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Effects of whole body vibration training combined with blood flow restriction on muscle adaptation

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Abstract

This study investigated the effects of whole body vibration (WBV) training combined with blood flow restriction (BFR) on muscle fitness. Twenty physically inactive adults were randomly assigned to a WBV + BFR group (8 men and 2 women) and a WBV group (8 men and 2 women). The participants in the WBV group were subjected to 10 sets of intermittent WBV exercise 20 min/day, 3 days/week, for 8 weeks. The participants in the WBV + BFR group received the same WBV treatment, but the proximal portion of their thighs was compressed using inflatable cuffs. Dual-energy X-ray absorptiometry estimated thigh muscle mass, one repetition maximal (1RM) leg press, and muscle endurance were measured before and after the training program. The results indicated that thigh muscle mass significantly increased (3%) after the 8-week training period only in the WBV + BFR group. Meanwhile, 1RM leg press and muscle endurance significantly increased in both groups after training ($p < 0.05$). Analysis of covariance revealed that the increase in 1RM leg press and muscle endurance was significantly higher ($p < 0.05$) in the WBV + BFR group than the WBV group (leg press: 11.1%. vs. 4.37%; muscle endurance: 48.84% vs. 15.19%, respectively). In conclusion, exposure to regular WBV + BFR training can increase thigh muscle mass, maximal strength, and muscle endurance compared with exposure to WBV training alone. WBV + BFR training appears to be a feasible strategy for improving muscle mass, strength, and endurance in previously untrained participants.

Keywords: physically inactive, inflatable cuffs, leg press, thigh muscle mass

Introduction

Blood flow restriction (BFR) resistance exercise is an emerging strength training method that typically entails fixing inflated cuffs or wraps around the proximal portion of the limbs during relatively low-load resistance exercise to maintain arterial flow to the muscle while reducing venous return (1). BFR resistance training is an attractive workout method because even for a 20%–30% one-repetition maximum (1RM) low-load resistance exercise combined with BFR, muscle hypertrophy is similar to that achieved through traditional high-load (70%–80% 1RM) resistance training (2, 3). It is speculated that the ischemic/hypoxic environment induced by BFR and the potentially magnified metabolic stress seem to play a key role in the induction of muscle hypertrophy (1, 4, 5).

BFR resistance exercise has been reported to have an additive effect on strength training adaptations; for example, it has been associated with increases in muscle mass (3, 6, 7), strength (6-8), and endurance (9-11). It has also been demonstrated to augment several acute resistance exercise–induced physiological responses (5, 12, 13) when compared with resistance exercise of the same intensity but without BFR. BFR resistance exercise benefits those who are unable to tolerate resistance training at heavy loads (1) and seems to be both an effective and safe alternative to heavy-load resistance training, particularly for frail individuals such as older adults (3, 7, 8, 9), for rehabilitation purposes (6), and for sedentary populations (2).

Both resistance exercise and BFR resistance exercise, when performed appropriately, can effectively improve muscle fitness (11). However, for some populations, such as people with poor time management ability or load-contraindicated individuals, engaging in resistance exercise can be difficult. Hence, using strategies that involuntarily induce muscle contraction as an alternative training modality might be of considerable value. For example, whole body vibration (WBV) training devices are specially designed machines that contract users' muscles passively and have been used as an alternative training modality for many years. Exposure to higher vibration frequencies within a specific range will cause a greater reactive force to the body that tends to induce greater muscle activation (14, 15). However, once the vibration frequency reaches a certain level, the complex interaction between mechanical (muscles and tendons) and reflex inhibitory factors may result in reducing muscle activation (14). Also, severe muscle soreness and even hematoma may occur (16). Thus, exploring a safe and feasible strategy for effectively amplifying WBV exercise response is of particular importance.

Because the additive effect of BFR resistance training is often evident in people engaging in low-load resistance exercise, BFR has recently been incorporated into other low-load exercise modalities, namely elastic band exercise (17), walking (18), cycling (19), and neuromuscular electrical stimulation (20). Altogether, the evidence suggests that these types of BFR exercise yield superior muscle fitness adaptation compared with the same exercise performed without BFR (17-20). Regarding WBV + BFR exercise, studies have demonstrated that people have a greater acute heart rate response (21) and rating of perceived exertion (RPE), blood lactate contraction ([La]), muscle activation (22), and satellite cell activation (23). Results of the aforementioned studies indicate that exposure to WBV + BFR may yield greater training potential in muscle fitness (e.g., muscle strength, endurance and mass). However, whether muscle fitness adapts to regular WBV + BFR training is currently unclear.

Therefore, this study investigated the effect of WBV + BFR training on muscle mass, strength, and endurance adaptations and examined whether WBV + BFR is more effective in training response than WBV alone. Acute physiological parameters such as RPE and [La] were also evaluated in this study. We hypothesized that exposure to WBV + BFR would increase both acute response and the effect of regular muscle training to a greater extent than exposure to WBV alone.

Material and method

Participants

Twenty-three untrained adults (17 men and 6 women) volunteered to participate in the study. All participants were identified as being physically inactive through screening with the International Physical Activity Questionnaire-Short Form (24). The participants were randomly divided into a WBV + BFR group (N = 11) and a WBV group (N = 12). The Institutional Review Board of Kaohsiung Medical University Chung-Ho Memorial Hospital approved all the methods and procedures employed in this study, and all the participants provided written informed consent. One participant from the WBV + BFR group and two participants from the WBV group withdrew after the training period began for reasons unrelated to the study. Finally, 10 participants (8 men and 2 women; age = 20.45 ± 0.21 years; height = 169.5 ± 2.77 cm; body mass = 69.4 ± 2.72 kg) from the WBV + BFR group and 10 participants (8 men and 2 women; age = 21.09 ± 0.55 years; height = 168.5 ± 2.01 cm; body mass = 64 ± 3.91 kg) from the WBV group were analyzed.

