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Original Article

Changes in muscle cross-sectional area, muscle force, and jump performance during 6 weeks of progressive whole-body vibration combined with progressive, high intensity resistance training

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Abstract

Objectives: We hypothesized that progressive whole-body vibration (WBV) superimposed to progressive high intensity resistance training has greater effects on muscle cross-sectional area (CSA), muscle force of leg muscles, and jump performance than progressive high intensity resistance training alone. **Methods:** Two groups of healthy male subjects performed either 6 weeks of Resistive Vibration Exercise (RVE, squats and heel raises with WBV, n=13) or Resistive Exercise (RE, squats and heel raises without WBV, n=13). Squats under RVE required indispensable weight loading on the forefoot to damp harmful vibrations to the head. Time, intervention, and interaction effects were analyzed. **Results:** After 6 weeks of training, knee extensor CSA, isometric knee extension force, and counter movement jump height increased equally in both groups (time effect, $P<0.001$, $P\leq0.02$, and $P\leq0.03$, respectively), whereas only in RVE ankle plantar flexor CSA and isometric ankle plantar flexion force reached significance or a tendency, respectively, (time effect, $P=0.015$ and $P=0.069$, respectively; intervention effect also for the latter, $P=0.006$). Drop jump contact time did significantly more improve in RVE (interaction effect, $P=0.042$). **Conclusions:** RVE showed better training effects than RE only in plantar flexor muscles. RVE seems to be suitable in professional sports with a special focus on calf muscles.

Keywords: Hypertrophy, Strength Training, Squats, Heel Raises, Maximal Voluntary Contraction

Introduction

Short and long-term effects of whole-body vibration training (WBVT) have been studied much over the last years and it has been used in various areas such as rehabilitation, athletic training, and bed rest studies[1,2]. Especially long-term effects of WBVT seem to be diverse. Some authors found no advantage of WBVT over conventional resistance training (RE) when either using conventional WBV without added weight[3,4] or when using Resistive Vibration Exercise, RVE[5-7]; whereas others found some advantages of WBVT when either using conventional WBV without added weight[8,9] or when using RVE[10,11]. Unfortunately, evidence-based WBVT recommendations (best setup for hypertrophy, maximum strength, etc.) are still non-existent, likely due to the high variation of subject characteristics and lack of consistency in methodologies of WBVT studies[12]. However, despite the numerous amounts of WBVT studies, there are few studies which used progressively increasing vibration frequencies and training loads[5-7,10,11] to minimize potential early adaptation processes.

The additional mechanical stimuli of WBVT lead to further muscle activation when using conventional WBV without add-

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ed weight[9,13,14] or when using RVE[15,16]. In detail, Ritzmann et al.[15] could demonstrate that higher vibration frequencies with additional load on a side-alternating platform led to the highest EMG activities. Furthermore, Marín et al.[17] showed that higher vibration amplitudes produce higher neuromuscular responses. A greater muscle activation may consequently improve the stimulation of muscle hypertrophy[18] and therefore, through e.g. exercising to muscular failure where as many motor units as possible are recruited, stronger increases in functional parameters can be expected from which the normal population and athletes may profit. However, Rosenberger et al.[16] could show that the increase in muscle activation evoked by WBV decreased to insignificant levels after 5 days of consecutive training when using the same vibration frequency and the same loading throughout the training period. This might explain why studies which used only a constant vibration frequency a) without additional load[19] or b) with progressively increasing training loads[20,21] instead of progressively increasing vibration frequencies and training loads[10,11] throughout their training period have been less provocative to the muscles to show significantly increased effects of RVE over RE. Conversely, some studies[5-7] which used progressively increasing vibration frequencies and training loads did not find any increased effects of RVE over RE which might be related to either a too low number of subjects, vibration amplitude, or vibration frequency increase. However, we focused on making sure that increased muscle activation throughout the training sessions of RVE was present and used vibration frequencies progressively increasing up to 40 Hz, which, for a side-alternating platform, is higher than ever used before to our knowledge, in combination with a progressively increasing training load.

The vibration stimulus of WBVT seems to be distance-dependent, meaning, the closer the muscle is to the vibration platform the stronger is the expected effect. Some authors[16,22] could show that the damping of the vibration along the vertical body axis includes a decline in the acceleration amplitudes, which is important to reduce the risk of transmitting harmful resonance frequencies through the trunk and head[1,23,24]. Thus, assuming a proper/vibration-reducing body posture, e.g. through flexed legs and body weight on forefoot, the vibration transmission to the trunk and head can be reduced[22,25,26]. Therefore, in terms of power output and force generation of the leg muscles, one would assume that the lower leg muscles are more prone to become positively affected than the upper leg muscles, since they are closer to the vibration platform. In detail, the vibration stimulus stresses the viscoelastic properties of leg muscles while mono- and poly-synaptic stretch reflex pathways including Ia afferent neurons from muscle spindles are activated which may enhance the stretch reflex activity[12]. Therefore, we tested the power output measured as counter movement jump (CMJ) height, mainly dependent on knee extensor muscle force development, and the neuromuscular performance measured as drop jump (DJ) contact time, mainly dependent on ankle plantar flexor muscle force development. In addition, we tested isometric and isokinetic force of the knee and ankle muscles. Again, we expected greater effects of RVE over RE in contact time than in CMJ height and in ankle muscle force than in knee muscle force, because of the vibration stress - and the potential increased stretch reflex activity - being greater in the calves than in the thighs.

