical example of eccentric muscle activity can be seen in landing. As well as highest forces are generated during reversible muscle action, when the muscle is forcibly stretched and then permitted to shorten (Figures 4.1).

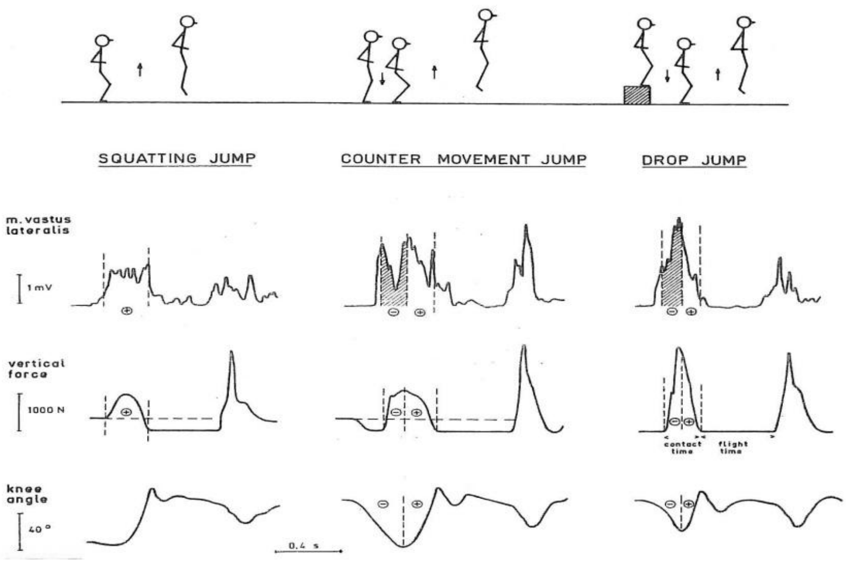


Figure 4.1. EMG activity of vastus lateralis muscle, knee angle and vertical force signals in squat jump, counter movement jump, and drop jump (from 40 cm). (From: Vitasalo and Bosco, 1982).

The magnitude of the force produced during stretch-shortening cycle and plyometric actions, as well as the magnitude of the stored and recoiled potential energy of deformation, depends on both the elastic properties of muscles and tendons and the neural control of muscle activity. The interplay of two spinal reflexes (stretch reflex and Golgi organ reflex) is considered to be a major factor toward determining neural inflow to the muscle during the stretch-shortening cycle (11, 12). In addition, the magnitude of the muscle force depends largely on body posture. For single-joint motions, joint strength curves (i.e. force-angle relations) are affected by changes in muscle-tendon forces and changes in the moment arms of these forces. In multi-joint body movements, the strongest as well as the weakest (sticking) points exist throughout the whole range of motion at which maximal (minimal) force values are manifested (101).

Individual athletes generate different maximal forces when they perform similar motions. These variations stem mainly from two factors:

- the maximal force capabilities of individual muscles, or peripheral factors;
- other factors: nutrition and hormonal status;
- the coordination of muscle activity by the central nervous system, or central factors.

Peripheral factors. It is a matter of common observation that regular high-resistance activity causes a substantial increase in muscle size after a few months of training. This has been extensively documented in the scientific literature. Investigations employing a range of scanning techniques (e.g. magnetic resonance imaging-MRI; computerized tomography-CT; and ultrasound) have typically found significant increases in muscle anatomical cross-sectional area (ACSA) over relatively short training periods (8-12 weeks) (reviewed in: 40). MRI is regarded as the superior method to determining muscle ACSA, because of its greater resolution, and has been used increasingly in the last decade. In a careful, longer-duration study, Narici et al. (cited in: 40) examined changes in muscle strength, ACSA (with MRI) and agonist muscle activation (EMG) over 6 months of standard heavy-resistance training. They demonstrate that whole-muscle growth (hypertrophy) evolved essentially in a linear manner from the onset of training, with no indication of a plateau in this process after 6 months of training. Furthermore, after the first 2 months of training, quadriceps strength and ACSA appeared to increase in parallel. However, this adaptation process is highly variable between the muscles exposed to the training and along their length. Whole-muscle hypertrophy is ascribed to hypertrophy of individual fibers by the processes of myofibrillar growth and proliferation, although hyperplasia may play a minor role. Whilst there may be an increase in the myonuclei to cytoplasm ratio by an upregulation of transcription or translation, satellite cells are activated in the very earliest stages of training. Their proliferation and fusion with existing myofibers enhances the number of myonuclei and appears to be intimately involved in the hypertrophy response. Muscle-fibers hypertrophy is typically greater in type II fibers and is accompanied by an increase in the angle of fiber pennation, which promotes a greater increase in PCSA (physiological cross-sectional area) and force production than is revealed by ACSA. These two factors are likely to contribute to increased strength and the apparent rise in whole-muscle specific tension, despite the fact that individual fiber-specific tension does not change (40).

Hormonal status. In addition to the amino acid supply, the hormonal status of an athlete plays a very important role. Several hormones secreted by different glands in the body affect skeletal muscle tissue. These effects are classified as either catabolic, leading to the breakdown of muscle proteins, or anabolic leading to the synthesis of muscle proteins from amino acids. Among the anabolic hormones are testosterone, growth hormone, and insulin-like growth factors. The predominant catabolic hormone is cortisol, which is secreted by the adrenal gland. While each hormone plays a role in anabolism or catabolism, all the hormones have multiple roles in regulating the homeostatic balance in the body and cannot be exclusively defined by their role in one physiological equation. However, the net effect of a hormone for the athlete may be either positive or negative as it relates to gains in muscle and the catabolic and anabolic balance. The concentrations of these hormones in the blood largely determine the metabolic state of muscle fibers (101). It has been hypothesized (95) that training exercises cause an accumulation of metabolites that will specifically induce the adaptive synthesis of structure and enzyme proteins related to the most active cellular structures and metabolic pathways. Among hormonal changes induced by the training session are those that amplify the inductor effect of metabolites. The hormonal influence is probably necessary to increase the rate of protein synthesis more than is needed for the usual renewal of structure and enzyme proteins. Therefore, the adaptive effect will be achieved-structures will enlarge and the quantities of enzyme molecules will be augmented (Figure 4.2). A number of results have confirmed the increased rate of protein synthesis in muscles hypertrophy (95).

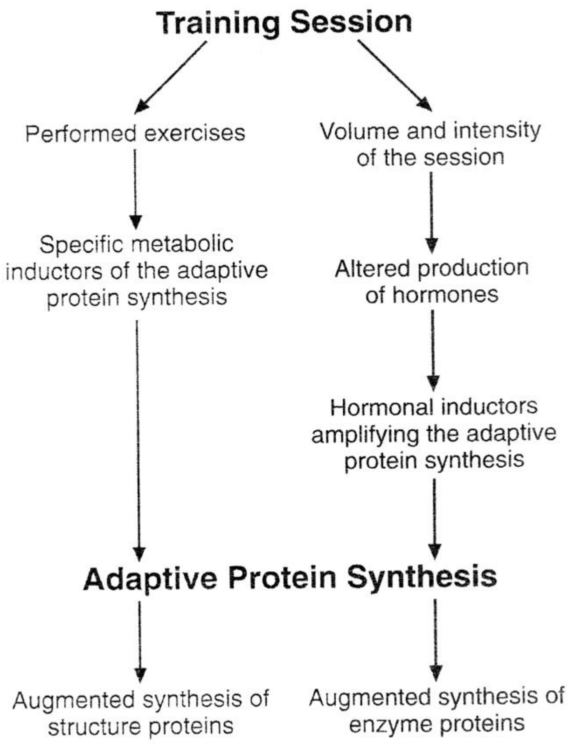


Figure 4.2. Adaptive protein synthesis triggered by training exercises (From: Viru A and Viru M, 2001).

Actually, the activity-induced increase in protein synthesis is controlled not only at the level of transcription but also at the levels of translation and posttranslational control (Figure 4.3).

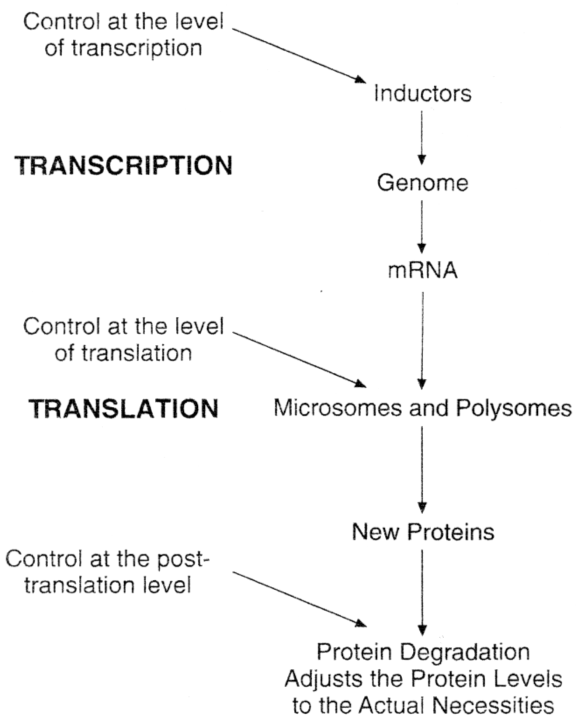


Figure 4.3. Three levels of control of adaptive protein synthesis (From: Viru A and Viru M, 2001).

Neural factors- the central nervous system (CNS) is of paramount importance in the exertion and development of muscle strength. In contrast with the morphological adaptations, considerable debate exists about the nature of the neurological changes that accompany strength training. Figure 4.4 indicates some potential sites within the nervous system where the adaptations may occur. The weight of indirect evidence (e.g. cross-over effects, task specificity, rapid gains in strength at the onset of a training program), whilst not definitive, suggest a substantial neurological adaptation that may will be predominantly due to learning and changes in inter-muscular coordination of agonists, antagonists, and synergists that facilitate improved recruitment and activation of the involved muscles during a specific strength task. More sensitive use of the interpolated twitch technique suggests that untrained individuals may not be able to fully activate agonist muscles, and this central reserve appears to depend upon a range of task-specific factors. In addition, whilst controversial, the weight of surface EMG measurements indicates an increase in agonist activation after training. Studies employing trans-cranial stimulation have found no evidence for cortical or corticospinal adaptation and are at odds with investigations of spinal reflexes that indicate an increased supraspinal drive, motoneuron excitability and a likely increase in motor unit firing frequency after training (38).

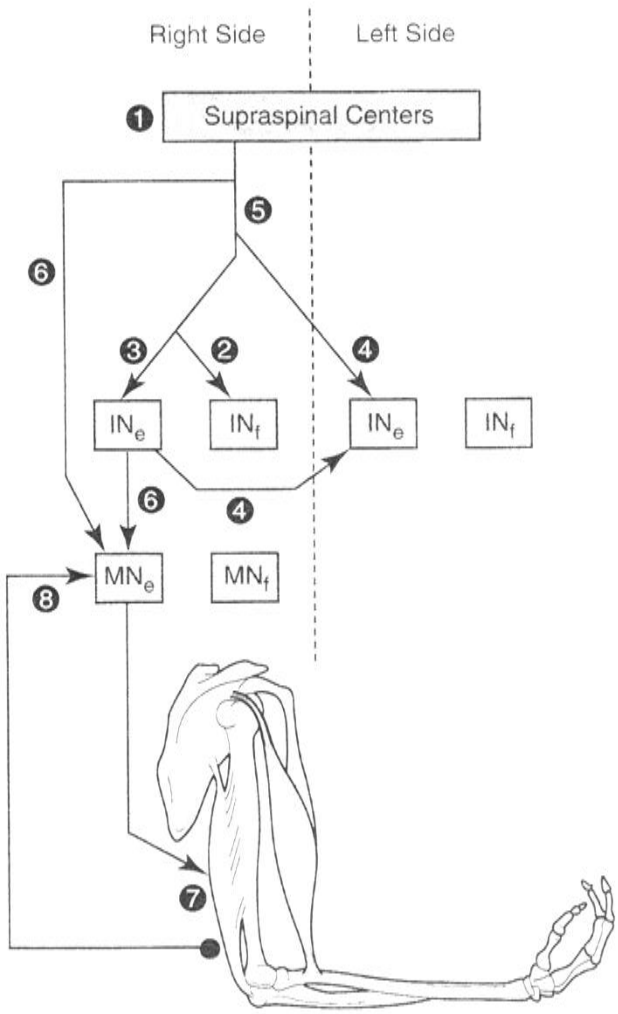


Figure 4.4. Potential sites of adaptations in the nervous system that might contribute to increases in strength: (1) enhanced output from supra-spinal centers, as suggested by findings with imagined contractions; (2) reduced co-activation of antagonist muscles;

(3) greater activation of synergist muscles; (4) enhanced coupling among spinal inter-neurons (IN) that produces cross education; (5) changes in descending drive that reduce the bilateral deficit; (6) shared input to motor neurons that increases motor unit synchronization; (7) greater muscle activation (EMG); and (8) heightened excitability and altered connections onto motor neurons (MN). The scheme indicates potential interactions between limbs (right and left side) and between extensor (e) and flexor (f) muscles (From: Enoka, 2002).

Neural versus muscular adaptation. The early increases in strength are associated mainly with neural adaptation (within the first two weeks). In contrast, progress at the intermediate and advanced stages of training may be limited to the extent of adaptations within muscles (e.g. hypertrophy) (Figure 4.5). It might be argued that specificity of movement pattern is not crucial in advanced training, because any training exercise that induces hypertrophy of the appropriate muscles would be effective. However, it would be most efficient to induce hypertrophy only in the muscle fibers of motor units that are activated in the sport movement. Hypertrophy of irrelevant muscles and motor units might even be counterproductive, particularly in sports which require a high strength to body mass ratio. Certain qualitative adaptations within muscle fibers (e.g. contractile speed) may depend upon the pattern of activation by motoneurones (e.g. high frequency bursts of impulses as in ballistic contractions). Therefore, it is important to pay attention to the nervous system and specificity even in advanced strength training (81).

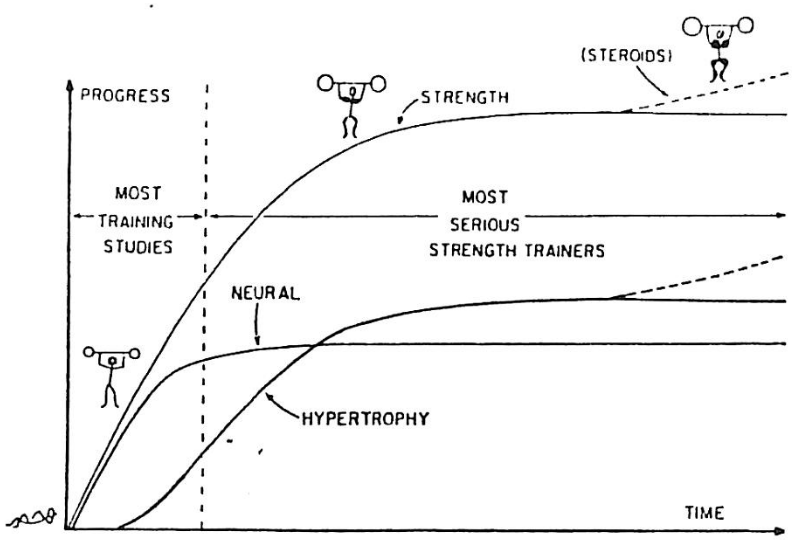


Figure 4.5. The relative roles of neural and muscle adaptation to strength training. In the early phase of training neural adaptation predominates. This phase also encompasses most training studies. In intermediate and advanced training, progress is limited to the extent of muscle adaptation that can be achieved, notably hypertrophy-hence the temptation to use anabolic steroids when it becomes difficult to induce hypertrophy by training alone (From: Sale , 1988).

4.2 Muscle flexibility

Divergent views on the importance of flexibility in injury and athletic performance are the rule. In part, debates about flexibility result from lack of consensual definitions and measurements and lack of scientific understanding about determinants of flexibility. While researchers have extensively studied endurance and strength training, they have placed less emphasis on flexibility training.

