

The effect of the training with the different combinations of frequency and peak-to-peak vibration displacement of whole-body vibration on the strength of knee flexors and extensors

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ABSTRACT: Whole-body vibration training has become a popular method used in sports and physiotherapy. The study aimed to evaluate the effect of different vibration frequency and peak-to-peak displacement combinations on men knee flexors and extensors strength in isokinetic conditions. The sample consisted of 49 male subjects randomly allocated to seven comparative groups, six of which exercised on a vibration platform with parameters set individually for the groups. The experimental groups were exposed to vibrations 3 times a week for 4 weeks. The pre- and post- isokinetic strength tests, with the angular velocities of 240°/s and 30°/s, were recorded prior to and 2 days after the training. After 4 weeks of whole-body vibration training, a significant increase was noted regarding the mean values of peak torque, average peak torque and total work for knee flexors at high angular velocity in Groups I (60 Hz/ 4 mm) and V (40 Hz/ 2 mm) ($p < 0.05$). The mean percentage values of post-training changes to study parameters suggest that the training had the most beneficial effect in Groups I (60 Hz/4 mm) and IV (60 Hz/2 mm) ($p < 0.05$). Whole-body vibrations during static exercise beneficially affected knee flexor strength profile in young men at high angular velocity. The combinations of 60 Hz/4 mm seem to have the most advantageous effects on muscle strength parameters.

CITATION: Stania M, Król P, Sobota G, Polak A, Bacik B, Juras G. The effect of the training with the different combinations of frequency and peak-to-peak vibration displacement of whole-body vibration on the strength of knee flexors and extensors *iol Sport*. 2017;34(2):127–136.

Received: 2016-05-19; Reviewed: 2016-06-23; Re-submitted: 2016-09-06; Accepted: 2016-10-02; Published: 2017-01-01.

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Key words:

Vibration
Muscle strength
Exercise
Healthy volunteers
Lower extremity

INTRODUCTION

Mechanical vibrations provoke a reflexive muscle contraction which is based on a specific myotatic reflex, commonly referred to in literature as a tonic vibration reflex (TVR) [1]. The size of a tonic vibration reflex depends on several factors including vibration frequency and peak-to-peak vibration displacement [2,3], initial position in a given exercise and related initial muscle extension [4,5], anatomical location of the investigated muscle [6], vibration type [5], additional load [5] and modifications to traditional exercises [7]. Vibration-evoked neuromuscular reflexes have been confirmed by an increase in the amplitude of bioelectrical signals from selected muscles as recorded by surface electromyography [2,3,5]. Since whole-body vibration (WBV) markedly activates the striated muscles, it was hypothesized that the long-term whole-body vibration training could result in strength increase in recreationally active young men.

Strength is defined as the maximal force or torque a muscle or muscle group can generate at a specified or determined velocity. The outcomes of maximum voluntary contraction, power, rate of force development and dynamic strength are used as an index of the force-

generating capacity of muscle [8]. The effects of WBV on muscle strength are often evaluated based on isokinetic measurements [9-14], which allow dynamic testing of the function of selected muscle groups during limb movements at a constant speed. When taken at low and high angular velocities, these measurements help precisely determine muscle characteristics under different biomechanical patterns of movement. Isokinetic dynamometry is used to measure changes in muscle strength following vibration training in different populations: healthy adults [10], older people [15], patients with cerebral palsy [16] and athletes [17].

The results obtained by several researchers carried out in healthy population confirmed an increase in muscle strength after WBV training [9,13,18-20] while some others did not reveal any significant effects of WBV on the strength profile of particular muscle groups [13,14]. The relative increase in isokinetic peak torque for knee extensors after WBV has been estimated to range between 2.1% and 22.14% [9,18,21]. However, a comparison of results from different studies poses problems due to differences

in WBV training and isokinetic measurements of muscle strength [9-14,20,21].

Marin and Rhea [22] identified the following moderators of the vibration effect on muscle strength development: the type of vibration platform, gender, training status and exercise protocol (including vibration frequency and peak-to-peak vibration displacement). Vertical-sinusoidal and side-alternating sinusoidal devices deliver vibrations across 20-50 Hz and oscillation amplitude between 2 and 14 mm. Stochastic resonance WBV typically uses a lower vibration frequencies ranging between 1 and 12 Hz, set at amplitudes between 3 and 6 mm [23]. Literature on the subject comprises a large number of scientific reports regarding the effects of WBV on isokinetic muscle strength; however, the majority of researchers tested one combination of vibration frequency and peak-to-peak vibration displacement [10,12,13,17,20].

Petit *et al.* [24] emphasized the significance of appropriate frequency and peak-to-peak vibration displacement selection. Using three different protocols, the investigators demonstrated beneficial effects with respect to knee extensor eccentric voluntary torque and knee flexor isometric voluntary torque after just high intensity vibration training of 50 Hz and 4 mm. Esmailzadeh *et al.* [21] showed that the parameters of 30 Hz / 2-4 mm were more effective than 50 Hz / 2-4 mm in increasing of isometric and concentric peak torque of knee extensor muscles after 8 weeks of WBV training and equally effective in increasing eccentric torque of knee extensors in young healthy participants. Chen *et al.* [25] indicated that there is a possibility of modulation of vibration parameters by combining higher frequencies with lower peak-to-peak displacements and lower frequencies with higher peak-to-peak displacements. According to Jackson and Turner [26], prolonged muscle vibration (both with high and low value of frequency) reduces the maximal force and maximum rate of force generation of the knee extensors. This reduction was significantly greater following 30 Hz vibration. However, the study of Salvberg *et al.* [27] shows that vibration frequency does not affect neuromuscular performance.