Bed rest studies serve as a model for unloading to counteract microgravity-induced muscle atrophy[27] and to improve musculoskeletal performance parameters. For astronauts, training of anti-gravity muscles such as m. quadriceps femoris and m. triceps surae is important for successful walking/working when returning to a gravity field (e.g. on Earth, Moon, or Mars). Since WBVT gives a stimulus to the leg muscles, it might also be a potential support of astronaut's in-flight countermeasures (e.g. on long duration missions to Mars) when exercising on the strength training device Advanced Resistive Exercise Device on the International Space Station. In addition, WBVT seems to reduce lower back pain[28] - commonly seen in astronauts in space[29] - and improve balance[30-33] - due to missing gravity, balance cannot yet be trained during missions on the International Space Station and is therefore one of the focusses of rehabilitation when returning to earth[34] and astronaut testing[35]. In a bed rest study, the combination of WBVT at 26 Hz with high intensity dynamic resistive exercises could almost stop muscle loss during 56 days of bed rest[36-38], whereas daily WBVT at 20 Hz with static low intensity body weight squats did not reduce the muscle loss[39]. Thus, not only progressively increasing the vibration frequency may play a major role in training studies to provoke muscles stronger than in RE, as mentioned above, but also the loading of the muscles seems to contribute to the effectiveness of WBVT. It seems to be important during bed rest studies to have a high enough loading of the leg muscles to introduce a positive growth effect, which should be considered in designing future WBVT studies. Similarly, astronauts being exposed to microgravity during long-duration missions seem to profit (indirect assumptions of positive effects on the musculature) from exercising with higher loads compared to lower loads (higher lean tissue mass, lower fat mass, higher bone mineral density, and higher bone mineral content)[40]. Thus, the lack of intensity/muscle activation during training may have not prevented atrophied muscles in unloading environments. Therefore, WBVT might be further developed as a potential countermeasure against muscle atrophy in space.

In summary, WBVT studies performed over weeks/months seem to be diverse with regards to their superiority over conventional resistance training[1,2]. In the present study, we focused on the changes in augmented body responses to WBV added to squat and heel raises exercises (Resistive Vibration Exercise, RVE) in comparison with squat and heel raises exercises alone (Resistive Exercise, RE) with the novelty of using progressive high intensity resistance training combined with progressively increased vibration frequencies from 20 to 40 Hz on a side-alternating vibration platform. We hypothesized that the following functional parameters will show elevated responses during RVE in comparison with RE: (1) muscle cross-sectional area (CSA) of upper and lower leg muscles, (2) muscle force (Maximal Voluntary Contraction, MVC) of the upper and lower leg during isometric and isokinetic conditions, and (3) jump height and contact time during jump performances. Furthermore, we think that training sustainability of WBVT is poorly investigated and therefore, we were interested in the retention of training benefits in both groups. Thus, we organized a 3-month follow-up.

Material and methods

Experimental approach

A 6-week strength training study was performed with one group training squats and heel raises alone (Resistive Exercise, RE) and the other group performing the same training with a vibration stimulus (Resistive Vibration Exercise, RVE). The increase in EMG amplitude evoked by WBV was shown to decrease to insignificant levels after one week[16]. To minimize this adaptation process to the vibration stimulus, we weekly increased the vibration frequency from 20 to 40 Hz over the 6-weeks of training in RVE. This study was designed to validate stronger functional effects after 6 weeks of strength training in RVE in comparison with RE alone by measuring: (1) the muscle CSA of knee extensor muscles (all mm. vasti combined, m. rectus femoris, and quadriceps femoris muscle as the sum of these muscles) and ankle plantar flexor muscles (m. gastrocnemius lateralis, m. gastrocnemius medialis, m. soleus, and the triceps surae muscle as the sum of these muscles), (2) the MVC of knee extension and flexion as well as ankle plantar flexion and dorsiflexion under isometric and isokinetic (60 °/s and 180 °/s) conditions, and (3) the jump performance of counter movement jump (CMJ, jump height) and drop jump (DJ, contact time). We were also interested in the retention of training benefits in both groups for these parameters and performed a 3-month follow-up. Therefore, the muscle CSA of upper leg and lower leg muscles, the MVC (isometric and isokinetic) of upper and lower leg muscles, and jump performance (CMJ and DJ) was measured in both intervention groups before the training started (pre), after the 6 weeks of training (post), and 3 months after the last training session was performed (follow-up). Post-study analysis showed that the follow-up measurement for RE took place 79.7±15.0 days and for RVE 73.6±15.0 days after the last training session.

Subjects

A total of 26 recreationally physically active (exercising 2-3 times per week) healthy male subjects participated in this study (RVE (n=13): age = 24.3±3.3 yrs., height = 1.79±0.05 m, body mass = 74.7±6.9 kg; RE (n=13): age = 23.4±1.4 yrs., height = 1.79±0.05 m, body mass = 75.0±4.7 kg). The mean age, height and body mass values were not significantly different between the two groups. The study received approval from the Ethics Committee of the North Rhine Medical Association (Ärztekammer Nordrhein), Düsseldorf, Germany. All participants volunteered to participate in this study and gave written informed consent. The subjects were aware that they could withdraw from the study at any time.

The 26 subjects were divided into two groups based on their maximum vertical jump height to have two groups with comparable neuromuscular fitness. A coin was then tossed to determine which group will perform RVE and which one RE. Smoking, regular medication, diabetes, participation in strength training during the past six months, and competitive sports were considered as exclusion criteria.