Definition of flexibility. Measures of flexibility are performed to assess the ability of skeletal muscle and tendon to lengthen. Flexibility can be both static and dynamic. Static flexibility is defined as the range of motion (ROM) available to a joint or series of joints (41). Typically, static flexibility measures are performed when the athlete is instructed to relax. Static flexibility should not be confused with joint laxity which is a function of the joint capsule and ligaments. However, it is sometimes difficult distinguish between a reduced ROM caused by a short muscle versus a tight joint capsule or arthritic joint (41). Dynamic flexibility refers to the ease of movement within the obtainable ROM. The important measurement in dynamic flexibility is stiffness, a mechanical term defined as the resistance of a structure to deformation. The converse of stiffness is compliance. Stiffness is measured by defining the slope of the load-elongation curve of a material. When the magnitude of the stretch is relatively small, force can represented by the relation for an ideal spring (Hooke's law):

$$F = k \cdot x, [N]$$

where F is the force applied, k is the spring stiffness, and x is the amount of stretch. From this equation we can derive the stiffness:

$$k = \frac{F}{x}, \ [N/m, \mathrm{J}]$$

Similarly, the modulus of elasticity (Young's modulus) which is defined as the ratio of stress (σ) to strain (ε), and represents the normalized stiffness of the tissue:

$$E = \frac{\sigma}{\varepsilon}, \ [N/m^2, Pa]$$

where σ (Pa) represents the force applied per unit area of tissue, and ε (%) indicates the change in length of the tissue relative to its initial length.

Flexibility measurements-static flexibility can be measured by a number of tests. A classic test of flexibility is the toe-touch or its gravity unassisted analogue, the sit-and-reach. These tend to be reliable measures and are indicative of vertebral and hip flexion extensibility but may be influenced by anthropometric factors. Goniometers measure ROM and also provide a continuous level variable for flexibility. Alternatively, categorical level measures (e.g. loose, normal, tight) can also be applied to the end of ROM movements such as the lotus position or Ober test. These scores can be summed to arrive at a total body flexibility score or viewed individually for the joints tested (41).

Dynamic flexibility (stiffness) can be measured either actively or passively. Passive stiffness is documented by quantifying joint angle at the same time as passive torque generation. The curve generated is in essence a force-deformation curve and the slope of the curve at any point in that ROM is the stiffness (41). Active stiffness is measured by the damped oscillation technique when a nearly instantaneous load is applied to a previously contracted muscle and the damped force versus time is plotted (41). Recently, the muscle-tendon behavior, has been investigated in vivo using the ultrasonography. This new technique have permitted studies on the in vivo interaction between muscle and tendon during activities that include also a stretch-shortening cycle. Although the technique is very attractive, and many limitations have been successfully addressed, several details have to be considered. The methods accounts for only two dimensions of structural deformation (i.e. in the sagittal plane), and cannot account for deformation in three dimensions, which may be of importance with respect to the aponeurosis (61).

Stretching techniques-a wide variety of stretching techniques are used in sports and rehabilitation programs to improve the ROM of joints. Some techniques target the viscoelastic properties of muscles and muscle-tendons unit (static stretching), whereas others target neurophysiologic reflexes, such as proprioceptive neuromuscular facilitation (PNF) techniques and ballistic stretching (3). From the PNF techniques have been derived three exercises (38):

1 the hold-relax (HR) consists of an initial maximum isometric contraction of the muscle to be stretched (antagonist), followed by relaxation and stretch of the muscle to the limit of the range of motion.

2 The agonist-contract (AC) stretch requires the assistance of a partner. The partner moves the subjects' limb so that the joint is at limit of rotation. The subjects then contracts the agonist (i.e quadriceps femoris) while the partner applies a force to the limb to stretch the antagonist muscle (hamstrings).

3 The hold-relax, agonist contraction (HR-AC) technique is a combination of HR and AC techniques. The HR-AC technique would involve an initial maximum isometric contraction of the hamstrings followed by a relaxation and stretch of the hamstrings; the hamstring stretch would be accomplished by manual assistance from the partner and by contraction of the quadriceps femoris.

The PNF stretches were designed on the basis of known connections and effects within the nervous system. The HR technique is intended to stretch the muscle while the alpha motor neurons are least excitable so that afferent input from the length detectors (muscle spindles) is least likely to elicit a stretch-evoked activation of muscle. To examine this possibility, both Hoffmann (H) and tendon tap (T) reflexes have been measured immediately after isometric contractions. The amplitudes of both the H and T reflexes are depressed after an isometric contraction and that the depression of the T reflexes is greater than that of H reflexes. Therefore, the excitability of both the muscle spindle and the motor neurons is decreased immediately after an isometric and that this depression lasts about 10 s. Furthermore, the depression of the reflexes is similar for contractions that vary from 1 to 30 sin duration. (reviewed in: 38). The rationale for the AC technique is to activate the reciprocal-inhibition reflex onto the motor neurons that innervate the antagonist (muscle to be stretched) by contraction of the antagonist muscle. In this scheme, voluntary activation of the agonist involves activation of both the alpha (α) and gamma (γ) motor neurons and the interneuron (I) that mediates the reciprocal-inhibition reflex (Figure 4.6). This interneuron is known as the Ia inhibitory interneuron. Activation of this interneuron causes action potentials to be transmitted to motor neurons that innervate the antagonist muscle, and subsequently causes a reduction in the excitability of these motor neurons. Consequently, the AC technique is presumed to involve an activation of the agonist muscle and, through reciprocal-inhibition, a relaxation of the antagonist muscle. In the several studies that compared the effectiveness of the various stretching techniques have not revealed consistent differences among the three PNF techniques (38).

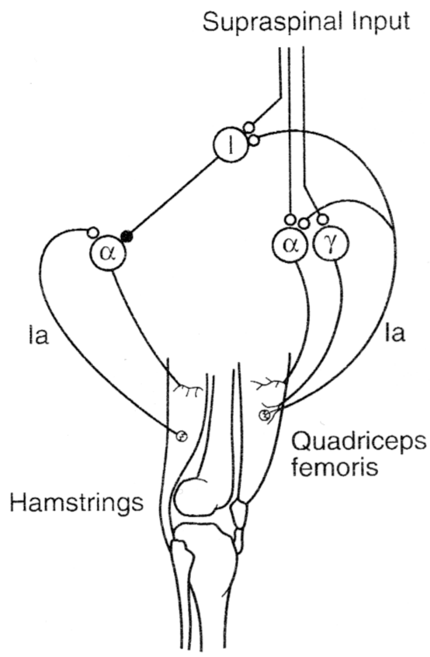


Figure 4.6. Neural pathways activated during the agonist contract stretch of the hamstrings. Activation of the quadriceps femoris by supra-spinal centers results in the concurrent activation of motor neurons innervating quadriceps femoris and the Ia inhibitory inter-neuron that mediates the reciprocal-inhibition reflex. This connection supposedly causes the antagonist (hamstrings) to relax during activation of the agonist (quadriceps femoris). (From: Enoka, 2002).

Mechanisms of the muscle flexibility. Evidence of a neurologic component to flexibility is based on the initial reflex-control animal studies of Sherrington (cited in 57). These initial studies provide the basis for an intricate stretch reflex neural system involving peripheral and central components. The neural system includes alpha motor neurons, gamma motor neurons, Renshaw cells, extra-and intra fusal muscle fibers, and supra-spinal pathways. Some believe these influences assist in dictating a resting tone and “set point” for the muscle. The set point controls the muscle’s preferred length, resistance to motion, and sensitivity to length changes. The stretch reflex arc is theorized to keep the agonist and antagonist muscles in a state of equilibrium during a stretch (57). Alternatively, it has been proposed that reflex EMG activity does not limit the ROM during slow stretches and that the increased ROM achieved from training is a consequence of increased stretch tolerance (62). The sensations associated with stretching a muscle to the limit of its range of motion are typically rather intense, so the acute post-training improvement in flexibility must be associated with a reduction in the sensory feedback or an attenuated interpretation of these signal (43).

A third explanation support the concept that muscle flexibility can be explained in mechanical terms rather than neural theories. Acute adaptations to passive stretch seem to related to the viscoelastic response of muscle to tensile stress (creep and stress relaxation) (66). However, this biomechanical rationale may explain short-term, reversible changes in muscle length but fails to explain the long-term, permanent changes. De Deyne (29) have proposed a theoretical model in which chronic changes in muscle flexibility can be explained if the muscle actually becomes longer, by adding sarcomeres in series, allowing further excursion (Figure 4.7). In this model, the application of passive stretch to muscle implies biological and molecular consequences. Force transmission is likely to occur through a chain of protein-protein interactions and may led to a chain of biological signal and ultimately to myofibrillogenesis. The potential mechanisms may be as follows: (1) the phosphorylation of integral membrane proteins and associated cytoskeletal molecules, (2) the secretion of selective growth factors, regulated by an autocrine or paracrine mechanism, and (3) changes in the intracellular ion flux through stretch-activated ion channels (29).

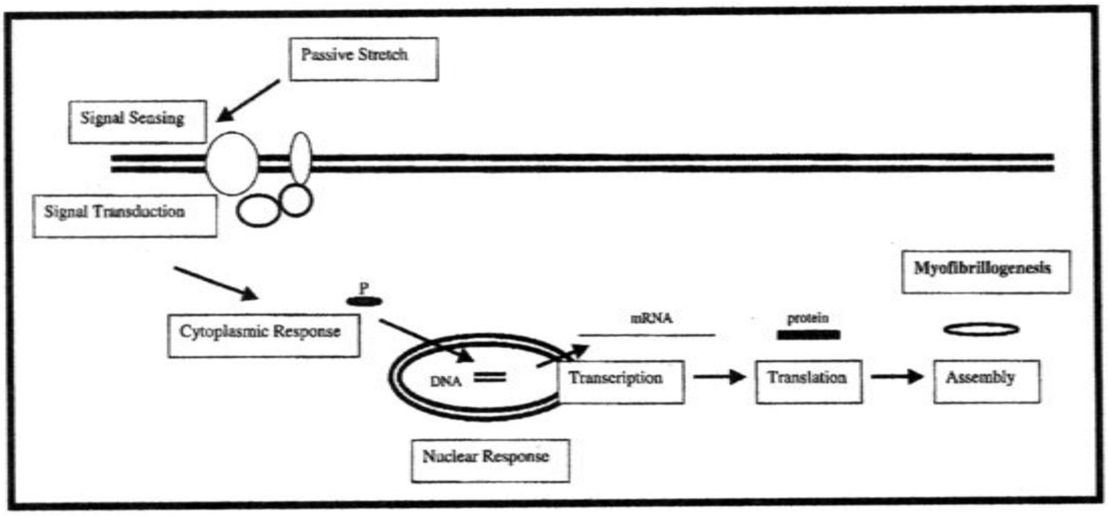


Figure 4.7. Conceptual overview how passive stretch can affect a muscle fiber. The biological response of passive stretch in a muscle fiber entails several basic steps. First, the stretch has to be sensed at the sarcolemma, most likely by a complex of integral membrane protein, before it is transduced to generate a cascade of one or more intracellular signaling molecules. Such events cal lead to several cytoplasmic responses. The one illustrated is the phosphorylation (P) of a transcription factor, resulting in its translocation to the nucleus. Specific genes (DNA) are than transcribed, and the messages (mRNA) are translated into specific proteins. Especially important for a muscle fibers is a coordinate assembly of contractile and non contractile proteins giving rise to functional sarcomeres (From:.De Deyne, 2001).

In synthesis, further investigations are needed to understanding this intricate interdependent relationship between neural and mechanical components of muscle flexibility, and to confirm experimentally the cellular and molecular adaptive mechanism of a muscle fiber to the stretching exercises.

Effect of strength training on flexibility. In the past athletes involved in activities requiring extreme flexibility, such as gymnastics and ballet, were discouraged from performing heavy training because they and their coaches believed that it would decrease their flexibility. A recent review of the clinical evidence (84) strongly suggests that pre-exercise stretching decreases force production and velocity of contraction for at least part of the range of motion.. Conversely, the effects of regular stretching are exactly opposite: regular stretching improves force production and velocity of contraction (84). In the latter study the measures included maximal voluntary contraction, power, jump height, jump force, and jump velocity, and the effects were observed for (1) static, ballistic, and PNF stretches; (2) males and females; (3) competitive and recreational athletes; (4) children and adults; (5) trained or untrained subjects; and (6) with or without warm-up.

A nonscientific observation can be made by looking at elite male gymnasts. They represent a population with both extreme flexibility and very high strength-to-weight ratio. By combining strength and flexibility training, these athletes do not compromise their flexibility with heavy resistance training.

4.3 Effects of whole-body vibration on human performance

Over the last decade numerous investigations have been carried out to study the effects of mechanical vibration on the physical performance of trained and untrained people. In the majority of cases the vibration has been applied to the muscles of the lower extremity in a standing crouched position, called whole-body vibration. Whole-body vibration assumes that the vibration frequency induced by a motor to the platform elicits tonic vibration reflex similar to the direct or indirect application of vibration on muscles or tendons. Cardinale and Bosco (20) in a systematic review, that included studies of both whole-body vibration exercise and locally applied vibration stimuli from 1966 to 2003, have proposed a schematic diagram illustrating the potential mechanisms determining an increase in neuromuscular performance (Figure 4.8). The neuromuscular system stimulated by a vibratory stimulus perceived by different sensory structures produces a reflex muscle activation. When this vibratory stimulus is relatively short, creates the potential for a more powerful and effective voluntary activation of skeletal muscle. This response mediated by monosynaptic and polysynaptic afferent pathways is capable to trigger specific hormonal responses. Consequently, the voluntary activation could be performed with central and peripheral structures in an elevated excitatory state. In addition, vibration appears to inhibit activation of antagonist muscles through Ia inhibitory neurons, thus altering the intramuscular coordination patterns leading to a decreased braking force around the joints stimulated by vibration.

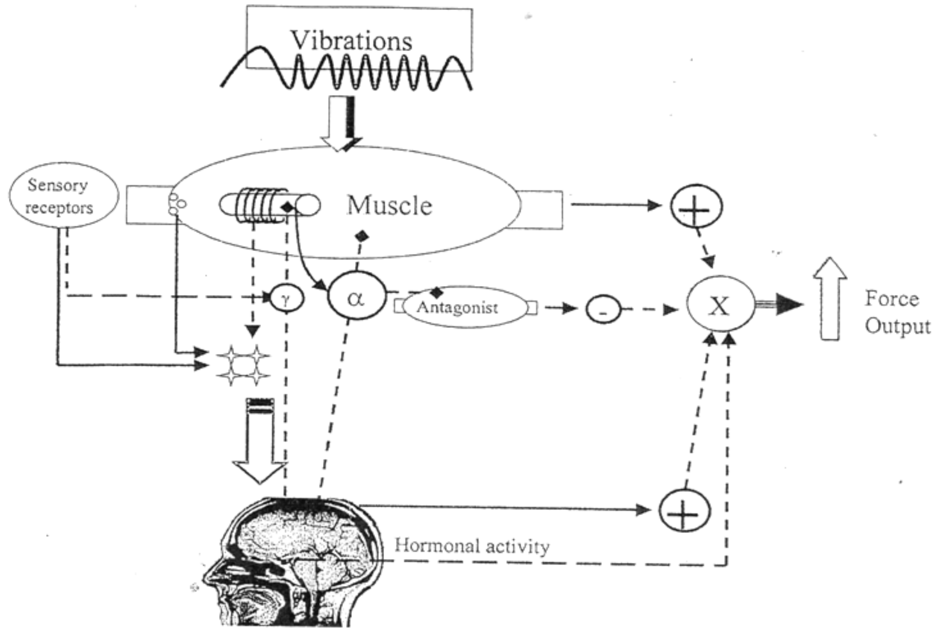


Figure 4.8. Potential mechanisms that mediate the enhancement of force-generating capacity after acute and chronic exposure (From: Cardinale and Bosco, 2003).

Luo et al. (59), based on studies involving both whole-body vibration and locally applied, also concluded that neuromuscular performance can be improved by vibration exercise and by the examination of acute effects they have shown that elite athletes may benefit more from vibration training. Vice-versa, in the Rehn's et al. review (73) appears that especially untrained people have a greater benefit from long-term vibration exercise than physically active people. According to Nordlund and Thorstensson (69) whole body vibration appears to provide no or only minor additional effects on muscle strength and jump performance as compared with performing the same exercises without whole-body vibration. In the latter study, the author's provide no basis for recommending whole-body vibration as a replacement, or addition, to resistance training, at least in physically active subjects.