Since vibrations may cause both positive [9,12,18,20] and negative effects [26], it is essential to select the frequency and peak-to-peak vibration displacement that will help activate the muscles most

efficiently and obtain optimal changes in neuromuscular function. Based on the observation that different vibration frequencies and movement amplitudes cause different levels of muscle activity [2], we hypothesized that a 4-week vibration training with different vibration parameters will have different effects on strength profile of the striated muscles. Hence, the main aim of the study was to evaluate the effect of different vibration frequency and peak-to-peak displacement combinations on men knee flexors and extensors strength in isokinetic conditions.

MATERIALS AND METHODS

An experimental, pretest/posttest randomized group, double blind design using six training groups and one control group was employed to examine the effect of whole body vibration training with different frequency and peak-to-peak displacement settings on the strength of knee flexors and extensors.

Subjects

Fifty two recreationally active male physiotherapy students were invited to participate. Recreationally active was classified as participating in low-to-moderate physical activities 2-3 times/week for approximately 20-30 minutes. Three of participants were excluded from the experiment since they met the exclusion criteria, and so ultimately forty nine male subjects entered the study. Four participants discontinued the training due to health reasons. Hence, the results of forty five participants were included in the statistical analysis. Physical characteristics of the participants are presented in Table 1. Exclusion criteria were: past injuries or surgery of the knee, hip joints, anti-pain blockades, acute inflammation of soft tissues and elevated temperature. All participants gave their written informed consent to participate in this study prior to the experiment, which was approved by an ethics committee of the Institutional Review Board. The experiment was carried out in the Department of Physiotherapy Basics at the Jerzy Kukuczka Academy of Physical Education in Katowice, Poland.

The subjects were randomly allocated to 6 experimental and the control group. Simple randomization technique with the use of numbered envelopes, was used in the experiment. The main coordinator

TABLE 1. Characteristics of the study participants.

Group	Parameters of vibrations	Age [years] mean \pm SD	Body mass [kg] mean \pm SD	Height [cm] mean \pm SD
I	4 mm/60 Hz	23.4 \pm 1.1	78.5 \pm 8.3	181.9 \pm 4.4
II	4 mm/40 Hz	22.2 \pm 1.2	75.5 \pm 6.8	178 \pm 1.7
III	4 mm/20 Hz	21.6 \pm 1.3	77.6 \pm 9.2	179.3 \pm 6.7
IV	2 mm/60 Hz	21.4 \pm 0.8	76.3 \pm 11.9	177.3 \pm 8.8
V	2 mm/40 Hz	22 \pm 1.3	87.3 \pm 12.2	184.3 \pm 5.6
VI	2 mm/20 Hz	21.7 \pm 1.2	75.3 \pm 8	180.7 \pm 5.6
VII	control group	21.7 \pm 0.8	75.4 \pm 7.6	178.1 \pm 4.7

who allocated the participants to groups had opaque, sealed envelopes, each containing a piece of paper marked with either group I–VII. The physician selected and opened an envelope in the presence of a physiotherapist to see the symbol and then directed the participant to the corresponding group.

Subjects in groups I–VI participated in 4-week whole-body vibration training on a vibration platform which produced vertical vibrations with a possible choice of two different peak-to-peak displacements (2 mm, 4 mm) and frequencies from the range between 20–60 Hz. Other authors, too, point to the importance of low (2 mm) and high (4 mm) amplitude of vibration in the muscle strength development [9]. In order to show a wider range of possible muscle reactions, specific combinations of low and high intensity parameters, available with the used platform, were applied. Peak-to-peak vibration displacement and vibration frequency were set individually for each group, i.e. 4 mm/60 Hz for group I, 4 mm/40 Hz for group II, 4 mm/20 Hz for group III, 2 mm/60 Hz for group IV, 2 mm/40 Hz for group V, 2 mm/20 Hz for group VI. Neither the participants nor the investigators, except the one responsible for vibration training, knew to which group the participants were assigned to.

The control group (group VII) subjects performed exercises similar to those in the other groups but without the concurrent application of vibration. The control participants assumed the same static position, which was standing with their knees and hips joints flexed to 90° while their arms were stretched horizontally in front. The control group was included to determine whether the expected training effect in the WBV groups I–VI resulted from the static exercise or from the vibration induced muscle activity. Subjects did not perform any resistance training within the time of the experiment.