Training protocol

The subjects in both groups trained 2-3 times per week (week 1 to 2:2 training sessions per week, week 3 to 6:3 training sessions per week) resulting in a total of 16 training sessions. On each of the training days, all of the subjects performed 3 sets of 8 squats and 12 heel raises with 1 minute break between the two exercises and each set. The third set was performed with maximum repetitions of both exercises. The loading was set to 80 % of the One-Repetition-Maximum (1RM) of the squat performance measured before the initial training session (RM tables used from[41]). The third squatting set was used as an indicator to adjust the training load for both exercises, the squats and the heel raises, for the next training session (less than 8 repetitions= decrease in training load by approx. 5%, 8 repetitions= the same training load, more than 8 repetitions = increase in training load by approx. 5% but with a maximum increase of 10 kg). The movement speed was controlled by a metronome with a 2 seconds eccentric and 2 seconds concentric phase for squats and a 1 second eccentric and 1 second concentric phase for heel raises and, if necessary, by the instructions of an operator. During squats, the subjects moved downward until the thigh was approximately horizontal to the ground and then upward until a knee flexion angle of approximately 5° was reached. Full extension of the knee was avoided. In addition, during squatting, the subjects of RVE were instructed to shift their total weight to the forefoot as much as necessary to dampen the transmission of inconvenient or even painful vibrations going to the head. In consequence of this indispensable safety measure during squats in RVE, the plantar flexor muscles were loaded more than in RE performing ordinary squats. During squats in RE, we did not instruct the subjects to load the forefoot similar to the RVE condition because this would be too difficult to control by the subjects and the operators and would have caused more variability in the exercise performance and its potential effects. During heel raises, the RVE subjects were instructed for the downward movement to go down as much as possible while avoiding strong vibrations going to the head. Similarly, the RE subjects were instructed for the downward movement not to touch the platform with their heels. This was necessary since during WBV a normal stance or exercising with small knee angles as experienced during squatting and heel raises increases the likelihood of negative side effects and should be avoided[26]. Therefore, the way that the vibration paradigm was presented in the present study was the best possible way to truly compare RVE and RE. RVE trained on a side-alternating vibration platform (Galileo Fitness, Novotec Medical GmbH, Pforzheim, Germany) at frequencies between 20-40 Hz and an amplitude of 3-4 mm (6-8 mm peak-to-peak). To our knowledge, 40 Hz is the highest vibration frequency on a side-alternating vibration platform used for testing by now. Vibration frequency was gradually increased by 5 Hz per week with the last two weeks of training at 40 Hz. This approach (progressively increasing vibration frequency and training load) should avoid an early muscle activity decrease especially in the upper leg[16] and keep the subject's training performance at its individual maximum during each training session. RE performed the same training while the vibration platform was turned off. Both groups performed their training with gymnastic shoes. Since this study is part of a bigger study, the "EVE" study ("Molecular and functional **E**ffects of resistive **V**ibration **E**xercise"), a complete study overview of the EVE study has been published elsewhere[42].

Accuracy of loading

The training load for squats and heel raises was based on 80% of the 1RM of the squat exercise, resulting in 8 repetitions[41]. Due to organizational reasons we had to keep the same loads for the heel raises (knowing that the stimulus will be lighter), but increased the repetitions by 50% (to 12 repetitions) to counteract the lighter stimulus. Post-study analysis showed that the maximum repetitions of the 3rd set for squats were approx. 75-77% of the 1RM (RE: 9.4±1.6 repetitions, RVE: 9.6±1.7 repetitions) and for heel raises approx. 60% of the 1RM (RE: 20.8±4.0 repetitions, RVE: 20.5±5.8 repetitions). Thus, the loading for squats seemed to be in the range of a hypertrophic stimulus, whereas the loading for the heel raises showed the expected endurance focused stimulus.

Training compliance

In RE, ten subjects completed all of the 16 training sessions, whereas the remaining three subjects missed one training session. In RVE, four subjects completed all of the 16 training sessions, whereas the remaining nine subjects missed one training session. The time between the last training session and the 3-month follow-up was not controlled for altered activity levels.

Training loads

The training loads were comparable between the two groups at the first training session (RE: 81.5±7.7 kg, RVE: 75.2±6.5 kg) and significantly increased in both groups compared with their last training session (RE: 130.2±18.5 kg, RVE: 110.2±15.8 kg). There was a significantly lower increase in training load over the 6 weeks of training (time * intervention effect: $P<0.05$) in RVE (RE: 59.8±17.3 %, RVE: 46.9±19.0 %). Post-hoc analyses revealed that RE trained with significantly higher training loads compared to RVE from training sessions 13 to 16.

Measurement of muscle CSA

Magnetic resonance imaging (MRI) was used to visualize the leg muscles of the right leg of all subjects for pre-, post-, and follow-up measurements. The measurements were performed by trained personnel of the hospital in Porz (NRW, Germany) with a MRI device (Siemens, Model: Sonata). The resolution of the analyzed images was 265x224 pixels with a thickness of 3 mm per image.

The images of the lower and upper leg for every subject were analyzed for knee extensor muscles (all mm. vasti combined, m. rectus femoris, and - as a summation of the two former muscles - m. quadriceps femoris) and ankle plantar flexor muscles (m. gastrocnemius lateralis, m. gastrocnemius medialis, m. soleus, and - as a summation of the three former muscles - m. triceps surae). To avoid bias in the analysis of the images, the subjects of both groups were randomized (1 to 26) and also the 3 measurements of all subjects for the lower leg and the upper leg were randomized (1-77; 1 subject did not show up for the follow-up measurement) using a Microsoft Excel macro.

240 images were taken for the whole leg (120 for the lower leg and 120 for the upper leg), but only for every third image the individual muscles were manually outlined (sliceOmatic, 5.0 Rev-1e, TomoVision, Magog, Canada) to get the dedicated CSA. Within these analyzed images, we used anatomical references as starting points for the analysis to be able to compare the same anatomical areas for all images (for the upper leg: transition from the patella bone to the quadriceps femoris muscle tendon, for the lower leg: splitting point of tibia and fibula at the ankle joint, whereas for one subject we had to use the splitting point from tibia and fibula at the knee joint downwards due to blurry images). In addition, we then had to determine the lowest common multiple of all analyzed images within the pre-, post-, and follow-up measurement for the lower leg and the upper leg of a single subject to compare the same number of images. This was necessary due to the variation in the positioning of the leg for the MRI scan within the same subject and the amount of usable images within pre-, post-, and follow-up measurements (images in the outer parts of the MRI scans were rather blurry/dark for which reason the different muscles could not be distinguished anymore). In the end, the sum CSA of the different muscles was calculated for all remaining images by adding up the single CSAs within each measurement.