In synthesis, the conflicting results in this area could be related to the training protocols used in terms of both vibration characteristic (method of application, frequency and amplitude) and exercise protocol (training type, intensity and volume).

Effects of whole-body vibration on the skeleton. According to Wolff's law, bone mass adapts to the demands of mechanical loading in addition to metabolic influences. Mechanical stimulation in the manner of whole-body vibration appears beneficial to the maintenance and/or enhancement of skeletal mass in individuals such as the elderly, postmenopausal women, and adolescents. Therefore, this may be an effective method by which therapy may be administered to mobility-limited individuals without the risks associated with high impact exercise. Whole-body vibration has been utilized to deliver mechanical accelerations (0.1, 0.3, and 1.0 g) to the appendicular and axial skeleton to elicit increased bone mass. Recently, a systematic review of Prisby et al. (71) have provided some evidence of the effectiveness of whole-body vibration in enhancing skeletal mass in the elderly, in individuals with low-bone mineral density, and adolescents. The mechanisms by which this occurs may be related to tissue perfusion, fluctuations in systemic hormones, and/or occur via direct mechanical stimulation. The potential effects of whole-body vibration on several physiological system may occur via direct or indirect mechanisms (Figure 4.9).

Figure 4.9. The potential effects of whole-body vibration on physiological systems and the potential interplay among systems. Whole-body vibration modulates the (A) skeletal, (B) muscular, (C) endocrine, (D) nervous, and (E) vascular systems, which may elicit secondary responses through interaction among the systems (From: Prisby et al., 2008).

***Effects of whole-body vibration on explosive and reactive strength*.** Research has focused extensively on both acute (13, 16, 31, 74, 89, 92) and chronic effects of vibrations (10, 14, 30, 32, 75, 76, 90, 91) using different types of vibratory methods. Presently, researchers agree that there are several factors which may influence in particular acute, residual and chronic effects of vibration exposure (59). Vibration characteristics, namely vibratory application, amplitude, frequency and exercise protocols, are the main factors influencing neuromuscular performance (59). Basically, the intensity of vibration load on the neuromuscular system is determined by the vibration frequency and amplitude. In most studies the frequency applied has ranged from between 20 and 45 Hz, and the amplitude between 1 and 5 mm.

In the aforementioned studies, however, the effect of vibration training has been tested on both young and old untrained people without adjusting the applied vibration frequency for each participant.

Findings of EMGrms recorded in the biceps brachii of boxers show significant enhancement of the neural activity during the vibration treatment period to more than double as compared to normal conditions (12). It seems that a high frequency vibration may decrease the harmonic synchronization of the motor units which then influences the neuromuscular performance in a negative way (64). Moreover, individuals react to the applied frequency differently which is to say that an individual frequency of vibration can elicit the highest reflex response during whole-body vibration (9, 21, 22).

In this respect, the use of EMG muscle response during vibration exposure as a neuromuscular index appears to be appropriate in identifying the individual frequency of stimulation, to induce specific adaptations. Therefore, individualized vibration frequency could be more effective than fixed vibration frequency in improving the dynamic strength of the lower extremity muscles, especially in trained people and shorter vibration intervention could be sufficient to elicit significant improvement in muscle strength variables.

Furthermore, the reflex response, defined as tonic vibration reflex, induced within the muscle being vibrated (36) can be altered by modifying the joint angle (52). It is likely that an increase in tonic vibration reflex reflects an improvement in both the static and dynamic sensitivity of the muscle spindles in the lengthened muscle (52). In addition, Caldwell et al. (19) have suggested there may be preferential recruitment of certain motor units at certain positions or angles.

During whole-body vibration, assuming that the neuromuscular response is modulated by Ia-afferents (32), similar to the vibration stimulus applied directly to a muscle (36), the sensitivity of muscle spindles in the lengthened muscle could be influenced by vibratory treatment. A recent study in which whole-body vibration was applied using different knee angles has shown in acute exposure a greater neuromuscular response at small knee angle of about 10-15° (squat to fully 40°) than at larger knee angle of 30-35° (1). Consequently, mechanical vibration may affect jumping performance differently in chronic exposure when the vertical jumps are carried out with different joint angular displacement and velocity.

Effects of whole-body vibration on muscle flexibility and mechanical power-. The use of mechanical vibration as a modality for increasing flexibility has been presented by only a few experiments (26, 39, 49, 51, 82, 93). Issurin et al. (49) noted a chronic post-vibration effect on flexibility by superimposing local vibration (vibrating cable) with conventional stretching exercises. A similar method, conducted by Sands et al. (82) revealed a residual and long-term influence of vibratory stimulation (vibratory device) on flexibility in young highly trained gymnasts who carried out stretching exercises during vibration. Both studies confirmed the hypothesis that vibration could induce an additional positive effect on flexibility by relaxing the stretched muscle. The mechanisms underlined by the authors were based on presynaptic inhibition of group Ia afferent fibres or a "busy line" phenomenon that is created when both vibration stimulation and stretching influence the same Ia pathways. In addition, combining a strong stretch stimulus and vibration may result in Golgi tendon organ activation via Ib pathways resulting in autogenic inhibition of the vibrated muscle (49, 82).
Recently, enhancement on hamstring flexibility through the application of whole-body vibration has also been reported after both acute (26, 51) and chronic treatment (39, 93).
During whole-body vibration the subjects stand on a vibrating plate with their feet placed on either side of the axle, maintaining a steady position while the oscillations of the platform produces a vertical ground reaction force. Whole-body vibration assumes that a tonic vibration reflex is elicited similarly to the direct or indirect application of vibration on muscles or tendons. The residual enhanced flexibility following one session of whole-body vibration (26, 51) suggests that vibration exposure may activate the Ia inhibitory interneurones of the antagonist muscle (42). Consequently, chronic exposure may lead to changes in intramuscular coordination thus reducing the

braking force around the hip and lower back joints, which could subsequently potentiate sit and reach scores and the reactive strength (39, 93).

However, in these studies the frequency of vibration during whole-body vibration was pre-selected rather than individually determined for each subject by using the EMG muscle response (35).

Effects of low frequencies of stimulation on muscle strength of elderly people when applying whole-body vibration. The chronic effect of WBV was tested in athletes (14, 33), in physically active young (31, 35) or untrained young (32, 76) or adult people (89, 90, 91, 92). Recent researches have demonstrated WBV can improve the strength and power of elderly people applying several weeks vibration intervention (5, 18, 54, 72, 75, 80, 94). However, there are several studies reporting neither acute residual or chronic effects (20, 27, 33, 30, 31, 55, 74, 78).

Most probably the reason of the controversial results can be attributed to the large diversity of the methods and subjects used. The frequency of vibration applied in these studies ranged between 12 and 45 Hz disregarding the individual differences in physical fitness level and in age with some exceptions in which the resonance frequency was selected on the basis of EMG activity elicited by different frequency domain acutely (8, 21, 22, 35). The peak to peak displacement of the sinusoid wave of the vibration was almost identical (4-6 mm) in all of the studies. The duration of one bout of vibration varied between 30 and 70 s. However, it is not known which duration can be considered optimal when long term vibration intervention is applied. Concerning the optimal duration of the training (rehabilitation) program is not either known because improvement was reported alike when long (six or twelve month) or short (ten days, one month) was applied.

In those studies aiming to investigate the WBV effects on physical fitness and muscle strength of elderly people the vibration frequency applied ranged between 12 and 45 Hz. Similar improvement was found when more than two months intervention was applied with 35-40 Hz (5, 6, 18, 72, 75, 76, 94) or when 26-27 Hz was used (18, 72). One can assume that in people with low or moderate level of physical fitness low frequency might be sufficient to elicit neuromuscular adaptation and to increase strength and other abilities associated with strength. This assumption is supported with the results of Cardinale and Lim (20) reporting significant acute residual improvement in jumping height and joint flexibility of young males and females applying 20 Hz resonance frequency. Concerning chronic effect of WBV there is one study only (54) reporting significant improvement in walking variables applying 12-20 Hz frequency during two month intervention.

Chapter 5

Materials and methods

5.1 Effect of individualized vibration frequency

Participants and study design. In the first instance, thirty-three physically active male and female participants (sports science students) were randomly assigned to either the individual-vibration group, the fixed-vibration group, or the control group. However, only nine participants in the individual-vibration group (5 females/4 males, age 22.0 years, s = 0.9; height 170.2 cm, s = 7.1; body mass 66.3 kg, s = 10.6), ten in the fixed-vibration group (5 females/5 males, age 21.9 years, s = 1.5; height 173.1 cm, s = 7.2; body mass 66.2 kg, s = 8.4), and eleven in the control group (5 females/6 males, age 22.0 years, s = 1.3; height 175.1 cm, s = 7.5; body mass 65.6 kg, s = 8.3) completed all testing sessions. All of the participants were engaged in systematic physical activities (gymnastics, swimming, and track and field activities) at least three times per week. The participants provided written informed consent before participating and the study was approved by the Ethics Committee of the L'Aquila University.

Estimation of the individual vibration frequency. The participants were exposed to a vertical sinusoidal whole-body vibration using a vibratory platform (Nemes-Lsb, Bosco-System, Rieti, Italy). The participants stood on a platform with an angle of 90° between the lower and upper leg, while grasping a railing in front of them (Figure 5.1).

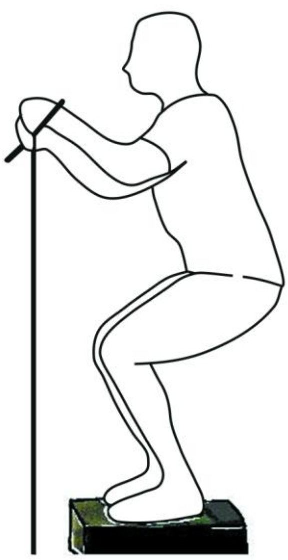


Figure 5.1. Position adopted by the participants on the vibrating plate during the vibratory treatment.

The amplitude of the vibration was about 1 mm. The vertical component of the acceleration was measured using an accelerometer (Type ET-Acc-02, Ergotest Technology, Langesund, Norway) placed in the middle of the vibration platform during a progressive incremental frequency protocol from 20 to 50 Hz. The accelerations in this test ranged from 1.1 to 53.6 $m \cdot s^{-2}$ (Figure 5.2).

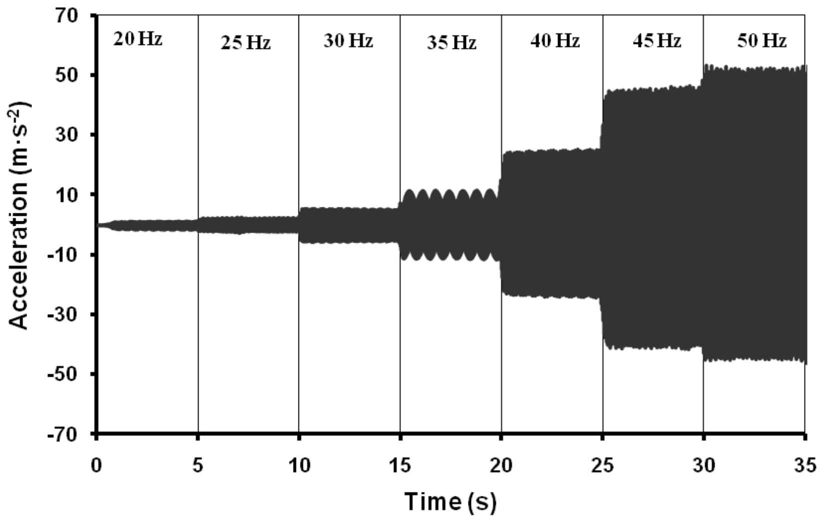
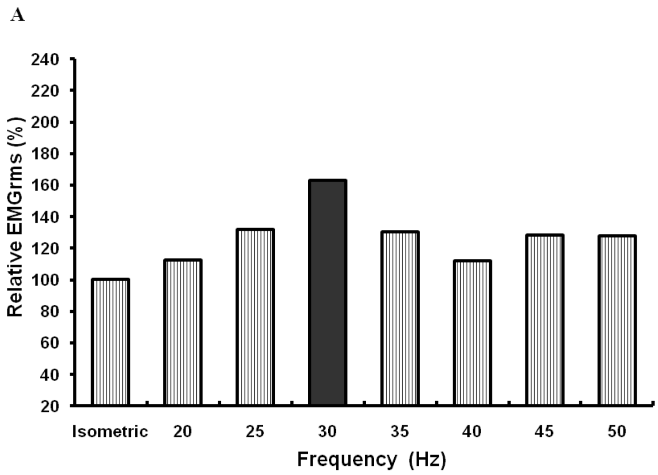


Figure 5.2. Acceleration of the vibrating plate as the frequency of vibration was increased by 5 Hz every 5 s from 20 to 50 Hz. The acceleration values ranged from 0.1 to 5.5 *g* (where *g* is the acceleration due to gravity; 9.81 $m \cdot s^{-2}$).

The frequency of the vibrations was determined for each participant of the individual-vibration group by monitoring the EMG_{rms} activity of the vastus lateralis muscle during trials performed at different frequencies. The participants performed an isometric half squat in the following conditions: no vibrations (i.e. 0 Hz), and randomly at 20, 25, 30, 35, 40, 45 and 50 Hz with a 4 minute pause between each trial, with each trial lasting 20 s. The highest neuromuscular response (EMG_{rms} activity) recorded during the trials was used for the vibration training (Figure 5.3). In a comparable group of participants, the day-to-day reliability of the individual vibration frequency was 0.92 (coefficient of variation = 6.2).



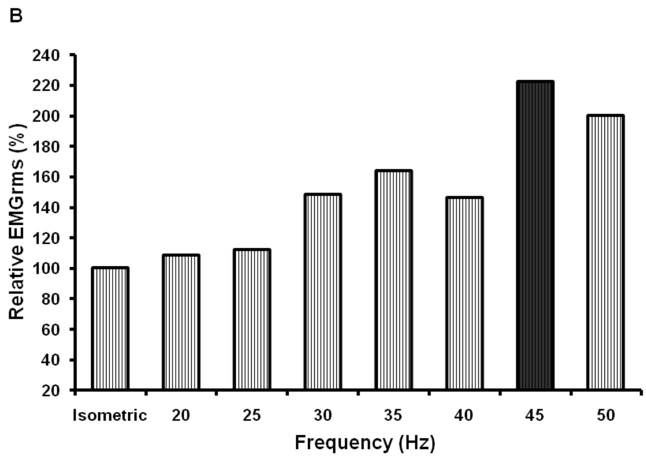


Figure 5.3. The EMGrms of vastus lateralis recorded during different vibration frequencies are normalized to the baseline isometric value. The participants performed an isometric half squat in the following conditions: no vibrations, and randomly 20, 25, 30, 35, 40, 45 and 50 Hz vibration frequency. The filled bars indicate the highest neuromuscular responses recorded during the test that were used as frequencies of treatment. Example for participant A and for participant B.

The EMG sensors and accelerometer were connected to a data collection unit (MuscleLab-Ergotest Technology, Langesund, Norway) that was in turn connected to a PC via the USB port.

Vibration intervention. The participants of the two vibration groups were exposed to whole-body vibration three times per week (Monday-Wednesday-Friday) for 8 weeks. During each training session they underwent 10 series of 1-minute (10 × 1) whole-body vibrations with a 1 minute pause between series and a 4 minute pause after the first five vibration series (5 × 1) (Table 5.1).

Table 5.1. Characteristics of whole-body vibration treatment.

Training volume and intensity of the vibration treatment	Values
Volume	
Total duration of vibration in one session (min)	10
Number of series	10
Duration of one series (s)	60
Number of training sessions in one week	3
Total number of training sessions	24
Total duration of vibration in 8 weeks (min)	240
Intensity	
Rest period after the first five series (min)	4
Rest period between series (s)	60
Rest period between two training sessions (days)	1-2
Vibration amplitude (mm)	□ 1
Vibration frequency (Hz)	From 20 to 50

The vibration frequency was set for each participant individually (for the individual-vibration group) or fixed at 30 Hz (for the fixed-vibration group). Participants in the control group stood on the vibration platform in exactly the same body position with knees flexed to 90°. However, the vibration was not turned on.

Testing procedures. The participants were tested on four occasions at the same time of day, and they were requested to withdraw from any tiring physical activity two days before the test. Measurements were taken before starting the whole-body vibration intervention, after four weeks of treatment, after eight weeks of treatment, and finally one week after the end of vibration treatment.