Vibration Training

The influence of a 4-week whole-body vibration training was assessed. Participants performed the exercises 3 times a week (Monday, Wednesday, and Friday); the program consisted of sixteen exercises sessions [13]. Whole-body vibration training was carried out on a vibration platform (Fitvibe 600, Gymna Uniphy N.V.). The test participant was in a static position during the exercises. Briefly, each subject was asked to stand on the platform, loading his feet uniformly, with the knee and hip joints bent at 90° and the upper extremities stretched horizontally forwards (fig. 1). The range of flexion of the hip and knee joints was measured with a goniometer. Krol et al. [2] reported significantly increased bioelectrical activity of the lower extremity muscles of subjects standing with the knee joints bent at 90°. The above mentioned position is quite safe as knee flexion reduces the amount of vibration that reaches the head [28]. The exercise and rest times were adapted from the procedures used by other researchers [9,29]. A single vibration session in the study was a series of 5 static exercises on a vibration platform for 1 min, followed by a 1 min break. Each participant performed few static stretch exercises of quadriceps femoris and gastrocnemius muscles before each training session.



FIG. 1. Whole-body vibrations.

Isokinetic Dynamometry

The subjects were told not to participate in any strenuous activities the day before the test sessions. The measurements were taken in morning hours to minimize the impact of daily tiredness. The pre- and post-tests were recorded prior to and 2 days after the vibration training intervention in order to avoid potential fatigue and acute effects of the last vibration session [13].

Isokinetic strength tests were performed bilateral using an isokinetic dynamometer En – Knee (Enraf – Nonius). The dynamometer was calibrated following the manufacturer's guidelines before data collection. The isokinetic strength tests were preceded by 5 minute warm-up exercises performed on a cycle ergometer with constant intensity of 50 W.

Prior to the start of the measurements, each participant was positioned on the isokinetic chair so that the knee movement could not be assisted with movement of other body parts. Participants were secured to the dynamometer chair in a seated position using chest, waist and thighs straps. The arms of participants were crossed in front of the chest. The axis of rotation of the dynamometer was aligned with the right/left lateral femoral condyle. The force pad was placed 3–4 cm superior to the medial malleolus. The knee extension was initiated at a joint angle of 90° and ended at 170° [30]. The evaluation of muscle strength consisted of 30-second dynamic work of knee joint flexors and extensors against resistance. The knee extensor and flexor muscles were tested concentrically at 30°/s and 240°/s. Participants were given 2 practice repetitions at each angular velocity immediately before the measurements. The recovery period of 90 seconds between legs were used. Five minutes rest intervals were

used between test velocities. Testing was conducted with visual and auditory feedback.

In order to measure the strength muscle ability and endurance ability, the following variables were calculated from the knee joint flexion and extension tests separately conducted at 240°/s and 30°/s: peak torque, average peak torque, total work. The peak torque was calculated as the highest value from all 30 sec testing contractions. The average peak torque was calculated as the mean of all peak torques from all testing contractions during 30 sec. The values were normalized to subject's body mass. The all individual repetitions of right and left lower limb were averaged into 1 mean value used in all subsequent statistical analysis.

The hamstring/quadriceps strength ratio (H/Q) was defined by calculating concentric hamstring strength relative to concentric quadriceps strength using the following equation:

$$H/Q = \text{peak hamstrings torque} / \text{peak quadriceps torque}$$

The conventional isokinetic hamstring:quadriceps strength ratio has been studied extensively [31-33].

Statistical Analysis

The Shapiro-Wilk test was used to check the data for normal distribution, while variance homogeneity was investigated using Levene's test. Because some parameters failed to meet the assumption regarding the normal distribution of variables and variance homogeneity,

the Wilcoxon matched pairs test was employed to assess the significance of the differences between the means of particular variables in the groups. To explore the effects of the applied vibration training programs the Cohen's effect size (ES) was used. ES of 0.2, 0.5, and 0.8 were considered as small, moderate, and large effects, respectively. The effectiveness of all types of vibration training was assessed by Kruskal-Wallis test for differences between pre- and post-test for each variable separately.

The level of statistical significance for all analyses was considered $p < 0.05$.

RESULTS

Angular velocity 30°/s

Following 4 weeks of the training, the total work during knee joint extension increased significantly in groups I and VII (ES=0.463-0.492; $p < 0.05$). In groups V and VII, knee extensor peak torque decreased significantly (ES=0.65-0.723; $p < 0.05$). According to the Cohen's effect size (0.436-0.723), the vibration training program in Group V had moderate to large effects for knee extensors (Table 2).

The vibration training significantly affected the mean values of total work during knee flexion in Groups I and IV (ES=0.285-0.362; $p < 0.05$). After 4 weeks of the intervention, Group VII exhibited significant reduction in the average peak torque for flexion (ES=0.46; $p = 0.019$) (Table 3).

TABLE 2. Mean values and SD of peak torque, average peak torque and total work for knee extensors – before and after a 4-week vibration training (angular velocity 30°/s) and mean values, SD and 95%CI (CI-confidence interval) for individual differences (Diff.).