Measurement of MVC

MVC muscle force was measured with a Biodex System 3 dynamometer (Biodex Medical Systems, Shirley, New York, USA) for pre, post, and follow-up. Knee extension and flexion as well as ankle plantar flexion and dorsiflexion were measured under isometric and isokinetic (60 °/s and 180 °/s) conditions. Before the testing of knee and ankle joint muscles, the subject performed a short warm-up of the tested muscle groups which consisted of 5 repetitions at subjectively perceived 50% of the maximum with agonist and antagonist followed by 3 close-to-maximum repetitions with agonist and antagonist. Each test consisted of 5 repetitions at maximum effort in the following order: 1. Knee extension: 60 °/s - 2 min break - 180 °/s - 2 min break, 2. Knee flexion: 60 °/s - 2 min

Table 1. The effects of 6 weeks of progressive RVE and RE on leg muscle CSA.

	Leg muscle CSA [cm^2]					
Study phase	**Pre**		**Post**		**Follow-up**	
Intervention	RE	RVE	RE	RVE	RE	RVE[a]
Mm. vasti	1533±240	1465±256	1692±252*	1619±274*	1601±250*	1546±251*
M. rectus femoris	151±50	141±52	152±52	143±48	151±52	145±46
M. quadriceps femoris	1684±285	1606±285	1844±295*	1762±303*	1752±295*	1691±279*
M. soleus	548±72	539±79	552±75	547±74	548±79	550±75
M. gastrocnemius lateralis	114±29	114±19	117±27	125±22*	113±28	120±20*,+
M. gastrocnemius medialis	224±51	215±40	227±47	231±45*,+2	224±52	226±38*,+2
M. triceps surae	886±133	868±113	896±124	904±126*	884±135	896±110*,+

*Leg muscle CSAs (means ± SD, cm^2, sum of all included MRI images) are shown for pre, post, and follow-up measurements of mm. vasti, m. rectus femoris, m. quadriceps femoris, m. soleus, m. gastrocnemius lateralis, m. gastrocnemius medialis, and m. triceps surae. [a]Only 12 subjects are included in this measurement. *Significant time effect compared with pre-values. +Significant interaction effect (time*intervention) compared with pre-values. +2Tendency for an interaction effect (time*intervention) compared with pre-values. No intervention effects were observed. CSA = Cross-sectional area, RE = Resistive Exercise, RVE = Resistive Vibration Exercise.*

break - 180 °/s - 2 min break, 3. Knee extension: Isometric - 2 min break, 4. Knee flexion: Isometric - 2 min break, 5. Ankle plantar flexion: 60 °/s - 2 min break - 180 °/s - 2 min break, 6. Ankle dorsiflexion: 60 °/s - 2 min break - 180 °/s - 2 min break, 7. Ankle plantar flexion: Isometric - 2 min break, 8. Ankle dorsiflexion: Isometric. For isokinetic testing, the 5 repetitions were executed one after the other with approx. 1-2 s rest in between repetitions. For isometric testing, the 5 repetitions were executed with 5 s contraction time followed by 30 s rest. Subjects were given strong verbal encouragement during these tasks.

Measurement of jump performance

CMJ and DJ were performed using a force plate (Leonardo Mechanograph GRFP, Novotec Medical GmbH, Pforzheim, Germany) at pre-, post-, and follow-up measurements. For standardization reasons, the subjects always had their hands on the hips while performing the CMJ and the DJ and were wearing gymnastic shoes. For the CMJ, subjects were instructed to jump as high as possible. The DJ was executed from a platform of 20 cm height, while subjects were instructed to jump up from the force plate as fast as possible (with stiff knee, only using the ankle muscles, no heel contact) after first contact of their toes with the force plate. The best out of 3 consecutive jumps (highest CMJ height and shortest DJ contact time) was taken for further analysis. The CMJ was analyzed for jump height, while the DJ was analyzed for contact time.

Statistical analyses

Statistical analysis was performed using the software SPSS 22 (IBM Corporation, Armonk, NY, USA). All variables were tested for normal distribution. Muscle CSA data was normally distributed, besides m. soleus values which did not need to be rejected with P=0.09, whereas the corresponding residuals were all normally distributed which is mandatory for further analysis with Linear Mixed-Effects (LME) models. MVC data was normally distributed, besides ankle plantar flexion values (not normally distributed, P=0.007) and ankle dorsiflexion values which did not need to be rejected (P=0.171). However, the corresponding residuals were all normally distributed, besides knee flexion values which did not need to be rejected with P=0.167. Jump performance data and residuals were all normally distributed. Changes in muscle CSA, MVC and jump performance of RE and RVE were compared for time effects (study phases: Pre, post, and follow-up), intervention effects (training group: RE and RVE), and interaction effects (time*intervention) using LME models. Differences in subject characteristics were tested using an independent t-test. For all tests, the significance level was set at $P<0.05$, also taking into consideration a tendency level of P=0.05 to 0.1. Values are presented as means±standard deviation (SD).

Results

Muscle CSA

One subject of the RVE group did not perform the MRI follow-up measurement.

The following changes were measured for the CSA of the upper leg (Table 1):

The CSA of the m. quadriceps femoris and the mm. vasti showed comparable significant increases in both groups after 6 weeks of training (RE: 9.9±5.9 %, P<0.001; RVE: 9.9±3.8 %, P<0.001 and RE: 10.7±6.1 %, P<0.001; RVE: 10.7±4.0 %, P<0.001, respectively). These effect were still significant at the follow-up measurement in both groups and both muscles (RE: 4.2±3.9 %, P<0.001; RVE: 3.9±1.7 %, P<0.001 and RE: 4.5±3.9 %, P<0.001; RVE: 4.5±2.1 %, P<0.001, respectively). No intervention or interaction effects were found for the m. quadriceps femoris and the mm. vasti. The CSA of the m. rectus femoris revealed no time, intervention, or interaction

Table 2. The effects of 6 weeks of progressive RVE and RE on leg muscle MVC.