Each testing session began with the anthropometric measurements being taken. Next, each participant completed a ten minute warm up (six minutes running on a treadmill at 6 $km \cdot h^{-1}$ speed and four minutes stretching) before performing a series of vertical jumps. Participants performed the squat jump, the countermovement jump, and the continuous rebound jumps on a resistive platform (Ergojump) (17). The maximum knee flexion in the squat jump and the countermovement jump (~90°) was measured using an electrogoniometer connected to a Muscle-Lab. In the continuous rebound jumps (lasting 10 s), the participants were instructed to jump as high as possible with the shortest ground contact time. The participants were also instructed to hold their hands on their waist and to keep the knees extended as much as possible during the test. Three repetitions each of squat jumps and countermovement jumps were performed, and the maximum vertical jumping height was calculated using a platform which has been described elsewhere (17). The continuous rebound jumps were performed twice in each testing session. Contact time and flight time were measured and power was calculated.

To avoid a small countermovement during the squat jump was used a string with metal stops placed under the gluteus of the participant at a position corresponding to an knee angle of 90° (measured using an electrogoniometer connected to a Muscle-Lab). If the string was moved during the jump, the performance was retained incorrect and therefore, repeated.

The height of rise of the centre of mass in the squat jump and the countermovement jump was determined by the flight time according to the method of Asmussen and Bonde-Petersen (2), and used in order to analyse the explosive strength characteristics of the leg muscles as reported elsewhere (14, 16, 32, 89, 90, 92).

The jump height, *h*, was calculated from

$$h = g\, t_f^{\,2} / 8 \text{ [m]}$$

where t_f is the flight time and g is the acceleration due to gravity (9.81 m·s^{-2}).

The continuous rebound jump, which involves rebounding vertically, is interpreted as an indicator of explosive strength in a stretch-shortening cycle, or reactive strength capacities similar to a drop jump (47, 98, 99). During the jumps, flight time and contact time were measured and used to calculate the jump height (2).

The average power was calculated from the contact time and flight time (17), and also used to estimate the explosive strength during a ballistic movement that involves a stretch-shorten cycle of the legs (25). The centre of mass displacement, the flight time, and the contact time in each single jump, as well as the overall number of jumps performed, were also recorded.

The average power, P, (in W·kg^{-1}) was calculated as follows:

$$P = (g^2\, T_f\, 10)/4n(10\text{-}T_f) \quad [\mathrm{W{\cdot}kg^{-1}}]$$

where g is the acceleration due to gravity (9.81 m·s^{-2}), 10 is the total performance time (in seconds), n the number of jumps, and T_f the total flight time of all jumps.

The day-to-day reliability of jumping measurements, tested in a comparable group of participants by Markovic, Dizdar, Jukic and Cardinale (63), was 0.97 (coefficient of variation = 3.3) for the squat jump and 0.98 (coefficient of variation = 2.8) for the countermovement jump. In a comparable group of participants the day-to-day reliability of the continuous rebound jump was 0.94 (coefficient of variation = 2.9) for jump height and 0.95 (coefficient of variation = 2.7) for power.

EMG analysis. The EMG activity was recorded using bipolar surface electrodes (inter-electrode distance: 2.0 cm) including an amplifier [gain at 100 Hz: 1000; input impedance: 2 GΩ□ common mode rejection rate: 100 dB; input noise level (1 kHz band with) : 20nV/Hz^{-2}] and a Butterworth band-pass filter (3-dB low cut-off frequency: 8 Hz; 3-dB high cut-off frequency: 1200 Hz) fixed longitudinally over the muscle belly. EMG cables were secured (the participants wore a suit next to the skin) to prevent movement artifact. The pre-amplified EMG signals were first converted to root mean squared and then sampled at 100 Hz. The averaged root mean square was expressed as a function of time in millivolts (mV).

Statistical analyses. Conventional statistics methods were employed, including mean values, standard deviations (*s*), and percentages (%). Normality tests, Shapiro-Wilk's W test, were performed for all dependant variables. Since the variables of interest were not normally distributed, the effect of intervention time of whole-body vibration (independent variable) on explosive and reactive leg strength (dependent variables: squat jump height, countermovement jump height, and the jumping height, power, flight time, and contact time during the continuous rebound jump) was statistically analyzed over time by means of the Friedman test in each group and by a Wilcoxon test for within-groups comparisons in order to locate differences. A Bonferroni correction was used to adjust the P-value in relation to the number of contrasts that were performed. The comparisons between groups were made using the Kruskal-Wallis test. The day-to-day reliability of the measurements (3 trials on successive days) was calculated using intra-class correlation (Crombach's α coefficient to determine between-subjects reliability) and by the coefficient of variation (to determine the within-subjects variation) as outlined by Hopkins (46). All analyses were executed using the SPSS package (version 12). The probability level was set at $P < 0.05$ to determine statistically significant differences.

5.2 Effect of acute, acute residual and chronic whole body vibration

Subjects and experimental design. The study procedures, including: recruitment, measurements and intervention were performed in the Faculty of Sport Sciences, University of L'Aquila, Italy. Among the 200 second year students of the sport sciences faculty a total of 40 subjects (20 males; 20 females) were enrolled (Figure 5.4). Exclusion criteria included a history of back pain, acute inflammation in the pelvis and/or lower extremities, acute thrombosis, bone tumours, recent fractures, recent implants, gallstones, kidney or bladder stones, any disease of the spine, peripheral vascular disease or pregnancy, and sever delayed onset of muscle soreness of hamstring muscles. Subjects were randomly assigned to either the Acute and Residual Flexibility Group or the Chronic Flexibility Group using a stratified randomization technique, according to gender (since this may be a factor in flexibility determination), with 10 males and 10 females in each Group. Subsequently, subjects in each Group were assigned to either the Vibration Group or the Control Group using the same stratified randomization technique (Figure 5.4).

Following approval by the University's Ethics Committee, all subjects provided written informed consent. During the follow-up study 6 subjects withdrew due to loss of interest. The subject characteristics for those who completed all the test sessions are provided in Table 5.2. The study began investigating the acute effects of vibration intervention on March 2004 and the residual effects were recorded in April. To conclude the study, the chronic effects of vibration intervention were completed from May to July 2004. Although the same subjects participated in both acute and residual effects of the vibration treatment, all the measurements were repeated; in acute, residual, and chronic. During the follow-up (chronic exposure), all subjects were engaged in systematic physical activities (swimming, gymnastics, and track and field activities) at least three times a week .

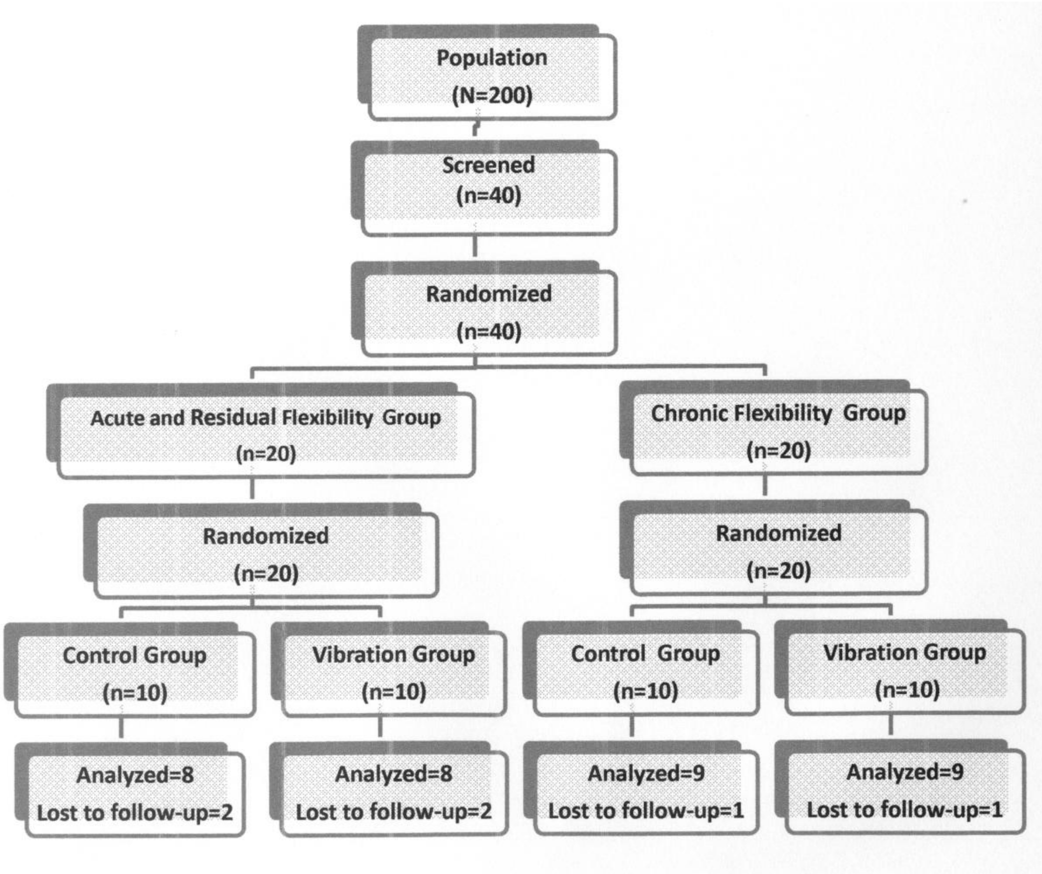


Figure 5.4. Flow diagram for selection of the subjects.

Table 5.2. Subjects characteristics.

Characteristic (mean±SD)	Acute and Residual Flexibility Group (n=16)		Chronic Flexibility Group (n=18)	
Males/Females (M/F)	Vibration Group (n=8; 4 M/4 F)	Control Group (n=8; 3 M, 5 F)	Vibration Group (n=9; 4 M/5 F)	Control Group (n=9; 4 M/5 F)
Age (years)	19.75±1.38	20.50±1.90	21.00±1.50	22.22±1.85
Height (cm)	168.87±5.61	170.80±10.65	169.22±7.06	166.88±7.34
Weight (kg)	63.53±8.59	67.22±10.72	65.27±10.20	62.88±9.61

Vibrating platform and flexibility test. The subjects underwent vertical sinusoidal whole-body vibration using a vibratory platform (Nemes-Lsb, Bosco-System, Rieti, Italy). The subjects stood on the platform at an angle of □ 90° between the lower and upper leg, while grasping a railing in front of them (Figure 5.5). The appropriate toe and heel positions were marked on the platform to ensure consistency of foot position and orientation among trials. The vibrating platform was modified in order to allow the subjects to perform the stand and reach test on the same plate. Toe and heel positions were also marked in order to define the positioning of the feet for testing, resulting in two different positions. This double foot position on the plate permitted the subjects to change their position easily on the plate; from a standing crouched position (vibration intervention) to a stand and reach test, particularly when determining flexibility during acute exposure (Figure 5.6). The stand and reach test was conducted on the vibrating plate with the feet placed against a graduated rules. The knees were held extended by the tester. The subjects leaned downward slowly as far as possible toward a graduated rules from -20 to +20, holding the greatest stretch for 2 seconds. The tester had to be sure that there were not jerky movements on the subject and that her/his fingertips remained at the level. The score was recorded as the distance before (negative) or beyond (positive) the toes.

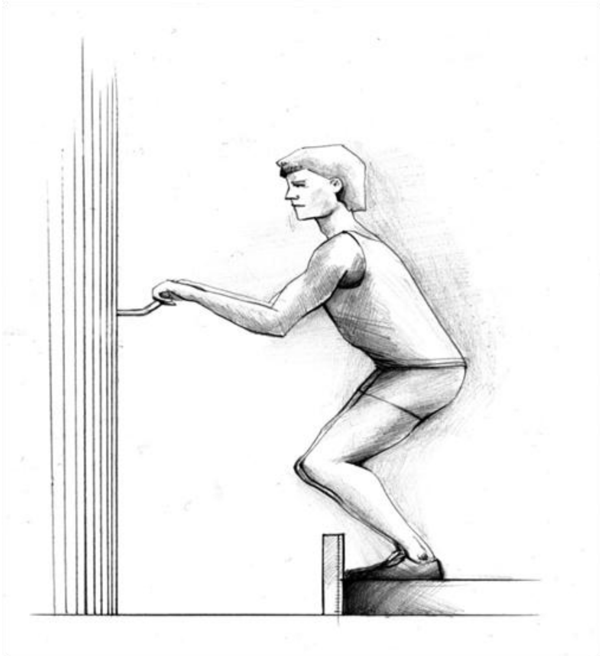


Figure 5.5. Position adopted by the subjects on the vibrating plate.

Figure 5.6. Stand and reach test performed by the subjects.

Estimation of optimum vibration frequency and EMG analysis. The subjects performed the test assuming the position presented in Figure 6.2. The amplitude of vibration was about 1 mm. The vertical component of acceleration was measured using an accelerometer (Type ET-Acc-02, Ergotest Technology, Langesund, Norway) placed in the middle of the vibration platform during a progressive incremental frequency protocol from 20 to 50 Hz. The acceleration in this test ranged from 1.1 to 53.6 $m \cdot s^{-2}$.

The frequency of vibration was determined for each of the subjects in the Vibration Group by monitoring the EMG_{rms} activity of the vastus lateralis muscle (dominant leg) during trials performed at different frequencies using the procedure described in details by Di Giminiani et al. in the first study (35). The highest neuromuscular response (EMG_{rms} activity) recorded during the trials was then used for the vibration intervention in acute, residual and chronic exposure. The EMG sensors and accelerometer were connected to a data collection unit (Muscle-Lab, Ergotest Technology, Langesund, Norway) which, in turn, was connected to a personal computer via the USB port.

The EMG activity was recorded using bipolar surface electrodes (inter-electrode distance: 2.0 cm) including an amplifier [gain at 100 Hz: 1000; input impedance: 2GΩ common mode rejection rate: 100 dB; input noise level (1 kHz band): 20 nV · Hz^{-2}] and a Butterworth band-pass filter (3-dB low cut-off frequency: 8 Hz; 3-dB high cut-off frequency : 1200 Hz) fixed longitudinally over the muscle belly. The EMG cables were secured (the subjects wore a suit next to the skin) to prevent motion artifact. The pre-amplified EMG signals were first converted to a root mean square and then sampled at 100 Hz. The averaged root mean square was expressed as a function of time in millivolts.

Vibration Intervention. All the subjects stood on the vibration platform in exactly the same body position (Figure 6.2) and the vibration frequency was set individually for each subject as described previously. The vibrating platform was turned off for the Control Group.

Acute and Residual Flexibility. The subjects of the Vibration Group who were tested for acute and residual flexibility, underwent 10 series of 1-min (10 × 1) whole-body vibration with a 1-min pause between series and a 4-min pause after the first five series of vibrations (5 × 1).

*Chronic flexibility and reactive strength***.** The members of Vibration Group were exposed to whole-body vibration three times a week (on Monday, Wednesday, Friday) for 8 weeks (Table 5.3). The training session was the same as that applied to test acute and residual effect (see above).

Table 5.3. Characteristics of whole-body vibration treatment during chronic exposure.

Training volume and intensity of the vibration treatment	*Values*
Volume	
Total duration of vibration in one session (min)	10
Number of series	10
Duration of one series (s)	60
Number of session training in one week	3
Total number of session training	24
Total duration of vibration in 8-weeks (min)	240
Intensity	
Rest period after the first five series (min)	4
Rest period between series (s)	60
Rest period between two training sessions (days)	1-2
Vibration amplitude (mm)	~1
Vibration frequency (Hz)	From 20 to 50

Test procedures

*Acute flexibility***.** All subjects underwent a pre-test using the stand and reach test (the mean value of 3 measurements was recorded) in order to assess muscle flexibility. The test was repeated in the last 10 seconds of each series of 1-minute performed by the subjects on a vibrating platform. Ten measurements of flexibility were carried out for each group performing the stand and reach test on the same vibrating platform. For subjects of the Control Group, however, the vibrating platform was turned off.

Residual Flexibility. A pre-test was performed by all subjects using the stand and reach test (the mean value of 3 measurement was recorded) in order to assess muscle flexibility. The test was repeated for the subjects of the Vibration Group immediately after the first five series of whole-body vibration, and then after 2 and 4 minutes. This was followed by a 4-minute pause after which the subjects completed the session of treatment (other 5 series), and the stand and reach test was performed at 0, 2, 4, 6, and 8-minutes after the end of vibration intervention. The same procedure was adopted for the Control Group but the vibrating platform was turned off.