Measurement	Group I	Group II	Group III	Group IV	Group V	Group VI	Group VII
<i>Peak torque [Nm/kg]</i>							
before	3.81±0.71	3.78±0.53	3.76±0.51	3.85±0.8	3.93±0.58	3.66±0.45	3.67±0.66
after	3.8±0.63	3.58±0.56	3.58±0.4	3.71±0.59	3.57±0.4	3.60±0.51	3.30±0.46
Diff.	-0.01±0.29 (-0.16÷0.15)	-0.19±0.41 (-0.45÷0.06)	-0.18±0.33 (-0.35÷-0.01)	-0.17±0.32 (-0.38÷0.03)	-0.36±0.45 (-0.65÷0.08)	-0.06±0.27 (-0.23÷0.11)	-0.37±0.34 (-0.5÷-0.19)
ES	0.015	0.367	0.392	0.199	0.723*	0.123	0.65*
<i>Average peak torque [Nm/kg]</i>							
before	3.44±0.7	3.45±0.41	3.38±0.48	3.48±0.7	3.45±0.58	3.45±0.49	3.16±0.52
after	3.48±0.56	3.24±0.54	3.26±0.37	3.41±0.54	3.19±0.4	3.32±0.48	3.03±0.39
Diff.	0.04±0.38 (-0.16÷0.24)	-0.21±0.39 (-0.45÷0.04)	-0.13±0.36 (-0.32÷0.06)	-0.08±0.29 (-0.27÷0.11)	-0.26±0.47 (-0.56÷0.04)	-0.13±0.22 (-0.27÷0.01)	-0.14±0.31 (-0.31÷0.04)
ES	0.063	0.438	0.28	0.112	0.522	0.268	0.283
<i>Total work [J/kg]</i>							
before	15.72±3.25	15.43±1.89	16.47±1.62	15.95±3.46	15.57±2.35	16.12±2.14	14.51±2
after	17.12±2.77	15.81±2.75	16.33±1.6	16.41±3.38	14.67±1.73	15.7±2.62	15.50±2.02
Diff.	1.4±2.03 (0.32÷2.47)	0.37±1.97 (-0.88÷1.63)	-0.14±1.82 (-1.11÷0.83)	0.44±1.78 (-0.69÷1.56)	-0.9±1.46 (-1.82÷0.02)	-0.42±1.49 (-1.36÷0.53)	0.98±0.99 (0.41÷1.55)
ES	0.463*	0.161	0.087	0.135	0.436	0.176	0.492*

* – $p < 0.05$; Wilcoxon matched pairs test, ES – effect size.

Effects of WBV on muscle strength

TABLE 3. Mean values and SD of peak torque, average peak torque and total work for knee flexors – before and after a 4-week vibration training (angular velocity 30°/s) and mean values, SD and 95%CI (CI-confidence interval) for individual differences (Diff.).

Measurement	Group I	Group II	Group III	Group IV	Group V	Group VI	Group VII
<i>Peak torque [Nm/kg]</i>							
before	2.26±0.41	2.26±0.48	2.34±0.34	2.18±0.54	2.04±0.34	2.29±0.34	2.34±0.47
after	2.33±0.47	2.16±0.49	2.27±0.39	2.24±0.46	2.08±0.42	2.31±0.42	2.15±0.36
Diff.	0.07±0.19 (-0.03÷0.17)	-0.1±0.28 (-0.28÷0.08)	-0.07±0.23 (-0.19÷0.06)	0.04±0.41 (-0.22÷0.31)	0.05±0.21 (-0.08÷0.17)	0.02±0.4 (-0.24÷0.08)	-0.19±0.34 (-0.38÷0.01)
ES	0.159	0.206	0.191	0.12	0.105	0.053	0.454
<i>Average peak torque [Nm/kg]</i>							
before	2.07±0.4	2.01±0.44	2.04±0.3	1.89±0.49	1.79±0.38	2.02±0.29	2.10±0.42
after	2.11±0.45	1.92±0.44	2.07±0.38	2.02±0.42	1.84±0.42	2.06±0.37	1.92±0.36
Diff.	0.04±0.19 (-0.06÷0.14)	-0.1±0.24 (-0.25÷0.05)	0.03±0.19 (-0.07÷0.13)	0.11±0.27 (-0.03÷0.26)	0.04±0.22 (-0.09÷0.18)	0.03±0.32 (-0.17÷0.24)	-0.18±0.22 (-0.31÷-0.05)
ES	0.094	0.205	0.088	0.285	0.125	0.12	0.46*
<i>Total work [J/kg]</i>							
before	10.39±2.53	10.35±2.06	10.89±1.46	9.73±2.6	9.12±1.68	10.53±1.99	10.59±2.35
after	11.16±2.87	9.92±2.06	10.9±1.67	10.65±2.48	9.41±1.49	10.56±2.42	10.05±1.99
Diff.	0.76±1.22 (0.11÷1.41)	-0.43±1.21 (-1.2÷0.33)	0.02±1.43 (-0.75÷0.77)	0.9±1.47 (0.03÷1.77)	0.29±1.38 (-0.58÷1.17)	0.03±1.48 (-0.91÷0.97)	-0.53±1.12 (-1.18÷0.12)
ES	0.285*	0.209	0.006	0.362*	0.182	0.014	0.248

* – p<0.05; Wilcoxon matched pairs test, ES – effect size.