	MVC [Nm]					
Study phase	**Pre**		**Post**		**Follow-up**	
Intervention	RE	RVE	RE	RVE	RE	RVE^{a}
Knee extension isometric	250.5±50.7	247.5±49.8	277.8±50.0*	267.5±58.1*	259.3±39.3	257.8±56.8
Knee extension 60 °/s	214.6±19.9	215.3±30.2	231.1±22.7^{*2}	218.1±28.1	224.8±26.0	213.3±26.7
Knee extension 180 °/s	155.4±14.5	156.2±20.9	168.5±17.6	166.6±22.1	165.8±17.7	165.5±19.3
Knee flexion isometric	126.9±31.1	119.4±16.5	115.9±36.6	120.8±15.3	127.0±34.7	119.7±12.9
Knee flexion 60 °/s	140.9±24.7	131.3±17.5	145.9±25.2	134.1±20.9	143.3±26.9	137.2±17.3
Knee flexion 180 °/s	120.9±20.9	117.9±16.2	125.7±22.9	122.0±18.2	126.5±22.2	118.9±11.8
Ankle plantar flexion isometric	172.0±27.4	181.4±22.7	169.0±25.3$^{\#}$	189.7±22.9$^{\#,*2,+}$	171.2±22.8$^{\#}$	190.8±21.0$^{\#,*,+2}$
Ankle plantar flexion 60 °/s	101.6±20.6	96.0±12.1	107.6±19.5	111.2±13.9$^{*,+}$	108.2±19.2	110.0±8.5$^{*,+2}$
Ankle plantar flexion 180 °/s	60.5±12.5	57.6±7.6	59.7±10.6	64.5±10.0^{+}	62.5±11.8	62.6±5.7^{+2}
Ankle dorsiflexion isometric	31.5±6.3	30.1±4.8	32.2±6.3	31.3±5.1	32.2±6.1	30.3±4.4
Ankle dorsiflexion 60 °/s	25.6±5.6	25.1±4.9	26.0±5.5	24.8±4.4	26.3±5.2	25.4±5.0
Ankle dorsiflexion 180 °/s	17.0±4.2	17.1±3.1	17.5±4.1	17.5±3.9	16.9±4.3	17.3±4.1

*Leg muscle MVCs (means ± SD, Nm) are shown for pre, post, and follow-up measurements of knee extension, knee flexion, ankle plantar flexion, and ankle dorsiflexion, each under isometric and isokinetic (60 °/s and 180 °/s) conditions. ^{a}Only 12 subjects are included in this measurement. *Significant time effect compared with pre-values. ^{*2}Tendency for a time effect compared with pre-values. $^{+}$Significant interaction effect (time*intervention) compared with pre-values. $^{+2}$Tendency for an interaction effect (time*intervention) compared with pre-values. $^{\#}$Significant intervention effect between RVE and RE. MVC = Maximal Voluntary Contraction, RE = Resistive Exercise, RVE = Resistive Vibration Exercise.*

effects indicating similar responses over time for both groups.

The following changes were measured for the CSA of the lower leg (Table 1):

RVE showed a significant increase in the CSA of the m. triceps surae after 6 weeks of training (4.1±4.9 %, P=0.015) with a still significant increase at the follow-up measurement (2.9±3.2 %, LME fixed effects showed a tendency for the overall time effect of both groups with P=0.077 while the Bonferroni post-hoc testing revealed a significant time effect in RVE with P=0.012). In RE, the CSA of the m. triceps surae was increased by 1.5±6.0 % after 6 weeks of training and decreased to pre-training values at the follow-up measurement (-0.1±4.0 %). There was also a significant interaction effect (time*intervention, P=0.049) between the two groups and their changes from pre-training to the follow-up measurement.

The CSA of the m. gastrocnemius lateralis and m. gastrocnemius medialis showed a significant increase in RVE after the 6 weeks of training (10.4±14.4 %, P=0.023 and 7.7±8.0 %, P=0.005, respectively) and at the follow-up measurement (M. gastrocnemius lateralis: 7.2±10.9 %, LME fixed effects showed only a significant interaction effect - time*intervention, P=0.046 - between both groups and their changes from pre-training to the follow-up measurement while the Bonferroni post-hoc testing revealed a significant time effect in RVE with P=0.017; M. gastrocnemius medialis: 5.4±5.9 %, LME fixed effects showed a tendency with P=0.082 for the overall time effect of both groups while the Bonferroni post-hoc testing revealed a significant time effect in RVE with P=0.014). The CSA of the m. gastrocnemius lateralis and the m. gastrocnemius medialis in RE was also increased after 6 weeks of training (5.4±18.0 % and 2.1±9.4 %, respectively) but both failed to reach the level of significance. At follow-up measurement, both increases were back to pre-training values (0.2±12.8 % and -0.2±8.1 %, respectively). For post and follow-up measurement of the m. gastrocnemius medialis, there was also a tendency for an interaction effect (time*intervention, LME fixed effects with P=0.085 for post measurement and P=0.056 for follow-up measurement) between the two groups and their changes from pre-training to the post and follow-up measurement, respectively, while Bonferroni post-hoc testing revealed a significant time effect in RVE with P=0.005 for the post measurement and P=0.014 for the follow-up measurement. No intervention effects were found for the m. triceps surae, the m. gastrocnemius lateralis, and the m. gastrocnemius medialis. The CSA of the m. soleus revealed no time, intervention, or interaction effects indicating similar responses over time for both groups.

MVC

One subject of the RVE group did not perform the MVC follow-up measurement.

The following changes were measured for MVC at the knee joint (Table 2):

Isometric knee extension force was significantly increased after 6 weeks of training in both groups (RE: 11.6±10.0 %, P=0.002, RVE: 8.0±8.2 %, P=0.02). This increase was not significant anymore at the follow-up measurement (RE: 5.6±16.8 %, RVE: 3.4±14.6 %).

Table 3. The effects of 6 weeks of progressive RVE and RE on CMJ jump height and DJ contact time.