*Chronic flexibility and reactive strength***.** The subjects were tested on four occasions at the same time of day, and were required to refrain from any tiring physical activity in the 2 days preceding the test. Measurements were made before starting the whole-body vibration intervention, after 4 weeks of treatment, after 8 weeks of treatment, and then 1-week following the conclusion of vibration treatment.

Each test session began with the measurement of anthropometric characteristics. Next, each subject performed the stand and reach test on the vibrating plate (Figure 6.3). The mean value of three measurements was recorded. Subsequently, they completed a 10-min warm-up (6 min running on a treadmill at a speed of 6 $km \cdot h^{-1}$ and 4 min stretching) before performing a series of drop jumps on a resistive platform (Ergojump-Bosco System, Rieti, Italy) (15). The best performance dropping from 20-30-40-50- and 60 cm was recorded. The centre of mass displacement, flight time, and contact time were also recorded. Mean power, P (in $W \cdot kg^{-1}$), was calculated according to Bosco's formula (16).

Reliability of measurements. The reliability of measurements taken on the same day was 0.92 (CV=2,2%) for estimation of individual frequency of vibration and 0.94 on different days (CV=3,7%) for the drop jump.

The reliability of flexibility measurements taken on the same day was 0.99 (CV= 2.2%) for acute analysis, 0.99 (CV= 2.4 %) for residual analysis, and 0.97 on different days (CV = 3.6 %) for chronic analysis.

Statistical analysis. Conventional statistical methods were employed, including mean values, standard deviations (SD), and percentages (%). The relative change percentage was calculated in each subject and the mean values were then calculated. Normality tests, Shapiro-Wilk's W test, were performed for all dependant variables. Since the variables of interest were not normally distributed, the acute, residual, and chronic effect of intervention time of whole-body vibration (independent variable) on flexibility and reactive strength (dependent variables: stand and reach test, and power during the drop jump) were assessed over the course of the test sessions by means of the Friedman test in each group and by using a Nemenyi bilateral test for within–group comparisons to locate differences. Bonferroni correction was used to adjust the P-value in relation to the number of contrasts performed. The comparisons between groups were made using the Mann-Whitney test.

The reliability of the measurements was calculated using intra-class correlation (Cronbach's alpha coefficient to determine between-subjects reliability) and the typical percentage error (to determine the within-subjects variation) as reported by Hopkins (46). All analyses were executed using the Addinsoft™ XLSTAT (version 2009.4.07). Statistical significance was set at P □ 0.05.

5.3 Effect of low resonance frequency

Subjects. Twenty stroke patients (12 men and 8 women) participated in this study. Their mean age was 58.6±6.3 years (range: 50-69 years). The patients hospitalized in the National Medical Rehabilitation Institute took part in daily conventional physiotherapy. The inclusion criteria was to be able to keep balance during quiet standing at least 2 minutes and capability executing the tests properly. The subjects were randomly assigned into two groups, i.e., vibrated (V, n= 10) and non-vibrated (NV, n=10) group. During the study every patients took part in conventional rehabilitation program provided by the institute. Subjects in the vibration group were exposed to a vibration treatment three times per week for four weeks using a vibration platform called Nemes (Bosco-System, Rieti, Italy). The patients were informed about the benefit and risk of the intervention and signed a written informed consent according to specified guidelines. The Research and Ethics Committee of the Semmelweis University, Budapest approved the study design according to the declaration of Helsinki.

Vibration intervention. Patients in V group were trained for four weeks three times per week applying WBV. Before starting the treatment the patients were familiarized to the vibration process. First the body posture was introduced without receiving vibration. They were instructed to stand on the vibration platform flexing the knee approximately at 80° (full extension is zero degree) grasping the handle bars and to load one of the legs by moving the center of gravity above the unaffected then above the affected leg meanwhile flexing and extending the knee with a range of motion of approximately 10-15 degrees. When the patients were able to perform the requested task the vibration device was turned on. First one bout of 30 s vibration with 12 Hz frequency was applied. Then a second bout of vibration was provided (30 s, 15 Hz). When they stood comfortable and well-balanced on the platform, 45 s, 20 Hz and ~1 mm amplitude vibration exposure was given twice with one minute rest between. This type of conditioning session was repeated once more having three day rest. After the familiarization sessions we applied four week vibration treatment three times per week. The duration of one vibration set was one minute. During each intervention session day six vibration sets was provided with one minute rest between. In the rest period the subjects sat on a chair placed near to the vibration platform. Care was taken during vibration by two persons standing next to patients giving instructions when it was necessary. We instructed the patients during vibration to move the center of pressure towards the affected and non-affected limb occasionally.

Testing procedure. Every subject participated in two test sessions, prior and after the four week long vibration treatment. Before the first test each subject was familiarized to the testing procedure. The second test was separated from the vibration session by at least three days to avoid the acute effect of the vibration. Prior testing the patients received their usual daily physiotherapy. Torque production of the knee extensor was determined under isometric and eccentric contraction by using a computerized dynamometer (MultiCont II, Mediagnost, Budapest and Mechatronic Kft, Szeged, Hungary). Subjects were seated on the dynamometer with their back against the dynamometer’s seat back tilted so that the hip joint was approximately 100 degrees. Crossover shoulder straps, a lap belt, and a wide strap across the thigh stabilized the torso and prevented hip extension. The two drivers with the lever arm were located at the left and right side of the dynamometer enabling the torque measurement of the affected and non-affected leg separately. The legs were attached through an ankle cuff to the dynamometer’s lever arm. The knee joint centre of rotation was aligned with the lever arm’s centre of rotation.

Maximum isometric torque was measured at a knee joint angle of 30 and 50 degrees. The subjects were instructed to carry out knee extension with the greater effort unilaterally three times with one minutes rest between. After 5 minutes rest the patients were requested carry out two isometric contractions concentrating on the fast torque development only. The torque-time curves were simultaneously recorded and stored for later analysis. Maximum torque (Mic), maximum rate of torque development (RTDc, dM/dt) was determined and calculated from the respective torque-time curves (Figure 7.1).

The eccentric contraction started at a knee joint angle of 30 degrees. The constant stretching velocity and the range of knee flexion were 60 degrees per second, and the 60 degrees, respectively. The patients were instructed to execute torque under isometric contraction and having reached 20 % of the maximum isometric torque determined at the knee joint angle of 30 degrees the motors automatically started to rotate and to flex the knee. We asked the patients to resist against the rotating lever arm with the possible greatest effort. Two contractions were performed with either right or left leg unilaterally. After the motor stopped flexing the knee, the leg passively returned to the starting position. Figure illustrates representative examples of torque-time, position-time, and velocity-time curves. Peak torque (Mec) and mechanical work (Wec) was determined or calculated from the respective torque-time curves (Figure 5.7).

Work done by the knee extensors during eccentric contraction was calculated as follows.

$$W = \int_{\theta_1}^{\theta_n} M_{(\theta)} \cdot d\theta \qquad [\mathrm{N \cdot m, J}]$$

where M is the torque measured at θ joint angle.

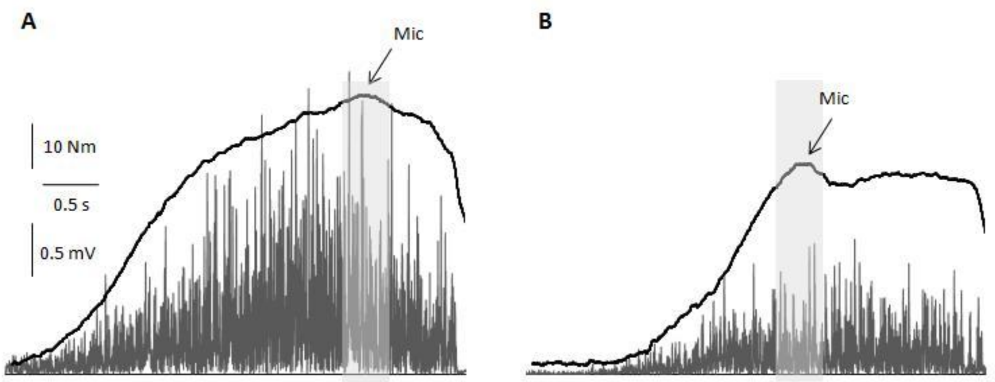


Figure 5.7. Representative isometric knee extension torque and rectified EMG data for vastus lateralis (VL) of the non-paretic (A) and paretic (B) leg performed without time constrait by one of the patients. The arrow indicates the location at which the maximum isometric torque (Mic) was determined. The shaded area represents 400 ms window used for computation of root mean square EMG (EMGrms) values for VL.

Myoelectrical activity (EMG) was measured and EMG data were collected with the TeleMyo telemetric system (Noraxon U.S., Inc., Scottsdale, AZ). Bipolar, 8-mm, silver-silver chloride electrodes were used to record myoelectrical activity. The electrodes were placed over the vastus lateralis of the paretic and non-paretic leg. The distance between pair of electrodes was 2.5 cm. The skin surface over the belly of the muscles were shaved and washed with alcohol. The ground electrode was placed above the patella after similar preparation. The signals were digitized at 1 kHz using the Myosoft software (Noraxon Myoclinical 2.10). EMG signals were full-wave rectified and root-mean-square (rms) conversion of the raw EMG data by a 20-ms smoothing window. Maximum torque was identified and the corresponding EMGrms activity digitized. Markers were inserted 200 ms before 200 ms after peak torque in on the recorded EMG signals obtained during both isometric and eccentric contractions (Figure 5.7). Within this 400 ms window the highest EMGrms value was determined as peak EMG (μV) activity. In fast isometric contractions, marker 1 was placed at the onset of EMG activity and marker 2 at 200 ms.

Statistical analysis. Mean and standard deviation (SD) were computed for the measured and calculated values. Because of the limited sample size and according to the requirements of using parametric statistical procedures all variables were tested with Shapiro-Wilk's W test for normality. The strength parameters obtained at the first and second test were compared with paired Student t-test. Means for V and NV group were compared by using unpaired Student t-test. The probability level for statistical significance was set at $p<0.05$.

Chapter 6

Results

6.1 Effect of individualized vibration frequency

During the first weeks of the treatment, two participants in the individual-vibrationgroup and one from the fixed-vibration group withdrew from the study due to loss of interest. All remaining participants of the vibration groups performed on average about 23 (96.2%) (range 22 to 24) of the 24 training sessions programmed during the 8-week period, without side effects or muscle-tendon injuries. The results of thirty participants were analyzed for four testing sessions (individual-vibration group, n = 9; fixed-vibration group, n = 10; control group, n = 11).

Explosive strength. Whole-body vibration increased the squat jump performance significantly in the individual-vibration group, by 3.1 cm, s = 2.0, (P = 0.001) after the vibration intervention, compared with a slight increase of 0.8 cm, s = 1.1, in the fixed-vibration group (P = 0.011), and of 0.7 cm, s = 1.1, in the control group (P = 0.006) (Figure 6.1), resulting respectively in a significant 11% benefit for the individual-vibration group, 3% for the fixed-vibration group, and 2% for the control group.
In the countermovement jump (Figure 5.4), none of the groups increased the jumping height significantly (P = 0.060 by the individual vibration-group; P = 0.185 by the fixed vibration-group; and P = 0.108 by the control group).

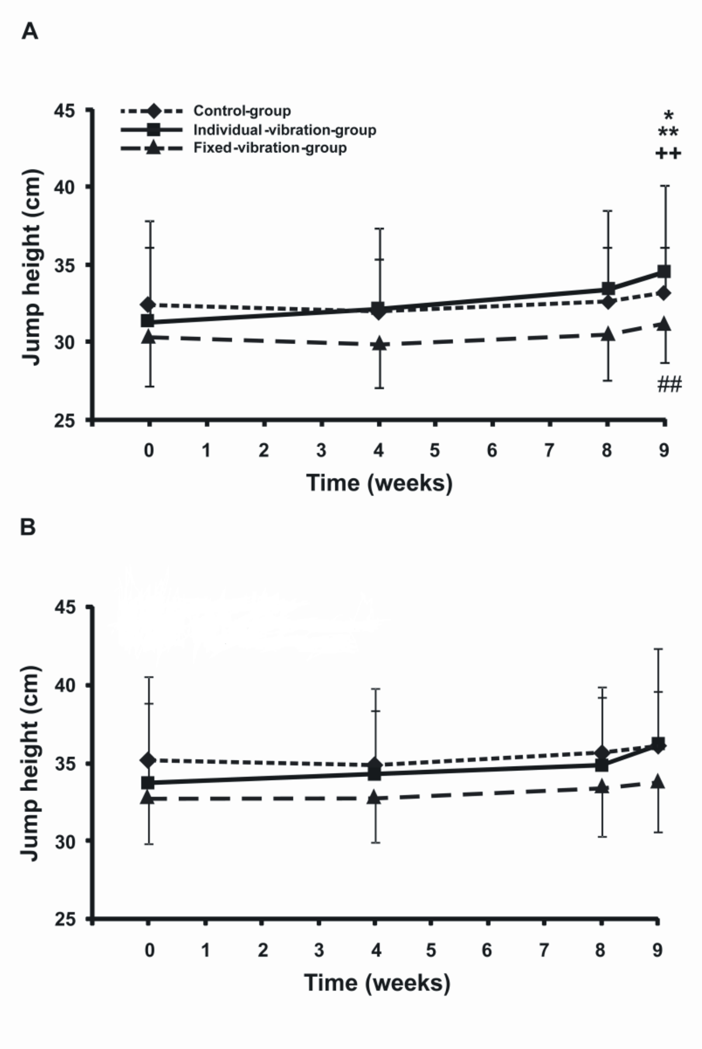


Figure 6.1. Change in jumping height during a squat jump (A) and countermovement jump (B) over time. 0-weeks = before vibration; 4-weeks = after 4 weeks of vibration; 8-weeks = after 8 weeks of vibration; 9-weeks = one week after the end of vibration treatment. Values are means and error bars are standard deviations. ##Significant difference for the fixed-vibration group from 4-weeks; ++Significant difference for the control group from 4-weeks; *Significant difference for the individual-vibration group from 0-weeks, and **from 4-weeks.

Reactive strength. The individual-vibration group showed a significant 4.7 cm, s = 3.6, improvement (22%, P = 0.006) in jumping height over the vibration treatment, and no effect was reported for the fixed-vibration group (P = 0.195) or the control group (P = 0.212).

The individual-vibration group increased mechanical power progressively (Figure 6.2), and statistical significance was reached at one week after the end of the vibration treatment (6.5 W·kg^{-1}, s = 4.0; 18%) (P = 0.002). The increase in mechanical power in the fixed-vibration group was slight (1.1 W·kg^{-1}, s = 1.6; 3%); however, the level of significance was not reached (P = 0.155). The control group showed a similar non significant increase at one week after the end of vibration (0.9 W·kg^{-1}, s = 1.6; 2%) (P = 0.183).

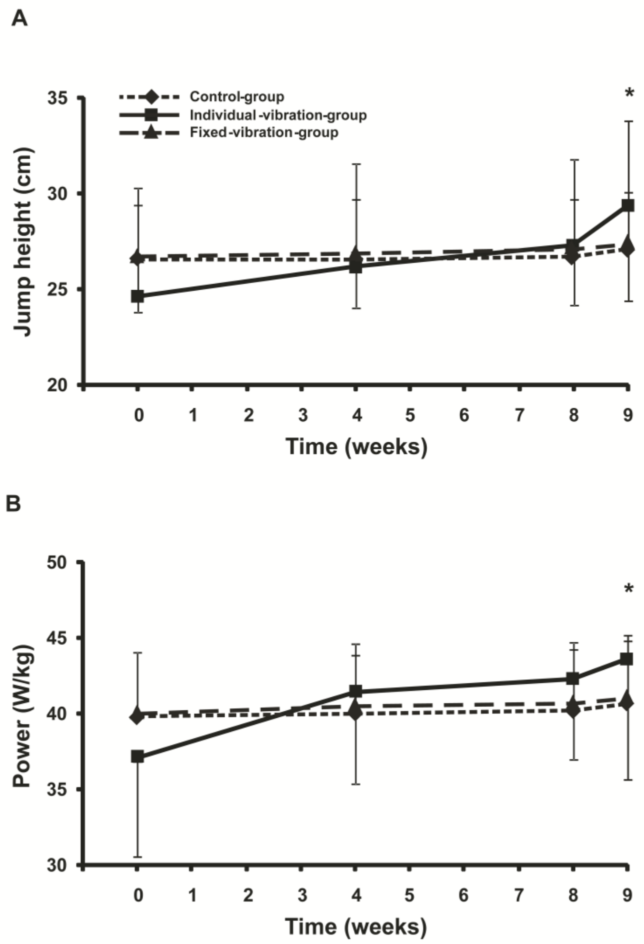


Figure 6.2. Change in jumping height (A) and power (B) for continuous rebound jump over time. 0-weeks = before vibration; 4-weeks = after 4 weeks of vibration; 8-weeks = after 8 weeks of vibration; 9-weeks = one week after the end of vibration treatment. Values are means and error bars are standard deviations. * Significant difference from 0-weeks.