Angular velocity 240°/s

After 4 weeks of the experiment, the following variables of knee extension increased significantly: total work (Groups I, IV, VII) (ES=0.359-0.67; p<0.05) and peak torque (Group V) (ES=0.935; p<0.05). The Wilcoxon matched pairs test revealed a significant

average peak torque decrease in Group III (ES=0.457; p=0.039) (Table 4). After 4 weeks of whole-body vibration training, a significant increase was noted regarding the mean values of all dependent variables for knee flexors in Groups I and V (p<0.05). According to the Cohen's effect size (0.542-1.081), the vibration training program

TABLE 4. Mean values and SD of peak torque, average peak torque and total work for knee extensors – before and after a 4-week vibration training (angular velocity 240°/s) and mean values, SD and 95%CI (CI-confidence interval) for individual differences (Diff.).

Measurement	Group I	Group II	Group III	Group IV	Group V	Group VI	Group VII
<i>Peak torque [Nm/kg]</i>							
before	2.1±0.6	2.15±0.26	2.17±0.3	1.97±0.6	1.88±0.28	2.4±0.4	2.34±0.2
after	2.31±0.33	2.16±0.37	2.04±0.3	2.03±0.55	2.09±0.15	2.24±0.3	2.26±0.18
Diff.	0.22±0.47 (-0.3÷0.47)	0.01±0.18 (-0.11÷0.12)	-0.13±0.28 (-0.27÷0.02)	0.06±0.24 (-0.11÷0.22)	0.21±0.24 (-0.04÷0.37)	-0.16±0.39 (-0.44÷0.12)	-0.08±0.23 (-0.21÷0.06)
ES	0.434	0.031	0.433	0.104	0.935*	0.453	0.42
<i>Average peak torque [Nm/kg]</i>							
before	1.47±0.33	1.41±0.22	1.41±0.18	1.37±0.41	1.34±0.25	1.5±0.21	1.45±0.14
after	1.59±0.2	1.42±0.18	1.34±0.12	1.36±0.28	1.44±0.17	1.45±0.22	1.49±0.11
Diff.	0.12±0.23 (-0.01÷0.24)	0.01±0.16 (-0.1÷0.11)	-0.07±0.16 (-0.15÷0.1)	0.01±0.17 (-0.12÷0.11)	0.1±0.22 (-0.06÷0.25)	-0.05±0.21 (-0.2÷0.1)	0.04±0.1 (-0.02÷0.09)
ES	0.44	0.05	0.457*	0.03	0.467	0.232	0.318
<i>Total work [J/kg]</i>							
before	30.17±8.5	29.24±5.52	27.64±5.45	26.81±8.59	26.15±6.1	31.33±5.65	32.37±4.12
after	33.33±4.57	30.73±5.18	28.61±4.84	29.79±7.99	28.82±6.07	30.62±6.5	34.96±3.59
Diff.	3.17±5.88 (0.35÷6.3)	1.5±3.51 (-0.74÷3.72)	0.98±4.74 (-1.61÷3.56)	2.97±3.21 (0.67÷5.27)	2.67±4.94 (-0.86÷6.21)	-0.72±4.21 (-3.73÷2.29)	2.59±2.35 (1.23÷3.94)
ES	0.463*	0.278	0.188	0.359*	0.439	0.117	0.67*

* – p<0.05; Wilcoxon matched pairs test, ES – effect size.

TABLE 5. Mean values and SD of peak torque, average peak torque and total work for knee flexors – before and after a 4-week vibration training (angular velocity 240°/s) and mean values, SD and 95%CI (CI-confidence interval) for individual differences (Diff.).

Measurement	Group I	Group II	Group III	Group IV	Group V	Group VI	Group VII
<i>Peak torque [Nm/kg]</i>							
before	1.39±0.33	1.31±0.27	1.52±0.18	1.28±0.23	1.26±0.18	1.59±0.24	1.6±0.23
after	1.6±0.4	1.38±0.27	1.58±0.24	1.47±0.24	1.46±0.19	1.67±0.24	1.63±0.26
Diff.	0.21±0.21 (0.1÷0.32)	0.07±0.16 (-0.03÷0.17)	0.06±0.21 (-0.05÷0.17)	0.19±0.29 (-0.01÷0.39)	0.2±0.16 (0.08÷0.32)	0.08±0.14 (-0.02÷0.18)	0.03±0.18 (-0.07÷0.13)
ES	0.572*	0.259	0.283	0.808*	1.081*	0.333	0.122
<i>Average peak torque [Nm/kg]</i>							
before	1.05±0.25	0.97±0.2	1.18±0.16	0.99±0.22	0.96±0.19	1.2±0.23	1.19±0.18
after	1.21±0.27	1.03±0.19	1.21±0.16	1.15±0.26	1.12±0.17	1.23±0.21	1.24±0.2
Diff.	0.15±0.11 (0.09÷0.21)	0.06±0.12 (-0.01÷0.14)	0.02±0.13 (-0.05÷0.09)	0.16±0.3 (-0.06÷0.37)	0.15±0.15 (0.04÷0.26)	0.04±0.16 (-0.07÷0.15)	0.05±0.1 (-0.01÷0.11)
ES	0.615*	0.308	0.188	0.664	0.886*	0.136	0.263
<i>Total work [J/kg]</i>							
before	20.92±6.86	20.38±5.96	26.06±4.77	19.7±7.4	18.63±5.47	26.96±7.4	27.78±6.81
after	24.93±7.9	23.03±6.23	26.34±4.17	25.45±6.92	22.46±5.56	27.24±5.92	28.16±7.7
Diff.	4.01±4.07 (1.5÷6.51)	2.65±3.23 (0.59÷4.71)	0.29±4.57 (-2.15÷2.72)	5.75±10.34 (-1.65÷13.15)	3.83±5.01 (0.25÷7.41)	0.28±6.56 (-4.41÷4.98)	0.38±4.84 (-2.42÷3.17)
ES	0.542*	0.435*	0.062	0.803	0.694*	0.042	0.052

