EFFECTS OF WHOLE-BODY VIBRATION TRAINING ON MUSCLE STRENGTH AND FLEXIBILITY: SIGNIFICANCE OF THE VIBRATION FREQUENCY

Outlined Booklet of the PhD Thesis

Riccardo Di Giminiani

Semmelweis University

Doctor School for Sports Science

Supervisor: Prof. Dr. József Tihanyi, DSc
Opponents: dr. Rita Kiss, associate professor, CSc
Prof. Dr. Gábor Pavlik, DSc

Chairman of the Committee: Prof. dr. Zsolt Radák, DSc
Members of the Committee: dr. Péter Apor, CSc
Prof. dr. Károly Bretz, DSc
Prof. Dr. János Mészáros, CSc

Budapest
2010

I. Introduction

Over the last fifteen years the use of mechanical vibration for training purposes has began attracting interest and many researchers have studied its effects on the physical performance of trained and untrained people.

In the whole body vibration intervention the 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 or vibrating cables and dumbbells if the stimuli involves a specific muscle.

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 $m \cdot s^{-2}$).

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. It has been found an elevated muscle activity and increased damping of vibration when the frequency of vibration is close to the natural frequency of soft tissues. This muscle tuning paradigm 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.

II. OBJECTIVES

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.

The particular objectives of the studies presented in the thesis 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;

(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) 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;

(4) to determine whether the applied vibration intervention over time influences flexibility and reactive strength differently;

(5) to investigate the effect of low frequency, short duration whole-body vibration on static and dynamic force production of intact and affected knee extensors of patients with stroke.

III. METHODS

III. 1. Selection of Subjects

Study I. 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.

Study II. 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. Subjects were randomly assigned to either the Acute and Acute 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.

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 1. 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 .

Study III. Twenty stroke patients (12 men and 8 women) participated in this study. Their mean age was 58.6±6.3 years (range: 50-69). 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. 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.

III. 2. Estimation of the individual vibration and EMG analysis

Study I and Study II. 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. 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 $m \cdot s^{-2}$. 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. In a comparable group of participants, the day-to-day reliability of the individual vibration frequency was 0.92 (coefficient of variation = 6.2). 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.

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. 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).

III. 3. Vibration Intervention

Study I. 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). 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.

Study II. All the subjects stood on the vibration platform in exactly the same body position 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. The training session was the same as that applied to test acute and residual effect (see above).

Study III. Patients in V group were trained for four weeks three times per week applying whole-body vibration. 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.

III. 4. Testing Procedures

Study I. The participants were tested on four occasions at the same time of day, and they were requested to withdraw from any exhausting 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, Bosco System, Rieti-Italy). 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. 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°. 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 and used in order to analyze the explosive strength characteristics of the leg muscles.

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 $m \cdot s^{-2}$).

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. During the jumps, flight time and contact time were measured and used to calculate the jump height.

The average power was calculated from the contact time and flight time, and also used to estimate the explosive strength during a ballistic movement that involves a stretch-shorten cycle of the legs. 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 $W \cdot kg^{-1}$) was calculated as follows:

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

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

Study II. *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.

Acute 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. 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). 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.

Study III. 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 residual 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. 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. Peak torque (Mec) and mechanical work (Wec) was determined or calculated from the respective torque-time curves.

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.

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. 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.

III. 5. Statistical analysis

Study I. Conventional statistics methods were employed, including mean values, standard deviations (*s*), and percentages (%). Normality tests, Shapiro-Wilk’s W test, were performed for all dependent 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. All analyses were executed using the SPSS package (version 12). The probability level was set at $P < 0.05$ to determine statistically significant differences.

Study II. 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. All analyses were executed using the Addinsoft™ XLSTAT (version 2009.4.07). Statistical significance was set at P □ 0.05.

Study III- 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 $p<0.05$.

IV. RESULTS

IV. 1. 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), 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, 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).

IV. 2. 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, and statistical significance was reached at one week after the end of the vibration treatment (6.5 $W \cdot kg^{-1}$, *s* = 4.0; 18%) (*P* = 0.002). The increase in mechanical power in the fixed-vibration group was slight (1.1 $W \cdot kg^{-1}$, *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 $W \cdot kg^{-1}$, *s* = 1.6; 2%) (*P* = 0.183). 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).

IV. 3. 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). 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).

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 %).

IV. 4. Acute 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). 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). 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 %).

IV. 5. Chronic Flexibility and Drop Jump

Chronic exposure of whole-body vibration did not produce significant changes in flexibility over time ($P > 0.05$), 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 % ($P = 0.019$). In comparison, the Control Group did not reach a level of significance ($P = 0.175$).

IV. 6. 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. 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. The EMGrms increased significantly with 37.2 % in V group for paretic knee extensors only.

IV. 7. 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. 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. 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.

V. CONCLUSIONS

The primary findings of this study were:

1) Compared with fixed frequencies, individualized whole-body vibration based on the EMG response to whole-body vibration produces greater improvement in explosive strength and reactive strength;

2) 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 is in rebound jumps;

3) Individualized whole-body vibration without superimposing other exercises is an effective method of acutely increasing lower back and hamstring flexibility (acute and residual effect);

4) Individualized whole-body vibration does not induce a chronic effect on hamstring flexibility;

5) Low vibration frequency results in significant improvements in both isometric and dynamic strength of knee extensors and the improvement is more pronounced in the affected side than in the intact side. This result indicates indirectly that effect of vibration frequency depends upon the physical and the neuromuscular condition of the treated muscles.

PUBLICATION LIST

A) Articles related to the PhD thesis:

Di Giminiani R, Tihanyi J, Safar S, Scrimaglio R. (2009) The effects of vibration on explosive and reactive strength when applying individualized vibration frequencies. J Sports Sci, 27:169-177.

Di Giminiani R, Manno R, Scrimaglio R, Sementilli G, Tihanyi J. (2010) Effects of individualized whole-body vibration on muscle flexibility and mechanical power. J Sports Med Phys Fittness (in press).

Tihanyi J, **Di Giminiani R**, Tihanyi T, Gyulai G, Lukasz T, Horváth M. (2010) Low resonance frequency affects differently strength of paretic and non-paretic leg in patients with hemiplegia. Acta Physiol Hun, 97: 174–184.

B) Articles not related to the PhD thesis:

Di Giminiani R, Manno R, Scrimaglio R. (2008) Nuove evidenze scientifiche della vibrazione indotta sulla forza esplosiva prodotta con e senza pre-stiramento. Atletica Studi, Fidal, 3:13-20.

Di Giminiani R, Scrimaglio R. (2008) Le vibrazioni indotte: recenti investigazioni con l'utilizzo della frequenza di vibrazione individuale. Rivista di Chinesiologia, 2:35-45.

C) Conference Proceedings (abstracts):

Di Giminiani R. Optimal frequency in whole-body vibration treatment. III International meeting on rehabilitation medicine. Faculty of Medicine-University degli Studi di Roma Tor Vergata. Roma, Italy September 9-11, 2009. (Published on Preceedings).