The flight time increased significantly in the individual-vibration group (P = 0.014), whereas the contact time did not show significant change in any of the groups (P = 0.162 by the individual vibration-group; P = 0.118 by the fixed vibration-group; P = 0.081 by the control group) (Figure 6.3).

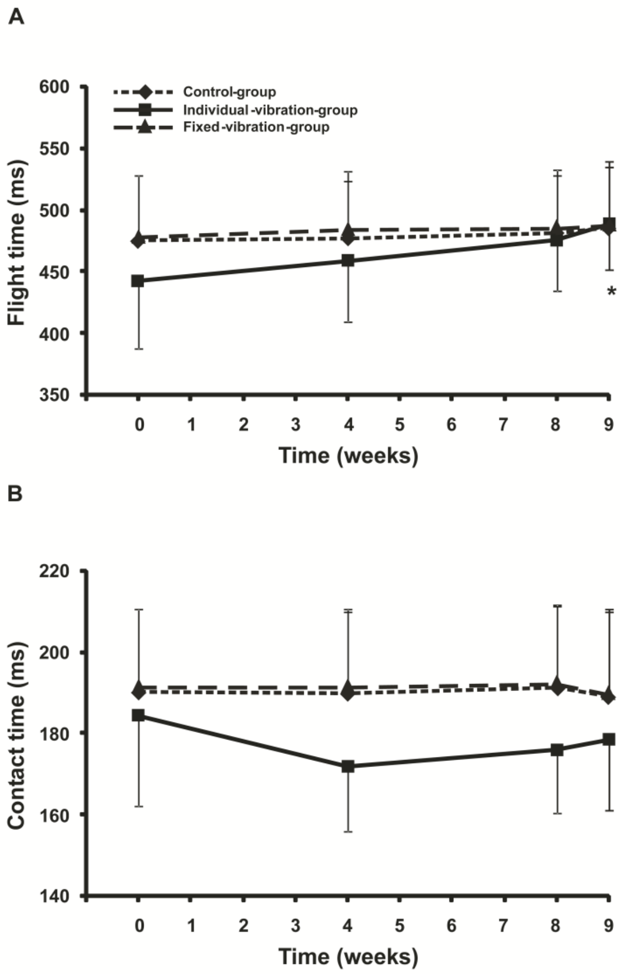


Figure 6.3. Change in flight time (A) and contact time (B) at for continuous rebound jumps over time. 0-weeks = before vibration; 4-weeks = after 4 weeks of vibration; 8-weeks = after 8 weeks of vibration; 9-weeks = one week after the end of vibration treatment. Values are means and error bars are standard deviations. * Significant difference from 0-weeks.

6.2 Effect of acute, acute residual and chronic whole body vibration

Acute flexibility. The Vibration Group progressively increased in flexibility and significant differences (P = 0.0009) were found in the 5th (from pre-test: 3.95±1.62 cm), in the 6th (from pre-test: 4.04±1.55 cm), in the 7th (from pre-test: 4.47±1.81 cm), in the 8th (from pre-test: 5.02±1.19 cm; from 1st series : 3.75±1.55 cm), in the 9th (from pre-test: 5.30±1.67 cm; from 1st series: 4.03±1.70 cm), and in the 10th series (from pre-test: 4.76±1.76 cm; from 1st series: 3.48±1.71 cm) (Figure 6.4). The Control Group showed significant differences (P = 0.0009) in the 5th (from pre-test: 3.02±2.17 cm), in the 8th (from pre-test: 3.06±2.86 cm), in the 9th (from pre-test: 3.14±2.11 cm; from 1st series: 2.29±1.38 cm), and in the 10th series (from pre-test: 3.93±2.53 cm; from 1st series: 3.08±1.80 cm; from 2nd series: 2.58±2.15 cm) (Figure 6.4).

During the 9th series, the maximal relative change for the Vibration Group (5.30±1.67 cm, 284 %) reached a level of significance (P = 0.038) compared to that of the Control Group (3.14±2.11 cm, 84 %) (Figure 6.5).

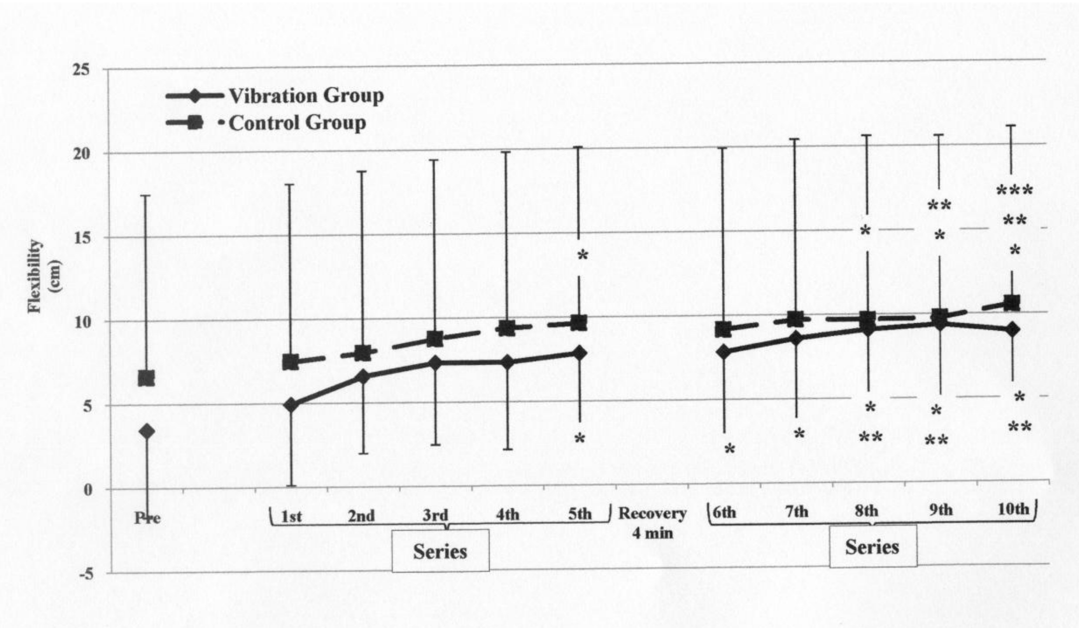


Figure 6.4. Acute effect during one session of whole-body vibration (mean values ± SD). The subjects underwent 10 series of 1-min (10 × 1) with a 1-min pause between series and a 4-min pause after the first five series (5 × 1). The measurements of flexibility were carried out in the last 10 seconds of each series. *Significant differences from pre-test, P = 0.0009; **significant differences from 1st series, P = 0.0009; ***significant differences from 2nd series, P = 0.0009.

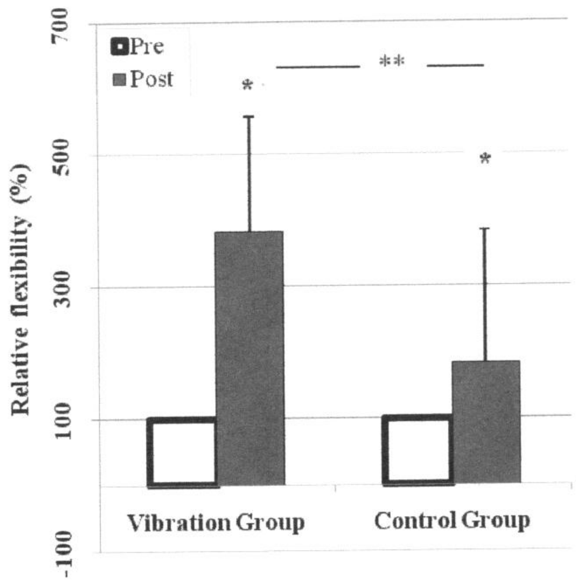


Figure 6.5. Relative change on acute flexibility during one session of whole-body vibration. The maximal differences was observed in the 9th series in both groups. *Significant differences from pre-test, P = 0.009. **Significant differences between the groups, P = 0.038.

Residual flexibility. Significant residual effects (P = 0.0014) on flexibility were found 4-min (t4) after the conclusion of the 10 series of whole-body vibration (from pre-test: 5.75±3.91 cm; from t0: 3.56±2.17 cm), as well as 6-min (t6) after (from pre-test: 6.31±3.36 cm; from t0: 4.12±2.16 cm), and again at 8-min (t8) after (from pre-test: 5.56±4.41 cm; from t0: 3.37±4.63 cm) (Figure 6.6). The Control Group showed significant differences (P = 0.0014) 2-min (t2) after the conclusion of the 10 series on the vibrating plate (from pre-test: 3.00±1.98 cm), as well as 4-min after (from pre-test: 3.12±1.63 cm), 6-min after (from pre-test: 3.06±1.87 cm), and finally at 8-min after (from pre-test: 3.43±1.84 cm; from t0: 1.75±1.55 cm) (figure 6.6). Statistical differences between the two groups were found at 6-min after the conclusion of vibration (P = 0.034), at which point the Vibration Group showed the maximal relative change to pre-test (6.31±3.36 cm, 138 %) versus the Control Group (3.06±1.87 cm , 20 %) (Figure 6.7).

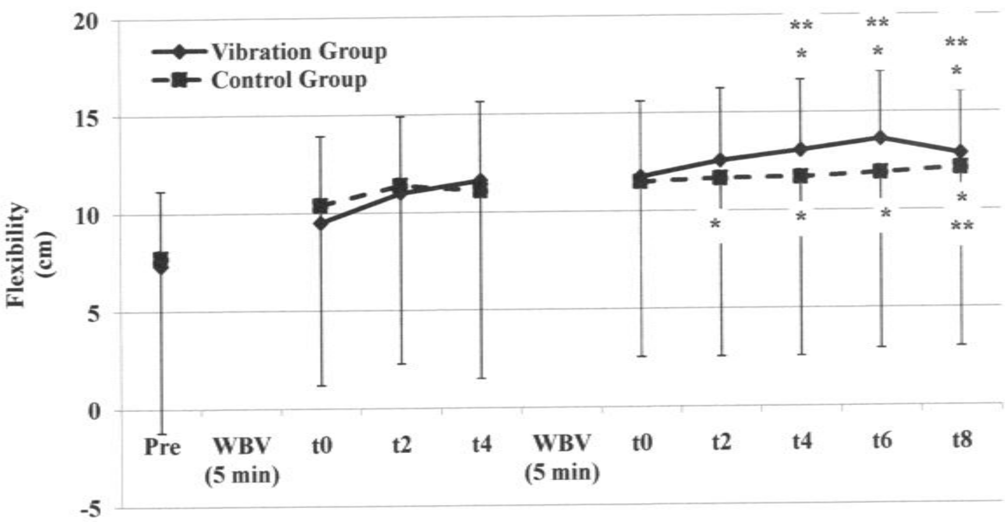


Figure 6.6. Residual effect after one session of whole-body vibration (mean values ± SD). The flexibility was assessed pre and at 0, 2, and 4 min (t0, t2, t4) after the end of the first five series, and at 0, 2, 4, 6, and 8 min after the end of 10 series (t0, t2, t4, t6, t8). *Significant differences from pre, P = 0.0014; **significant differences from t0 (after 5-min), P = 0.0014.

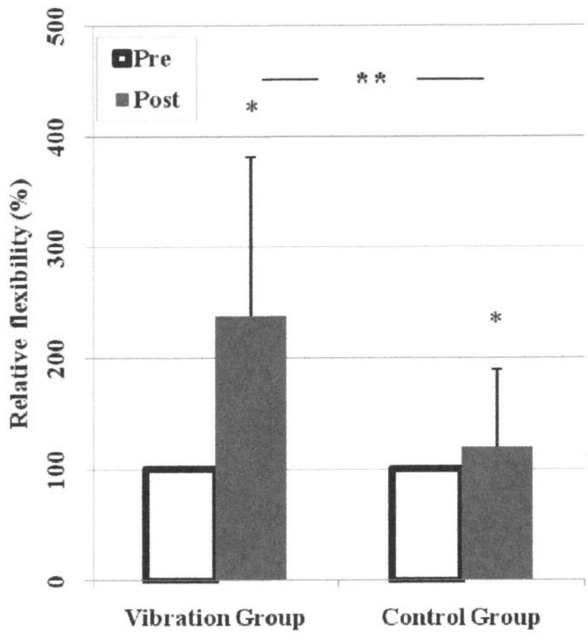


Figure 6.7. Relative change on residual flexibility after one session of whole-body vibration (6-min after the end of treatment). *Significant differences from pre-test, P = 0.009; **significant differences between groups, P = 0.034.

Chronic flexibility and reactive strength. Chronic exposure of whole-body vibration did not produce significant changes in flexibility over time (P > 0.05) (Figure 6.8), whereas power in the Drop Jump performance (1-week after the end of treatment) of the Vibration Group increased significantly resulting in a benefit of 16 % (P = 0.019) (Figure 6.9). In comparison, the Control Group did not reach a level of significance (P = 0.175).

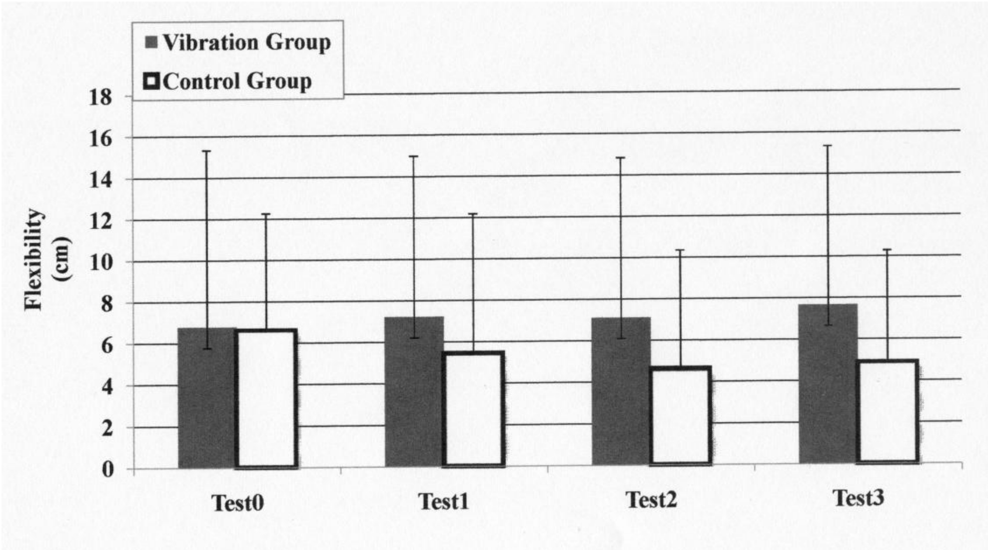


Figure 6.8. Chronic effect of whole-body vibration on flexibility (mean values ± SD). The test was performed before the treatment (Test0), after 4-weeks of treatment (Test1), 8-weeks of treatment (Test2), and 1-week after the end of treatment (Test3).