* – p<0.05; Wilcoxon matched pairs test, ES – effect size.

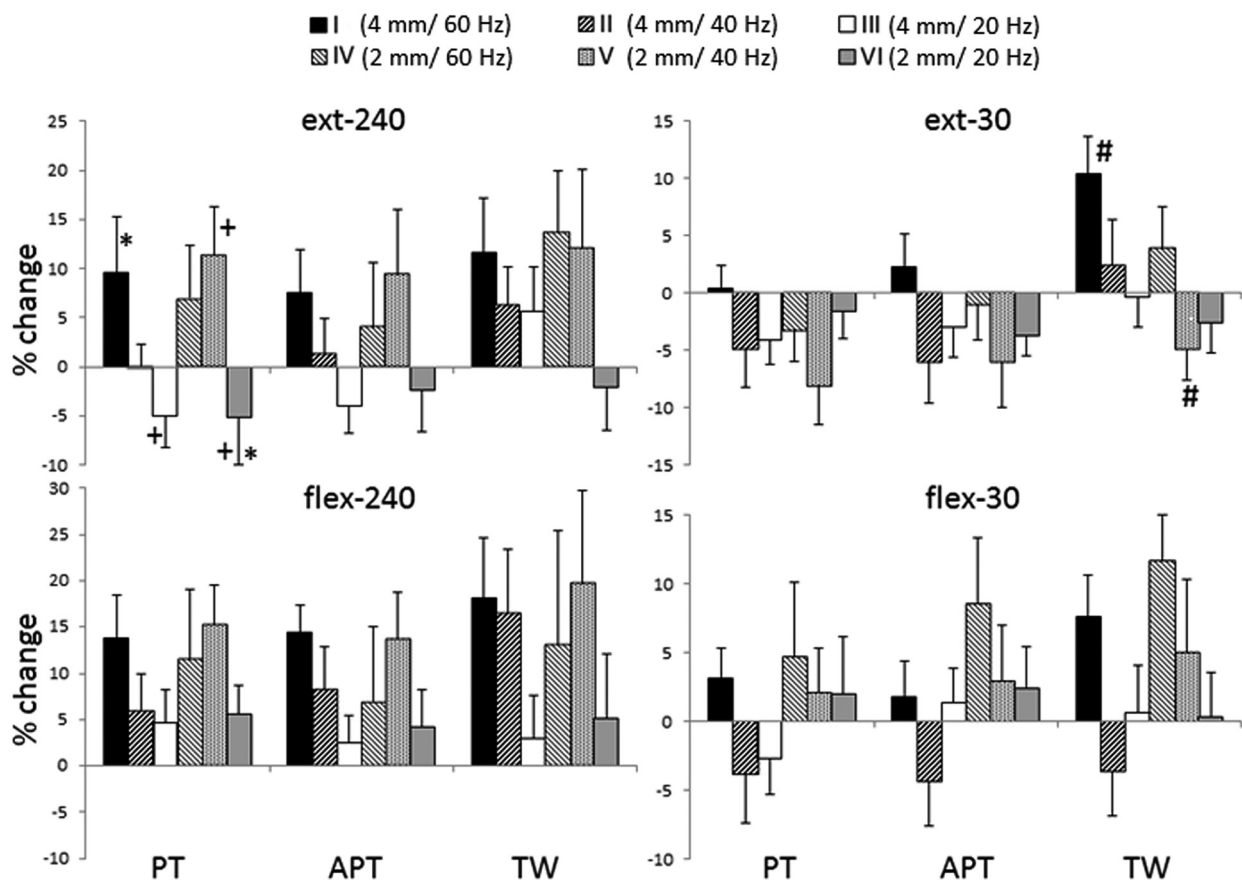


FIG. 2. Percent differences between the pre- and post-measurement of peak torque (PT), average peak torque (APT) and total work (TW) for flexors (flex) and extensors muscles (ext) at low and high angular velocity (30°/s and 240°/s). Error bars represent standard errors. Significant intergroup differences were marked at p<0.05 (Kruskal-Wallis test).

TABLE 6. Mean values and SD of the hamstring/quadriceps strength ratio (H/Q) at angular velocities of 30°/s and 240°/s – before and after a 4-week vibration training.