	CMJ jump height [cm] and DJ contact time [s]					
Study phase	**Pre**		**Post**		**Follow-up**	
Intervention	REa	RVE	RE	RVE	RE	RVE[a]
CMJ jump height	0.43±0.04	0.44±0.03	0.46±0.04*	0.47±0.03*	0.43±0.03	0.44±0.03
DJ contact time	0.172±0.017	0.168±0.021	0.171±0.021[#]	0.153±0.017*,#,+	0.165±0.021	0.156±0.012*

*CMJ jump height (means ± SD, cm) and DJ contact time (means ± SD, s) are shown for pre, post, and follow-up measurements. [a]Only 12 subjects are included in this measurement. *Significant time effect compared with pre-values. [+]Significant interaction effect (time*intervention) compared with pre-values. [#]Significant intervention effect between RVE and RE. CMJ = Counter Movement Jump, DJ = Drop Jump, RE = Resistive Exercise, RVE = Resistive Vibration Exercise.*

The isokinetic knee extension force at 60 °/s and 180 °/s was increased after 6 weeks of training in both groups (RE: 7.9±8.3 %, tendency with P=0.053, and 8.6±8.0 %, respectively, RVE: 1.7±7.1 % and 6.9±6.8 %, respectively) and increased in general (decrease only for RVE 60 °/s) at the follow-up measurement (RE: 4.8±8.1 % and 6.9±9.5 %, respectively, RVE: -1.3±9.9 % and 5.7±6.6 %, respectively) but all measurements failed to reach the level of significance.

For the isometric knee flexion force, we found a decrease in force after 6 weeks of training in RE (-6.6±24.8 %) but it failed to reach the level of significance. At the follow-up measurement, the force was back at the pre-training value (0.5±14.7 %). The isometric knee flexion force in RVE was increased for post (2.1±12.8 %) and follow-up measurement (1.3±12.5 %) but failed to reach the level of significance.

The isokinetic knee flexion force at 60 °/s and 180 °/s was increased in both groups after 6 weeks of training (RE: 3.9±6.7 % and 4.6±11.8 %, respectively, RVE: 2.1±8.7 % and 4.2±15.1 %, respectively) and increased in general (decrease only in RVE 180 °/s) in both groups at the follow-up measurement (RE: 1.9±8.2 % and 5.6±15.1 %, respectively, RVE: 3.9±8.0 % and -0.5±8.6 %, respectively) but all measurements failed to reach the level of significance.

No intervention or interaction effects were found for any knee extension and knee flexion force measurements.

The following changes were measured for MVC at the ankle joint (Table 2):

Isometric ankle plantar flexion force and ankle plantar flexion force at 60 °/s increased in RVE after 6 weeks of training (5.0±9.6 %, tendency with P=0.069, and 16.3±9.6 %, significance with P=0.001, respectively), whereas the follow-up measurement was significantly increased (5.8±8.8 %, P=0.045 and 14.1±10.9 %, P=0.002, respectively). Isometric ankle plantar flexion force and ankle plantar flexion force at 60 °/s increased in general (decrease only for isometric) in RE after 6 weeks of training (-1.2±9.4 % and 7.0±13.4 %, respectively) and at the follow-up measurement (0.4±10.2 % and 7.3±9.8 %, respectively) but all measurements failed to reach the level of significance. Isometric ankle plantar flexion force also showed a significant intervention effect at post measurement (LME fixed effects showed only a significant interaction effect - time*intervention, P=0.012 - between both groups and their changes from pre-training to the post measurement while the Bonferroni post-hoc testing revealed a significant intervention effect at post measurement with P=0.006) and at follow-up measurement (LME fixed effects showed only a tendency for an interaction effect - time*intervention, P=0.075 - between both groups and their changes from pre-training to the follow-up measurement while the Bonferroni post-hoc testing revealed a significant intervention effect at follow-up measurement with P=0.008).

Ankle plantar flexion force at 180 °/s was increased in RVE after 6 weeks of training (12.4±14.3 %) and at the follow-up measurement (8.3±11.7 %), but both failed to reach the level of significance, whereas RE values showed a slight decrease after 6 weeks of training (-0.7±7.3 %) and an increase at the follow-up measurement (3.7±6.6 %).

No intervention effects were found for ankle plantar flexion force at 60 °/s and 180 °/s.

For all ankle dorsiflexion force measurements, no time, intervention, or interaction effects were found indicating similar responses over time for both groups.

Jump performance

One subject of the RVE group did not perform the jump performance follow-up measurement and one subject from the RE group did not perform the jump performance pre measurement.

The following changes were measured for the jump performance of the DJ and CMJ (Table 3):

DJ contact time was significantly reduced by -8.2±9.4 % only in RVE after 6 weeks of training (LME fixed effects showed a tendency with P=0.068 for the overall time effect of both groups while the Bonferroni post-hoc testing revealed a significant time effect in RVE with P=0.008), while RE increased the DJ contact time by 1.5±9.8 %. During the follow-up measurement, RVE still showed a significantly reduced DJ contact time (-6.0±11.7 %, P=0.044), while RE value was reduced by -2.9±8.9 %).

DJ contact time also showed a significant intervention effect at post measurement (LME fixed effects showed only a significant interaction effect - time*intervention, P=0.042 - between both groups and their changes from pre-training to the post measurement while the Bonferroni post-hoc testing revealed a significant intervention effect at post measurement with P=0.024). There was also a significant interaction effect (time*intervention, P=0.042) between the two groups and their changes from pre-training to the post measurement.

CMJ jump height was significantly increased in both groups after 6 weeks of training (RE: 5.3±10.4 %, P=0.03; RVE: 7.0±5.8 %, P=0.007). At follow-up, both groups were still slightly increased (RE: 0.9±9.4 %, RVE: 1.3±6.2 %) but failed to reach the level of significance. No intervention or interaction effects were found for CMJ jump height.