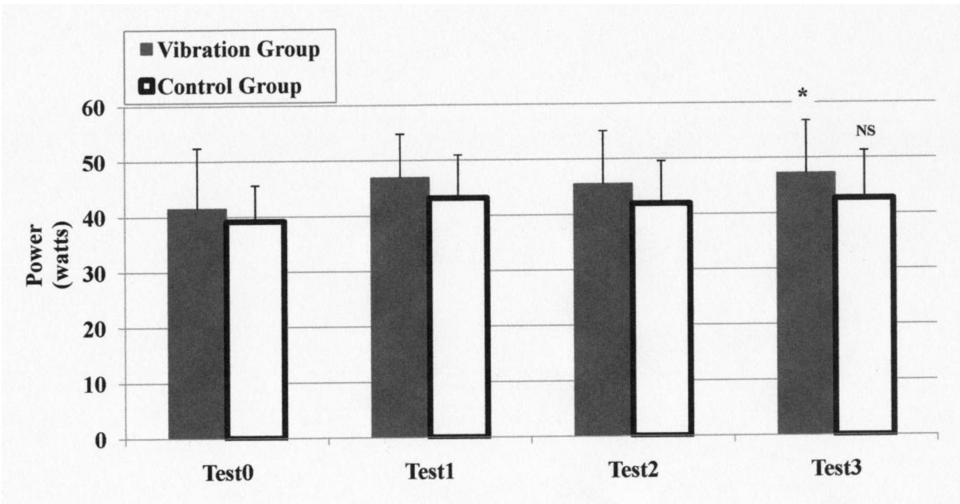


Figure 6.9. Chronic effect of whole-body vibration on Drop Jump (mean values ± SD). The test was performed before the treatment (Test0), after 4-weeks of treatment (Test1), 8-weeks of treatment (Test2), and 1-week after the end of treatment (Test3). The Vibration Group showed a significant difference from Test0 at Test3: *P = 0.019. The Control Group did not show significant differences, NS: P = 0.175.

6.3 Effect of low resonance frequency

Isometric contraction. Patients in the V group increased Mic significantly with both legs. At the affected side the improvement was 32.8 % (P=0.009) and 10.4 % (P=0.031) for the affected and non-affected knee extensors, respectively. The improvement was significantly greater for the affected leg than for non-affected leg (P=0.02). Mic in the non-vibrated group did not altered significantly for either affected or non-affected side. The RTD did not change significantly in either group and in either side (Table 6.1). The ratio of isometric strength for the non-affected and affected knee extensors (NP/P) decreased with 20.0 % in V group (p=0,019). There was no difference between the two groups at post intervention test (Figure 6.10). The EMGrms increased significantly with 37.2 % in V group for paretic knee extensors only (Table 6.2).

Table 6.1. Means and (SD) for knee extension variables in the paretic (P) and non-paretic (NP) side before and after whole body vibration in the Vibration (V) and Non-vibration (NV) group.

Variable	Leg	Group	Pre	Post	Δ, Nm	Δ, %	P
Mic, Nm	P	NV	38,2 (23,1)	39,9 (17,8)	1,8	4,7	0,635
		V	40,7 (32,1)	54,1 (38,1)	13,4	32,8	0,009
	NP	NV	83,9 (32,3)	80,5 (21,9)	-3,4	-4,0	0,765
		V	95,1 (35,5)	105,3 (39,9)	10,4	10,9	0,031
RTD, Nm/s	P	NV	188,2(173,3)	213,4(221,1)	25,2	13,4	0,567
		V	148,1(59,3)	188,2(155,1)	40,1	27,0	0,064
	NP	NV	274,5(211,1)	300,3(240,2)	25,8	9,4	0,786
		V	265,2(101,8)	303,7(181,2)	38,5	14,5	0,293
Mec, Nm	P	NV	59,1(36,7)	64,4(28,8)	4,9	8,4	0,234
		V	73,5(57,1)	91,5(65,7)	17,9	24,0	0,009
	NP	NV	99,3(35,7)	105,1(40,2)	6,8	6,9	0,289
		V	116,1(61,2)	130,9(55,8)	10,0	11,6	0,021
Wec,	P	NV	53,8(33,3)	57,3(53,2)	3,5	6,5	0,341

Joule		V	49,2(34,2)	65,5(42,2)	16,3	33,1	0,007
	NP	NV	98,8(43,9)	107,8(52,2)	9	9,1	0,125
		V	112(45,8)	125,6(52,3)	13,6	12,1	0,074

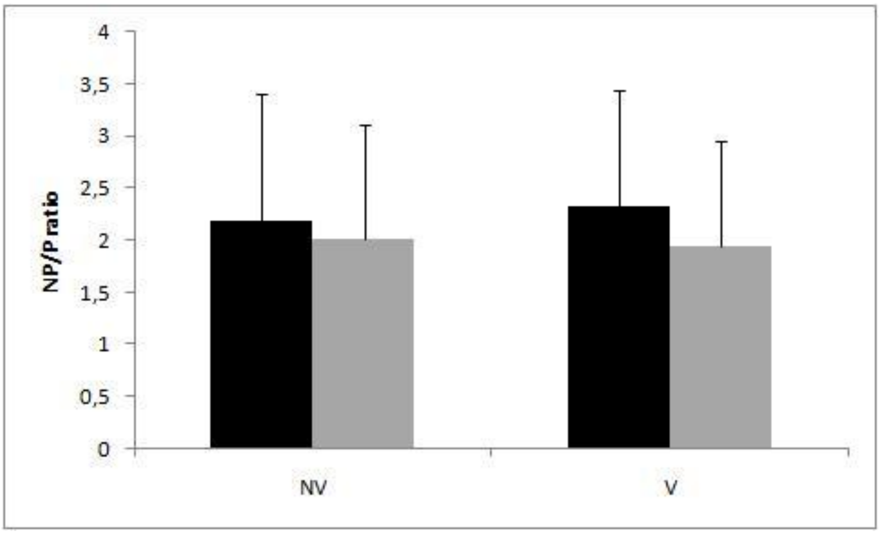


Figure 6.10. Ratio of non-paretic (NP) and paretic (P) leg strength during isometric contraction before and after intervention. The NP/P ratio decreased significantly for patients int he vibration group.

Table 6.2. Means and (SD) for myoelectrical activity (EMGrms) of vastus lateralis muscle in the paretic (P) and non-paretic (NP) side before and after whole body vibration in the Vibration (V) and Non-vibration (NV) group.

Variable	Leg	Group	Pre	Post	Δ, μV	Δ, %	p
Mic EMGrms, μV	P	NV	185,5 (143,0)	209,2 (172,5)	23,7	12,8	0,304
		V	195,6 (160,3)	268,3 (186,3)	72,7	37,2	0,011
	NP	NV	480,1 (286,5)	465,2 (308,9)	-14,9	-3,1	0,738
		V	490,1 (222,1)	518,7 (226,6)	28,6	5,8	0,738
Mec EMGrms, μV	P	NV	241,2 (143,8)	225,1 (183,5)	-16,1	-6,7	0,585
		V	185,5 (98,3)	255,1 (101,7)	69,6	37,5	0,012
	NP	NV	386,5 (169,6)	452,2 (231,9)	65,7	17,0	0,242
		V	422,8 (387,3)	464,4 (301,3)	41,6	9,8	0,471

Eccentric contraction. Patients in the V group increased Mec with 24.0 % with the affected leg (p=0.009) and with 11.6 % with the non-affected knee extensors (p=0.021). Although Mec increased in the non-vibrated group the differences in pre-post comparison were not significant (Table 6.1). The EMGmrs was significantly elevated (37.5%) for paretic leg in V group only (p= 0.012). Wec was significantly greater (33.1 %; p=0.007) in V group, but for the affected leg only. Although patients produced greater mechanical work with the non-affected leg after WBV intervention, but the difference between pre-post Wec was not statistically significant. The NV group did not improved Wec significantly (Table 6.1). The NP/P ratio decreased in both NV and V group with 2.9 and 10.4 %, respectively, but the difference was not significant in either group in pre-post comparison (Figure 6.11).

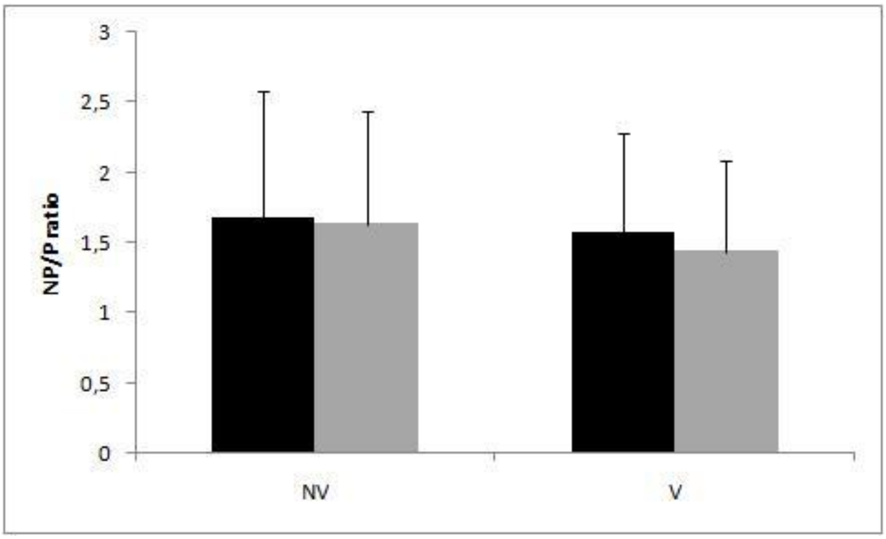


Figure 6.11. Ratio of non-paretic (NP) and paretic (P) leg strength during eccentric contraction before and after intervention.

Chapter 7

Discussion

7.1 Effect of individualized vibration frequency

Whole-body vibration versus individualized whole-body vibration. Whole-body vibration, applied at individual vibration frequencies, produced statistically significant improvements in selected vertical jump performance. Vertical jump performance improved by 11% (P = 0.01), and 22% (P = 0.001) in the individualized-vibration group when performing both the squat jump and the continuous rebound jump. The fixed-vibration group and, surprisingly, the control group significantly increased performance in the squat jump by 3% (P = 0.011) and 2% (P = 0.006), respectively. The small but significant improvement in the fixed-vibration group and the control group may be attributed to the participant's other training that was carried out during the time of the vibration intervention, but it is not clear as to why a significant change was not also found (across all groups) in the countermovement jump and the continuous rebound jump (fixed-vibration group).

These results partly support our hypothesis and also agree, in part, with previous results (14, 15, 27, 30, 32, 33, 70, 75, 76, 78, 80, 89, 90, 91). Partial agreement between the current results and those reported previously are most likely due to substantial differences in experimental designs, participants, and outcome measures used in those studies.

The use of the individual vibration frequency. It is unclear whether or not there is an optimal vibration frequency for each individual and, if so, whether such a frequency would improve performance more than any other frequency. Unlike the present study which used individualized frequencies, previous studies used frequencies that were fixed or which progressively increased for each participant during the period of treatment. Indeed, whole-body vibration at various vibration frequencies has produced inconsistent results. In some studies, muscle strength increased (14, 32, 70, 75, 76, 80, 89, 90, 91), whereas in other studies it did not change (27, 30, 33, 78, 83). We suspect that these inconsistent results could be due to differences among individuals in their sensitivity to vibration frequency. We suggest that the frequency characteristics of whole-body vibration should be prescribed in an individualized fashion similar to exercise prescription for progressive resistance exercise in terms of loads, number of repetitions, and series. There is evidence to suggest, for example, that the determination of optimal dropping height for drop jump training improved performance in vertical jumps more than non-customized training programs (11, 96). In addition, recent studies have demonstrated that individuals react differently to a similar vibration frequency (21, 22).

In the present study, the individual frequency to be used during whole-body vibration for each participant was estimated on the basis of EMG_{rms} activity. An important observation was that the individual frequency estimated for whole-body vibration varied between participants. For example, if participant B had been vibrated at 30 Hz, the EMG_{rms} activity would have been about 74% less than the EMG_{rms} that occurred at 45 Hz, the individual frequency estimated for this individual. As another example, if participant A had used 45 Hz he would have had about 34% less EMG_{rms} (Figure 4.3).

Results from previous studies suggest that untrained young males and females (32, 89, 90, 91, 94) as well as elderly females (75, 76, 80, 94) may benefit the most from whole-body vibration. In addition, performance in vertical jumps improved significantly in young adults (32, 89, 90, 91) but the largest change, 19%, occurred in post-menopausal women (75). In contrast, whole-body vibration produced little improvements in vertical jump height in trained and physically active individuals (30, 33). These data suggest that the potential to improve performance is associated with training history.

Although the participants in the present study were physically active males and females, they still showed significant improvements in vertical jump height after whole-body vibration when an individualized frequency was used for the vibratory treatment. De Ruiter *et al*. (30) used similar participants and used fixed instead of individualized frequency for whole-body vibration. We, like de Ruiter *et al*. (30), did not observe significant improvements in jump height in the fixed-vibration group. In total, these data suggest that individually estimated versus fixed vibration frequency may indeed improve physical performance even in previously trained males and females, and the extent of such improvement can be similar over a shorter time as that observed in sedentary participants.

Effect of whole-body vibration on different type of vertical jump. The second aim of this study was to determine if whole-body vibration produces similar improvements in vertical jumps that use different muscle contractions in the preparatory phase. If whole-body vibration decreases the recruitment threshold of the fast motor units (77), then individualized whole-body vibration should increase jumping performance in all three types of vertical jumps as each form of jump requires rapid muscle activation. It is also possible that whole-body vibration would increase jump height more in both the countermovement and continuous rebound jump than in the squat jump because the stretch reflex evoked in those jumps would increase motoneurones excitability, and hence jump height (65). Unexpectedly, we found less improvement in the countermovement jump than in the squat jump. Most probably the large and relatively slow angular displacement in the countermovement jump did not elicit a stretch reflex, which is more influenced by the whole-body vibration than by voluntary effort. As we expected, the greatest improvement in jumping height was in the continuous rebound jump as it has the shortest angular displacement. Although both the countermovement jump and the continuous rebound jump are characterized by the stretch-shortening cycle, the neuromuscular activation in the countermovement jump is different from that found in the continuous rebound jump. The countermovement jump is characterized by large angular displacement and slow stretching speed (3-6 $rad \cdot s^{-1}$), while the continuous rebound jump is performed at a fast stretching speed (10-12 $rad \cdot s^{-1}$) and small angular displacement (14). This explanation is supported by the fact that stretch reflex is most capable of accommodating small length change in the muscle (65).

In relation to this finding, Nardone and Schieppati (68) reported that lengthening of triceps surae resulted in selective recruitment of fast motor units. Since the triceps surae play a more significant role in the execution of vertical jumps than the knee extensors which are the dominant muscle group in the countermovement jump (56), this also explains why significantly greater improvement was observed in the continuous rebound jump. In general, we may conclude that the influence of individualized whole-body vibration on physical performance is the greatest when movement or strength exertion is carried out with short angular displacement and when the muscle stretch is fast.

7.2 Effect of acute, acute residual and chronic whole body vibration

To our knowledge, this is the first study to investigate acute, residual and chronic effects of individualized whole-body vibration in young physically active subjects, using the stand and reach test. The novel aspects of this investigation include: the effects on flexibility were assessed during and not only immediately after whole-body vibration; several measurements were carried out to construct a kinetics of flexibility during and following exposure to vibration; an individual frequency of vibration was used.

Acute flexibility. *T*he acute effects of whole-body vibration treatment resulted in a progressive increase in flexibility that reached maximum relative change during the 9th min of treatment (Figures 6.4, 6.5). This pronounced effect, was, in part, expected and cannot be compared to other studies considering that no other research has been directed at the acute influence of whole-body vibration on flexibility enhancement. In an attempt to identify the mechanism that determined the large effect on flexibility in both groups, it is necessary to clarify what was measured with the stand and reach test and make an analysis of the position adopted by the subjects on the vibrating plate.