Measurement	Group I	Group II	Group III	Group IV	Group V	Group VI	Group VII
<i>The hamstring/quadriceps strength ratio H/Q – angular velocities of 30°/s</i>							
before	0.6±0.08	0.6±0.11	0.63±0.1	0.57±0.11	0.53±0.11	0.63±0.09	0.64±0.08
after	0.62±0.08	0.61±0.11	0.64±0.12	0.6±0.08	0.59±0.11	0.65±0.13	0.65±0.06
ES	0.25	0.091	0.091	0.312	0.545*	0.179	0.141
<i>The hamstring/quadriceps strength ratio H/Q – angular velocities of 240°/s</i>							
before	0.69±0.16	0.61±0.11	0.71±0.07	0.7±0.2	0.68±0.12	0.69±0.19	0.69±0.1
after	0.69±0.13	0.65±0.14	0.79±0.13	0.75±0.11	0.70±0.09	0.76±0.16	0.73±0.14
ES	0	0.318	0.766*	0.31	0.189	0.399	0.329

* – $p < 0.05$; Wilcoxon matched pairs test, ES – effect size.

in Group I and V had moderate to large effects for knee flexors (Table 5). A statistical analysis also revealed a significant increase in total work in Group II (ES=0.435; $p=0.015$) and peak torque in Group IV (ES=0.808; $p=0.037$). The effect size for all dependent variables for knee flexors in Group IV was between 0.664 and 0.808 (Table 5).

Intergroup differences between the pre- and post-measurements

Intergroup differences were only noted regarding the extensor peak torque and total work at the angular velocities of 240°/s and 30°/s, respectively. In general, over 10% increase in the study parameters for knee extensors was noted for Groups I, IV and V (at high angular velocity) while significant differences always resulted from parameter decrease after 4 weeks of training – mainly in Groups III and VI. At low angular velocities, the values of peak torque and average peak torque for knee extensors decreased for all groups except Group I. The value of total work decreased in Group V resulting in a significant difference compared to Group I (Fig. 1).

Irrespective of angular velocity, no intergroup differences were noted for knee flexors. Although all parameters increased at high angular velocity, the highest increase was observed in Groups I and IV; the highest total work increase at 240°/s was found in Group V. At angular velocity of 30°/s, over 10% increase in total work was only observed in Group IV (Fig. 1).

The hamstring/quadriceps strength ratio H/Q

After 4 weeks of vibration training, in Group V participants, the H/Q ratio increased significantly compared to the baseline at angular velocity of 30°/s ($p=0.049$). Group III members exhibited a statistically significant increase in the H/Q ratio at angular velocity of 240°/s compared to the initial measurement ($p=0.017$) (Table 6).

DISCUSSION

Electromyographic signals recorded during vibration exercise demonstrated that bioelectrical activity of the striated muscle increased with an increase in vibration frequency and amplitude [2]. We there-

fore assumed that, during our experiment, the major beneficial changes to the parameters of the dynamics of muscle activity would be observed in Group I, whose members participated in high intensity vibration training (60 Hz/4 mm). It should be emphasized that the 4-week vibration training resulted in a significant increase in total work under all testing conditions (flexion, extension at angular velocities of 30°/s and 240°/s) ($p < 0.05$; Wilcoxon matched pairs test), although the Cohen's effect size was small for isokinetic testing at angular velocity of 30°/s for the knee flexors and extensors and 240°/s for the knee extensors.

There is scientific evidence regarding the positive effect of high-intensity whole-body vibration training on knee extensor strength in young men [24]. A 6-week WBV training at vibration frequency of 50 Hz and peak-to-peak displacement of 4 mm (18 sessions of 20 minutes each) significantly improved knee extensor eccentric voluntary torque and knee flexor isometric voluntary torque. No significant changes were found with respect to maximal concentric voluntary torque (at angular velocities of 60°/s and 180°/s). Martinez-Pardo et al. [9] also observed a significant increase of isokinetic strength of knee extensors at angular velocity of 270°/s after 6 weeks of high frequency and amplitude vibration training (50 Hz/4 mm). Similar to our study, the participants took part in 12 training sessions (but within 6 weeks) with 1-min exercises on a vibration platform, followed by a 1-min break. However, the number of exercises on the vibration platform increased during the training period.

According to Rogan et al. [34], static positions over a longer period (which in our experiment was standing with knees and hips joints flexed to 90° for 60 sec) promote mainly strength endurance capacity of the striated muscles, although muscle strength and power have to be addressed. For this reason, we measured both endurance ability (average peak torque, total work) as well as the strength muscle ability (peak torque).

The testing of two angular velocities (30°/s and 240°/s) could help elucidate the effect of vibration training on muscle performance.

Our results are also consistent with Rittweger *et al.*'s [35] suggestion that whole-body vibration training mostly activates fast-twitch fibres, which are identified by quick contraction time, rapid fatigue and the use of anaerobic metabolism; they predominate in muscles engaged in activities in which short-bursts of intense energy [36]. An analysis of our results revealed that the beneficial changes in the isokinetic parameters mainly occurred during the tests performed at higher angular velocity, *i.e.*, 240°/s (Table 4, Table 5). Martinez-Pardo *et al.* [9] had similar observations: after 6 weeks of whole-body vibration training (vibration frequency 50 Hz, peak-to-peak vibration displacement 4 mm, 2 training sessions a week), a statistically significant increase of isokinetic strength was observed at the highest angular velocity (270°/s).