Discussion

Our aim for the present study was to use progressive high intensity conventional resistance training (RE) and compare it against the same training regimen plus WBV (RVE) with progressively increased vibration frequencies. To avoid potential early (within days) neuromuscular adaptations to the vibrations stimulus, e.g. a muscle activity decline[16], we increased the vibration frequency on top of progressive training load adaptations over the training period. The main finding of this study was a distance-dependent effect of WBVT to evoke functional performance increases such as CSA growth, isometric strength, and DJ contact time. The closer the trained muscle was towards the vibration platform, the more pronounced was the effect of RVE. In detail, we found a significant increase in quadriceps muscle CSA for post and follow-up measurement in RE and RVE, whereas the triceps surae muscle CSA only significantly increased in RVE for post and follow-up measurements. For maximum isometric knee extension, both groups significantly increased their force for post measurement, whereas maximum isometric ankle plantar flexion force was only significantly increased in RVE (post: tendency to increase, follow-up: significant increase) with an additional intervention effect (significantly higher forces in RVE compared with RE) at post and follow-up measurement. The power output measured as CMJ jump height, which is mainly dependent on thigh muscle force development was significantly higher in both groups at post measurement. The neuromuscular performance measured as DJ contact time, which is mainly dependent on calf muscle force development was only significantly shorter in RVE at post and follow-up measurements with an additional intervention effect (significantly shorter DJ contact time in RVE compared with RE) at post measurement. In addition, training load increases were hampered in RVE from the 13th training session onwards (vibration frequency at 40 Hz) likely due to vibration-induced elevation of musculoskeletal forces[42]. Overall, RVE showed better training effects than RE only in the ankle plantar flexor muscles, which are closer to the vibration platform than the knee extensor muscles. However, during squats under RVE conditions, subjects had to shift their weight to the forefoot as much as necessary to dampen the transmission of inconvenient vibrations going to the head and in consequence, their plantar flexor muscles were loaded more than in RE performing ordinary squats. Beside the likely major stimulus of the calves during RVE heel raises, the additional loading of the calves during RVE squats was representing an unspecific, minor training stimulus of RVE.

In general, performing sets to muscular failure seem to facilitate stronger chronic muscle growth than performing submaximal sets[43,44]. In our study, subjects performed their training based on their individual 80 % 1RM load while the loading could be continuously increased over the training period, supporting a hypertrophic effect of our training. However, the last set of our training (till muscular failure = maximal number of repetitions) revealed that the stimulus for the squats was slightly below the anticipated load of 80% of the 1RM (approx. 75-77%, which is still in the range of a hypertrophic stimulus), whereas the stimulus for the heel raises - as expected - was much lower (approx. 60%, which is in the range of an endurance stimulus). Moreover, the use of multiple sets - as performed in our study - seem to be favorable over a single set for optimized strength gains[45-47].

Also, it is commonly known that conventional resistance training leads to muscle hypertrophy[18,48], while the additional benefit of WBVT (both, using conventional WBV without added weight and RVE) is still imprecise[1,2,49]. However, on a functional level, at least muscle strength (knee extension force) and muscle power (CMJ height) seem to be more increased after RVE than after RE[1,12]. Conversely, our study showed similar effects for knee extension force and CMJ height for both training groups. This might be related to the fact that when RVE training started with 40 Hz vibration frequency, the training load used for RVE subjects became significantly lower compared with RE (= 13th training session onwards) and thus, the increase in vibration frequency to 40 Hz led to pronounced elevations of musculoskeletal forces[42] limiting the quadriceps muscles (main muscle group for performing squats, generating knee extension force, and generating jump height during CMJ) in RVE. In conclusion, 40 Hz vibration frequency seemed to reduce the ability of force generation in knee extensors with respect to the current 80% of 1 RM training regime, which led to a significantly lower progression of training load/squat strength during RVE in comparison with RE.

The muscle CSA of the m. quadriceps femoris increased significantly for both groups with similar magnitudes in our study. Similarly, muscle size loss on the quadriceps muscle was prevented in a 60-day bed rest study[50] for both groups (RVE and RE). Diverting results were found in our study for the triceps surae muscle, which was significantly increased after the training period only in RVE, whereas another study yielded no additional mitigation effect of this muscle in RVE[50]. Interestingly, that other study[50] already used an increased training volume for the calf muscles trying to compensate for their reduced responsiveness[51], whereas our training intensity was adjusted to the squat exercise (less stimulus for the calf muscles which are able to lift heavier loads than with squats). But since triceps surae muscles are usually more prone to atrophy than quadriceps femoris muscles due to their daily degree of loading[52], it seems that the additional stimulus of normal daily activity (our study was ambulant) exceeds possible (vibration) training effects during unloading. In our study, detailed analysis of the triceps surae muscle CSA revealed that its significant increase in RVE is due to an increased m. gastrocnemius lateralis and medialis but not m. soleus. This is in conjunction with Beijer et al.[53], who found no muscle fiber hypertrophy in m. soleus biopsies in our study. We think this can be attributed to the different fiber type composition of those muscles. First, m. soleus is composed of more slow twitch fibers than fast twitch fibers (approx. 72% vs. 28%, respectively)[53] and second, it has more slow twitch fibers than the gastrocnemius muscle (approx. 80% vs. 57%, respectively)[54]. Therefore, the m. soleus might not be as much susceptible to the fast vibrations of a vibration platform as the gastrocnemius muscle. Furthermore, there might also be an additional training effect of the calf muscles during squatting in RVE due to the different feet position. In detail, RVE subjects were instructed to slightly lift their heels up from the vibration platform during squatting to avoid vibrations going to the head. For the quadriceps femoris muscle, our results show that the significant increases in muscle CSA for both groups are related to an increase in mm. vastii and not m. rectus femoris. Since the m. rectus femoris is composed of even less slow twitch fibers than the gastrocnemius muscle and the mm. vastii[55], its not responding to the hypertrophic stimulus cannot be explained with the specific fiber type composition. The m. rectus femoris is not only a knee extensor muscle but also a hip flexor muscle, but since strong damping of vibration occurs at the hip[16], it seems that the stimulus for the m. rectus femoris was not high enough to hypertrophy. However, the mm. vastii function as knee extensor muscles only with no physiological function at the hip. Therefore, they were fully stimulated during squatting also with less damping of vibration occurring at the knee[16]. In conclusion, WBVT performed over several weeks and months seems to have no additional effect on upper leg muscle mass in RVE compared with RE. However, our study could show that the combination of progressively increasing vibration frequency and training load in RVE provoked higher lower leg muscle mass increases than the progressively increasing training load alone in RE. In addition, we could show that all the significant hypertrophic effects in both groups were still present at the follow-up measurement.