The stand and reach test protocol allows the indirect assessment of the influence of the 4 major muscle groups that affect the scores: erector spinae, hip rotators, hamstrings, and gastrocnemii (45). On the other hand, the half-squat position adopted by the subjects was sustained by a moderate isometric contraction of quadriceps, tibialis anterior, gastrocnemii and gluteus muscle. Furthermore, by superimposing whole-body vibration in this position, a significant enhancement in EMG activity has been revealed in the quadriceps, tibialis anterior, and gastrocnemii but not in the hamstring muscles (1). Whole-body vibration assumes that the vibration induced in these muscles by a vibrating plate elicits a tonic vibration reflex similar to the direct application of vibration on muscles or tendons. This so-called tonic vibration reflex (TVR) is to a large extent mediated by IA polysynaptic excitatory projections to the alpha motoneurones. The motor effect of muscle vibration in healthy subjects is not restricted to the muscles undergoing vibration (which respond with a contraction); the vibration also induces the relaxation of antagonist muscles, as a sign of a reciprocal inhibition (42). Increased flexibility could also be caused by the stimulation of the Golgi tendon organs (gluteus, and gastrocnemius), which, unlike the muscle spindles, results in inhibition of the contraction, followed by relaxation of the muscle (42). These mechanisms could partially explain the increase in flexibility in our study. The mechanical action of vibration is to produce fast and brief changes in the length of the muscle-tendon complex. This perturbation applied to muscles in a lengthened position (gluteus, hamstring, and gastrocnemius) over time could have modified the viscoelastic properties of the muscle-tendon complex, increased stretch tolerance as with stretching exercises (43, 66) and/or reduced stretch pain as there is evidence that vibration has analgesic effects during and after immediate application of such stimuli to the muscle or tendon (58). The influence on the mechanical properties of the muscle-tendon complex could also explain the significant enhancement in flexibility observed in the Control Group. In addition to this, the viscoelastic behavior of the muscle-tendon complex appears to be insensitive to increases in intramuscular temperature in a physiological range (60). Therefore, the enhancement in flexibility seen in the Control Group should be attributed not to the effects of warm-up but to the position assumed by the subjects.

Acute residual flexibility. In a similar manner to acute flexibility, the residual changes started to increase progressively in both groups immediately after 5-min on the vibrating plate, although the level of significance was reached after the end of the entire 10 minute session, with a maximum relative increase at 6-min (t6) after the end of treatment (Figures 6.6, 6.7). It is interesting to note that the maximum relative change observed in acute was nearly confirmed as residual effect in the Vibration Group, while the residual effect in the Control Group was less. These results emphasize the large residual effect of whole-body vibration on flexibility.

Cochrane and Stannard (27) and Jacobs and Burns (51) reported a significant improvement of 8.2 % and 16.2 % respectively in the sit and reach test following 5-min of whole-body vibration. Sands et al. (82) superimposing vibrating cushions (vibrating device) on forward split stretching positions showed a benefit of about 6 cm in the right rear split position and 7.5 cm in the left rear split position. However, differences in protocol training, testing and the number of pre-post comparisons, makes it difficult to directly compare our results with these studies. For example, if we had tested the flexibility using a single pre-post comparison after 5 min of whole-body vibration, the relative change would have been 81 % (P = 0.021) for the Vibration Group and 34 % (P = 0.022) for the Control Group. We also specify that these relative changes were calculated in each of the subjects and the mean relative change (reported in section statistical analysis) was then calculated. Alternatively, calculating the relative change by the mean values, the relative change could be different. In the example reported above the relative change for the Vibration Group would be 50 % and 47 % for the Control Group.

Investigations into hamstring flexibility (as determined by increased knee-extension range of motion) revealed that following 1-session of static stretching the increase of 4% lasted only 3 minutes after cessation of the stretching protocol (34) whereas following 1-session of hold-relax stretches the relative change of 7 % lasted 6 minutes after the stretching protocol ended (85). Recent research has reported that a single massage of the hamstring muscle group is not associated with any significant increase in sit and reach test performance immediately after treatment in physically active young men (4).

In the present study, flexibility was measured for no longer than 8-min after the protocol ended, therefore the duration of maintained flexibility was not exactly defined, even though the maximum relative change occurred at 6-min and significant changes were measured after the end of treatment in both groups. Finally, the large improvement in flexibility resulted from the combination of the vibratory treatment and position adopted on the vibrating plate.

***Chronic flexibility and reactive strength*.** Unexpectedly, the vibratory treatment did not produce a significant adaptive response over the 8-week period in flexibility test (Figure 6.8). On the contrary, the Vibration Group improved reactive strength (16 % in Drop Jump Power) significantly over the same period of treatment (Figure 6.9).

Vibrations applied locally and conventional stretching exercises resulted in a mean increase of 8.7 % in a two-leg split exercise for flexibility after three weeks of treatment (49). A similar long term-term study reported a significant increase in forward leg splits exercises that ranged from 6 to 9 cm (82). Furthermore, when 4-weeks of whole-body vibration are combined with the contract-release stretching method there may be an additional positive effect of 30 % on flexibility in the hamstring muscles (93).

The disagreement between the current study and those aforementioned is most likely due to marked differences in experimental designs, subjects, and outcome measures used in those studies. In particular, the vibration load was superimposed on stretching exercises in all of the studies, which is completely different from whole-body vibration being applied alone. From a methodological point of view only the Fagnani' et al. study (39) seems comparable to the present study. Contrary to our results, they reported a significant effect of 13 % using the sit and reach test, after 8-weeks of whole-body vibration in female competitive athletes. However, in the latter study the subjects stood with one leg flexed at 90° degrees on the vibrating platform and the other leg held in the air. Therefore, the subjects assumed a one-legged half-squat position that clearly differs from the standard two legged half-squat position as reported both elsewhere and in the present study. Our impression is that the other leg "held in the air" might have produced a positive effect similar to stretching exercises. Another important feature in the study of Fagnani et al. (39) and in contrast to the present study, was that the subjects in their control group did not perform any exercise on the vibrating plate at all but nevertheless showed a tendency to increase scores in the sit and reach test (6-7 %; not significant). In light of these considerations a benefit derived from the combination of the regular training load which these female competitive athletes underwent and whole-body vibration cannot be excluded in the vibration group. In fact, stretching training sessions were always included in their activities (volleyball, basketball, gymnastic, and track and field) unless special instructions were given to the subjects during the follow-up which, however, the authors did not report in the text.

In the present study, a potential point of concern, although in line with others studies, was the relatively small sample size (n = 9). Post hoc analysis of our data showed that we could have obtained training effects in the order of 13 % on flexibility test. It may be argued that the present study was under-powered to detect relatively small but functionally relevant changes in chronic flexibility. However, the effect size (ES) was less than 0.2, which means just a 20-30 % chance of detecting a real difference with 100 subjects (n = 100). It is highly unlikely, therefore, that a larger sample size would have led to a different outcome in flexibility. In addition, the same vibration treatment improved the power in drop jump (16 %, P = 0.019) significantly and post hoc analysis of these data revealed a moderate effect size (ES = 0.6).

These results confirm a previous study (35) in which both jumping height (22 %) and power (18 %) increased significantly during 10 seconds of continuous rebound jump following 8-weeks of whole-body vibration. In the latter, the authors argued that the influence of whole-body vibration is most notable when movement or strength exertion is performed with short angular displacement and when the muscle stretch is fast; that is vertical jumps characterized by a stretch-shortening cycle induced by a brief phase of impact (drop jumps and rebound jumps) (98, 99). Moreover, since the triceps surae are the dominant muscles in this type of vertical jump, it could explain the greater improvement compared to the squat jump and counter movement jump (56). In light of these results, we can point out that reactive strength is more sensitive to whole-body vibration than flexibility.

7.3 Effect of low resonance frequency

The main finding of the present study is that low vibration frequency applied in four weeks resulted in significant improvement in both isometric and dynamic strength of knee extensors and the improvement was more pronounced in the affected side than in the intact side. The EMG activity of knee extensor muscle increased with similar manner indicating neural adaptation due to the vibration intervention.

We hypothesized in this study that low frequency WBV could result in significant improvement in muscle strength in elderly people with low physical fitness. We also hypothesized that the effect of WBV could be more pronounced in that case when the force exertion capacity is low due to either low or restricted physical activity. To test our hypothesis we selected a specific population, i.e. stroke patients. It is well demonstrated in the literature that because of the damaged hemisphere the neural drive for the affected side is weak and as the consequence the force generation is depressed (7, 48). However, the muscle force generation in the intact side is also less than in the aged matched healthy elderly people reported by Jones et al. (53). These facts provided a good basis to test our hypothesis within one person with the same motivation and voluntary effort.

The amount of force that can be exerted isometrically depends upon the physiological cross-sectional area of the muscle and on the level of the facilitation of the respective motor area, i.e. on the capability to recruit motor units (67). We observed 32.8 % and 10.9 % improvement in Mic at the paretic and non-paretic side, respectively, which can be attributed mostly to the increased activation of the motor cortex. This assumption is supported by the findings of several authors reporting cerebral representation of muscle or tendon vibration (28, 55, 86). However, we have to note that Mic increased three times more in the affected side than in the intact side indicating that the damaged hemisphere probably was more sensitive for the low vibration frequency than the other side. It seems that WBV elicit similar effect as the direct muscle vibration that induces focused motor cortical activation reducing activity of intra-cortical inhibitory inter-neural circuit (79). In conjunction with this finding we found that the EMG activity increased significantly in the affected knee extensors only, which may support the aforementioned assumption. We did not measure the morphological change of the knee extensors, but we cannot expect significant increase of the physiological cross-sectional area due to the relatively short intervention time (67). However, it should be mentioned that the great difference between the affected and non-affected leg in improvement of Mic proposes the possibility of alterations in muscle level, too. It is important to note that the decreased NP/P ratio indicates reduced strength deficit which may help to improve gait variables (54).

Concerning the ability to develop torque rapidly (i.e. RTD) no significant improvement was observed despite the RTD increased with 27.0 % and 14.5 % for the affected and non-affected leg, respectively. It seems that the rapid recruitment of motor units and their synchronized function is not associated with the greater facilitation of the motor cortex albeit the increased isometric force usually results in the augmentation of RTD. However, our previous observation may contradict to the present result in which we were able to demonstrate a weak, but significant acute residual effect on RTD after one session WBV (88). It is very probably that the great inter-individual variability due to the non uniform reaction to WBV resulted in the insignificant improvement. Also, it can be assumed that chronic vibration intervention of four weeks does not provide stimuli strong enough for chronic residual improvement in motor unit synchronization.

The muscles can produce greater force under eccentric contraction than under isometric contraction due to the resistance of elastic elements and the stretch reflex. We applied relatively low stretching velocity (60°/s) and medium range of motion (60°). The low stretching velocity is not probable to elicit stretch reflex and therefore we assumed that the enhanced force could be attributed to the increasing resistance of the elastic elements. It could be assumed that WBV influences muscle stiffness which may result in increased peak eccentric torque and working capacity. However, the influence of the increased excitability of motor cortex and as a consequence improved voluntary activation of the motor areas on eccentric torque also can be expected because of the improved isometric strength. Indeed significant improvement (24.0% and 11.6 % for P and NP leg) in V group was found in peak eccentric torque associated with significant improvement of EMG activity of vastus lateralis muscle, but only in the paretic side. From this result we may conclude that the significant improvement in the intact side could be attributed to the increased isometric force resulting in enhanced stiffness of the serial elastic elements (mainly tendon). This assumption is supported by the results of Svantesson et al. (87) suggesting that tendon stiffness is greater in non-affected limb contrary to the affected limb at which the muscle stiffness is greater. Indeed we found twice as much torque improvement and 3.7 folds EMG enhancement at the paretic side compared to the intact side indicating greater torque production of the knee extensors and in consequence to the greater muscle stiffness during eccentric contraction. This increased muscle force resulted in three fold greater improvement in mechanical work in the paretic side.

In relation with the enhanced eccentric torque production the mechanical work increased with 33.1% for paretic and with 12.1 % for non-paretic side in the vibrated group. It should be mentioned that despite the 12.1 % improvement in non-paretic side the treatment effect just failed to reach the significant level. The enhanced working capacity of the muscles in the paretic side indicates that the patients might be able to keep exciting motor cortex longer in time which resulted in greater torque production during the eccentric contraction. However, it should be mentioned that 20 Hz vibration frequency may be not effective enough to increase the working capacity of the non-affected muscles significantly.

There is no common stand concerning the most effective vibration frequency domain. Similar improvement in muscle strength was reported when high or medium frequency was applied. Reviewing the literature we find eight experiments studying the effect of WBV on static and dynamic muscle strength in older healthy population. Four of them applied high frequency (35-40 Hz) vibration intervention during six (94) or twelve month (5, 6, 75). The greatest improvement in knee extensor isometric (15.0%) and dynamic (16.1%) strength was reported by Roelants et al. (75) after 12 month WBV intervention. Verschueren et al. (94) applying same intervention reported similar improvement, but the duration of WBV training was only six months. In young untrained females Delecluse et al. (32) reported similar improvement in isometric knee extensor strength (16.6 %) after three month WBV intervention with frequencies of 35-40 Hz. Unfortunately, no study has been found in the literature investigating the effect of high frequency WBV with shorter duration in older adults. It seems that the duration of the WBV treatment does not influence the degree of improvement, at least beyond six month. Rees et al. (72) studied the effect of eight week WBV with 26 Hz frequency, and found 7,9 % and 18,2 improvement in isometric strength for knee extensors and plantar flexors, respectively. This finding indicates that relatively short intervention time and so called optimum frequency results in almost similar effect than three or six time longer duration in isometric strength. Consequently, the long duration (more than two month) WBV with high vibration frequency treatment is not more beneficial than WBV with relatively short and medium frequency is. Furthermore, the result of the present study indicates that even low frequency and relatively short WBV intervention can induce significant augmentation in muscle strength.

Chapter 8

Conclusion

8.1 Effect of individualized vibration frequency

The results suggest that chronic whole-body vibration can significantly improve performance in vertical jumps. Compared with fixed frequencies, individualized vibration frequencies based on the EMG response to whole-body vibration seem to produce superior improvements in vertical jumps, especially those performed with small joint excursions. Whole-body vibration performed at individualized frequencies may increase performance in a shorter time compared to whole-body vibration which uses a fixed frequency. Future studies will have to confirm the present results and also determine the mechanisms mediating the performance-enhancing effects of whole-body vibration.

7.2 Effect of acute, acute residual and chronic whole body vibration

The results show that individualized whole-body vibration without superimposing other exercises is an effective method of acutely increasing lower back and hamstring flexibility compared to a two-legged half-squat position. These findings suggest that whole-body vibration intervention is an appropriate preparatory activity for training or competition. Since whole-body vibration failed to induce a chronic effect on flexibility, the reduced stretch pain seems to be the major mechanism responsible in mediating the flexibility performance by enhancing acute and residual effects of whole-body vibration. Finally, whole-body vibration intervention may be a more successful training method in developing reactive strength rather than flexibility. Future studies should try to confirm the present results and also determine the relative role of the nervous system and viscoelastic properties of the muscle-tendon complex, both associated with functional changes induced by whole-body vibration.

7.3 Effect of low resonance frequency

The presented results may allow us to conclude that the effectiveness of vibration frequency applied depends upon the condition of the neuromuscular system, may be independently of the age. Our result clearly shows that WBV with low frequency domain can contribute to the improvement of muscle strength when it is applied on individuals with restricted physical activity due to neurological and/or muscular impairment. It seems that WBV with low frequency can influence the central nervous system and the neural drive indicating with the enhanced myoelectrical activity of the muscles during voluntary effort.

Chapter 8

Summary

Three separate studies were carried out to test the acute, acute residual and chronic effect of whole body mechanical vibration (WBV). In the first and second study eight week WBV was used either with individually selected vibration frequency that ranged from 20 to 35Hz frequency or 30 Hz frequency for each subject. In the third study 20 Hz frequency was applied during four weeks for acute stroke patients. In the first study dynamic force was estimated by using squat jumps, countermovement jumps or 10 s rebound jumps. In the second study the flexibility of the hamstring and lower back muscle were tested during vibration, after having finished the vibration exposure, and before and after eight week vibration intervention. In addition the reactive muscle strength of the extensors in lower limbs were determined before and after eight week vibration intervention. In the third study maximum isometric force and force development, maximum eccentric force and mechanical work were determined for the affected and non-affected knee extensors.

The results of the present investigation may allow us to conclude the followings:

- The individually selected vibration frequency based on the EMG response for WBV intervention results in greater improvement in explosive and reactive strength as compared with fixed frequencies vibration intervention;
- The improvements in vertical jumps are greatest when movement or strength exertion is carried out with short angular displacement and when the muscle stretch is fast that occurs in rebound jumps;
- Individualized whole-body vibration without superimposing other exercises is an effective method of acutely increasing lower back and hamstring flexibility (acute and residual effect);
- Individualized whole-body vibration does not induce a chronic effect on hamstring flexibility;
- The results indicates indirectly that effect of vibration frequency depends upon the physical and the neuromuscular condition of the treated muscles based on the study in patients with stroke.

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