Pre- and post-training and at both angular velocities, *i.e.*, 240°/s and 30°/s, higher values of the dependent variables were obtained for knee extensors compared to knee flexors, which is consistent with the observations of other authors [13,32,33]. Major improvement of our variables was noted for knee flexors at angular velocity of 240°/s. Karatrantou *et al.* [13] also showed a beneficial effect of sixteen whole-body vibration sessions on strength profile of the hamstring muscles (frequency 25 Hz, peak-to-peak vibration displacement 6 mm, two sets of 5 min each, training duration – 3 weeks) with no improvement for knee extensors. The researchers used a side-to-side vibration platform; they believe that the lack of improvement in strength profile of knee extensors might be associated with a static exercise position with the knees at 10° flexion. Based on the conclusions of Karatrantou *et al.* [13] and the results of Krol *et al.* [2], who observed that static squat with 90° of knee flexion significantly increased the activity of knee extensors, we decided to use a static position with the knee and femoral joints bent at 90°. It might be that high degree knee flexion resulted in an increase in knee extensor strength at some selected vibration parameters (Table 4). The lack of better results with respect to knee extensors might be attributed to the lack of changes in the training load. Devising a resistance training program requires the consideration of exercise mode as well as training frequency, intensity, and duration [37]. Positive adaptations in muscle strength might stem from dynamic exercises [12,22] or resistance training [10] on vibration platforms. Considering the results of other researchers [10,21] it seems that 4 weeks of vibration training is too short a time to obtain noticeable training effects.

After a 4-week vibration training, all experimental groups (I-VI) exhibited a comparable trend of all dependent variables for knee flexors to increase at angular velocity of 240°/s. The increase reached statistical significance in Groups I and V for all dependent variables (Table 5). Therefore, the combinations of 60 Hz/4 mm and 40 Hz/2 mm seem to have the most advantageous effects on flexor strength profile at high angular velocity.

The mean percentage values of post-training changes to study parameters suggest that the training had the most beneficial effect in Groups I and IV. This seems to indicate that high frequency

vibration (irrespective of its amplitude) yields the best effects – but only at high angular velocities. At low velocities, only high-amplitude and high-frequency vibrations, as in Group I, have a major impact in the form of total work increase (fig. 2).

The hamstring/quadriceps strength ratio (H/Q) has been frequently used to evaluate strength symmetry of reciprocal muscle groups stabilizing a given joint – the most often the knee joint [31-33,38]. H/Q ratio abnormalities indicate increased susceptibility of an area to injury; in patients after knee injuries the ratio is significantly decreased [33]. Normal concentric H/Q ratios range from 0.42 to 0.8, depending on measurement condition (angular velocity, testing position and side) [31-33]. In all experimental groups, the increase in angular velocity was associated with an increase in the mean values of the H/Q ratio (at angular velocity of 30°/s H/Q ranged from 0.53 to 0.65 and at 240°/s from 0.61 to 0.79). This is consistent with the observations of Kong and Burns [32], who obtained significantly higher H/Q ratios at angular velocities of 180°/s and 300°/s as compared to 60°/s.

After 4 weeks of vibration training, the H/Q ratio showed a tendency to increase (angular velocity of 30°/s), which turned out to be significant in Group V. At 240°/s the ratio increased noticeably in all study groups although statistical significance was only reached in Group III. A possible explanation is that the initially weak hamstring muscles strengthened as a result of the vibration training (Table 5). It has been suggested that hamstring strengthening improves joint stabilization and reduces the risk of lower limb injury [38]. Since vibration training reduces strength asymmetry between the quadriceps and the hamstrings (as confirmed – in our study – by a tendency of the H/Q ratio to increase) and improves muscle strength imbalance between the lower extremities [39] it might be used for prevention and rehabilitation in patients with muscle and knee joint injuries including anterior cruciate ligament injury [13].

A 4-week whole-body vibration training with vibration frequency and peak-to-peak displacement of 60 Hz/4 mm beneficially affects knee flexor strength profile in young men. Hence it seems that this protocol might be used by recreationally active subjects in sports training provided there are no contraindications to WBV application. Thus, we consider the high intensity WBV training as a useful method for personal trainers and fitness coaches.

Limitation of the study:

Our study has several limitations including a relatively small number of study participants in each of the research groups. The findings of this study are limited to synchronous platforms generating vertical vibrations. Also, we did not compare the functional ratios of eccentric hamstring to concentric quadriceps moments (extension), and concentric hamstring to eccentric quadriceps moments (flexion). Finally, we did not measure the actually generated vibration parameters and skidding of the feet as recommended by the International Society of Musculoskeletal and Neuronal Interactions [40].

CONCLUSIONS

Summing up it can be concluded that:

- Whole-body vibrations during static exercise beneficially affected knee flexor strength profile in young men at high angular velocity.
- The combinations of 60 Hz/4 mm seem to have the most advantageous effects on muscle strength parameters of knee extensors and flexors.

Conflict of interests: the authors declared no conflict of interests regarding the publication of this manuscript.

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