Our training focused on the quadriceps and calf muscles, so we expected positive training effects only in these muscles. First, MVC muscle force increased only during knee extension and ankle plantar flexion testing. In detail, isometric knee extension strength was significantly increased for post measurement in both groups with an additional advantage in dynamic knee extension strength at 60 °/s for RE in comparison with RVE, whereas isometric knee flexion strength showed a decrease in RE and was only slightly increased in RVE after the 6 weeks of training. Similarly, ankle strength testing revealed significant increases only during isometric and dynamic (60 °/s) plantar flexion for post and follow-up measurements (in RVE), but no significant increases in dorsiflexion for both groups. Second, with regards to jump performance, we found similar significant improvements in CMJ height, which mainly relies on upper leg force generation, for both groups at post measurement, whereas DJ contact time, which mainly relies on lower leg force generation, was only significantly reduced in RVE at post and follow-up measurements with an additional intervention effect at post measurement. In detail, the CMJ stretch phase is relatively slow and a reflex contribution to the stretch shortening cycle (SSC) potentiation seems to be less than in hopping[56], while a DJ execution is similar to a single hop and thus, a shorter DJ contact time might be attributed to a WBV-induced stretch reflex[57,58] at the ankle, which improved the SSC of the calf muscles after chronic exposure to WBVT. This leads to the assumption that WBVT triggers the regulation of muscle spindle sensitivity to e.g. increase muscle stiffness and dampen the vibration[58]. Third, muscle CSA increases in our study were similar for RE and RVE in the upper leg, but increased only in RVE in the lower leg. Therefore, our high intensity training regimen was successful in stimulating the quadriceps and calf muscles.

Perez-Turpin et al.[11] performed a 6 week training intervention with and without WBVT with sub-elite male volley ball and beach volleyball players and found significant higher CMJ heights and leg press strength in both groups, but with stronger increases in the WBVT group. Similarly, Fagnani et al.[8] found in competitive athletes after a 8 week training intervention with RVE or RE significant improvements in knee extensor strength and CMJ height only for RVE. Our results can also support these findings of increased performances in both groups, but CMJ height and knee extension forces were similar in our groups. This might be due to the different subject profile in both studies. Perez-Turpin and Fagnani examined athletes, who might be very responsive towards jumping movements and strength training, as opposed to our moderately trained subjects. Also, Mester et al.[10] could find stronger increases in isometric leg press strength in RVE in comparison with RE during a 6 week training period with sport students. However, the increase in CMJ height and the decrease in DJ contact time were not significantly different. Our results can partially support these findings (similar CMJ height), but we found no stronger knee strength in RVE compared to RE and we found a stronger decrease in DJ contact time in RVE. Since the training period was the same as in our study, we assume that the different subject profile and the higher training load in our study might have driven varying results.

In congruence to our study, which also examined non-athlete subjects, Bertuzzi[7] found similar increases in dynamic leg strength for RVE and RE in recreational active long-distance runners undergoing a 6 week strength training program with no greater effect of RVE. In addition, Kvorning et al.[5] et al found during a 9-week training period with moderately trained people increases in isometric leg press strength and CMJ height in RE and RVE, but with no additional benefit of RVE. Similarly, no additional effect of RVE over RE could be found for isometric and isokinetic knee extensor strength of untrained female students who followed a 24 weeks training program[3]. However, Delecluse et al.[4] could show no effect on isometric and dynamic knee strength and CMJ height of a 5 week RVE or RE training in sprint-trained athletes. They concluded that this type of athletes has already well developed muscle strength and reflex sensitivity so that WBVT did not affect their muscle performance.

In sum, evidence seems to be diverse whether: (1) WBVT can elicit stronger effects than RE and (2) athletes or non-athletes profit more from RVE than RE.

To make sure that the results of our study can be derived from the training intervention itself and is not attributed to external factors, a Freiburg Questionnaire for daily physical activities was analyzed. Beijer et al.[42] showed that the subject's daily physical activities were comparable between the two groups and did not change over the duration of the study.

In conclusion, within 6 weeks of squat and heel raises exercises, RVE showed higher (significance or tendency) responses than RE in calf muscles (muscle CSA, isometric and isokinetic strength) and DJ contact time, which confirms our hypotheses for the calf muscles. Also, most of these effects were still persistent at the follow-up measurement. For the quadriceps muscle (muscle CSA, isometric and isokinetic strength) and CMJ height, it seems that RVE and RE show similar responses. Thus, we could find a distance-dependent effect for our hypertrophy training with WBV. However, the absolute training load increased significantly more in RE after approx. 5 weeks of training. No changes in knee flexion and ankle dorsiflexion strength were found, which was not surprising because these muscles were not specifically trained. We are assuming that a training intensity which would have been adjusted to the heel raises instead of squats could have further improved the WBVT effect on the calf muscles. In addition, we can see this type of protocol implemented in professional sports with a special (but not only) focus on calf muscles such as sprint, skiing, and high jump. The relatively specific benefits of RVE over RE, the discomfort of the vibration stimulus, and the distinct health risks that may occur at least in case of an inappropriate performance of RVE - especially with high loads - in the absence of an instructor make RVE a rather inappropriate training method in recreational sports. With regards to astronaut training, the above mentioned concerns and the high technical effort required to isolate vibrations from the structure of a space vehicle make WBVT rather challenging and - at best - a supportive in-flight countermeasure.

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