Experimental procedures

A week before the experiment, the participants were familiarized with the experimental procedures and devices. After that, muscle mass, muscle strength, and endurance measurements were obtained 6 days before the start of the study and then 3 days after the training period concluded (Figure 1). Muscle strength and endurance were determined the day after the muscle mass measurement. Then, the participants performed the given training regimen for 8 weeks. The participants in the WBV group engaged in 10 sets of intermittent static WBV exercises for 20 min/day, 3 days/week, for 8 weeks. The participants in the WBV + BFR group received the same WBV treatment, but the most proximal portions of both their thighs were compressed with inflatable cuffs. The acute effect was assessed on the first training day. The participants arrived at the laboratory between 07:30 and 09:30 hours and sat for 10–15 min. Then, a registered nurse collected fasting blood samples as a baseline measurement. The participants then completed 10 sets of WBV exercises with or without BFR. At the end of each set, the participants' RPE were recorded. Blood samples were also collected again from each participant immediately after exercise. All the female participants reported having regular menstrual cycles of 28−30 days in duration. No measurements were carried out on their menstrual bleeding days. Accordingly, pre and post muscle strength and endurance were tested during luteal phase (approximately days 15–20 of the menstrual cycle). In addition, pre and post blood samples were taken during luteal phase (approximately days 20–24 of the menstrual cycle).

Following the first training session, each participant trained on the same separate days each week at approximately the same time for the duration of the study. All measurements and training were performed in a thermoneutral room, which was maintained at 24°C–26°C and 40%–60% humidity. All training sessions were conducted strictly under the direct supervision of personnel technically familiar with WBV and BFR training.

WBV protocol

The WBV training protocol and vibration frequency applied at the beginning were adapted from previous studies (21, 22, 25), because greater acute metabolic and neuromuscular responses were observed when external BFR was applied (21, 22). Our study extended these acute results by employing an 8-week training regimen to investigate whether WBV training combined with BFR would have an additive effect on muscle adaptation compared with WBV alone. On this basis, the participants stood on a commercially available platform (BH YT18, Taipei, Taiwan) in a static squat position at 100° knee flexion with their hands placed on the rigid lever arms. The vibration frequency was set at 26 Hz, and the amplitude of vibration was 4 mm. The participants were instructed to wear thin socks without shoes. The participants then performed 10 sets of WBV, each for a 1-min duration with a 1-min rest between sets. After the fifth set, 2 min of rest was allowed (21, 22). During the rest intervals, the participants were instructed to stand on the vibration platform.

Thereafter, the progressive overload training protocol was increased by increasing the the vibration frequency rather than the duration to prevent any potential disadvantages caused by prolonging the occlusion time. Progression of a WBV training protocol by increasing the frequency was also used in a previous study (26). In addition, given that greater vibration frequencies (>35 Hz) have been shown to induce greater muscle activation than lower frequencies (<35 Hz) (15), the final vibration frequency was less than 35 Hz, in case the intensity was not tolerated when BFR was applied. On the basis, the vibration frequency was increased progressively every eight sessions for that individual in 4-Hz increments from 26 to 34 Hz. The same progression was held for every group.

BFR device and pressure applied

The BFR device was custom made and is similar to a handheld sphygmomanometer. It is composed of two inflatable cuffs made of nylon (width = 9 cm, length = 70 cm), a hand bulb pump with a check valve, a pressure gauge, and rubber tubes. The two cuffs are connected to the hand bulb pump by the rubber tubes, through which air passes during pumping. Another tube from the bulb connects the pressure gauge, from which the pressure of the cuffs is obtained. The occlusion target pressure for a participant in the WBV + BFR group was on the basis of mid-thigh circumference [<50 cm, 140 mm Hg (N = 1); 50–55 cm, 160 mm Hg (N = 5); 55–60 cm, 180 mm Hg (N = 3); >60 cm, 200 mm Hg (N = 1)] (20), because arterial occlusion pressure is largely influenced by thigh circumference (27). Pressure was maintained throughout the duration of exercise (20 min), including rest periods. Cuff air pressure was released immediately upon completion of each session. Our pilot study confirmed the feasibility of these pressures.

Rating of perceived exertion (RPE).

For safety concerns, RPE was recorded immediately after each set of WBV exposure by using the Borg Category Ratio 10 scale (CR10). To represent an accurate assessment of the average workload during the entire exercise regimen, we calculated the average of 10 sets of RPE values for statistical analysis in accordance with a previous research (22).

Measurements of muscle mass

Muscle mass of the thigh was determined with an electric scale and measured to the nearest 0.1 kg using a dual-energy X-ray absorptiometry (DEXA) scan (software version 3.6; Lunar DPX, Madison, WI). The participants were positioned on the DEXA machine in a supine position with their palms on the lateral aspect of their thighs. Then, the participants' lower extremities were placed in a comfortable position within the parameters of the DEXA machine. All scans were performed according to hospital protocol by a licensed technician. The participants refrained from any strenuous exercise for 48 h before the measurement. The coefficient of variation (CV) of DEXA from previous research is 0.3% for lean mass (28).

Maximal strength test

Maximal strength was determined by assessing the participants' 1RM leg press on a resistance machine (Matrix, Leg press, G3-S70, Taipei, Taiwan). Range of motion was controlled for this exercise. The participants were instructed to adjust the seat carriage to set the knee angle at appropriately 90°, ensuring that their knees were not anterior to their toes. Then, they lightly squeezed the grips, pushing away the given load until their legs were fully extended while their head, shoulders, back, and buttocks remained in contact with the pad. Details of the testing procedure have been mentioned elsewhere (29), but briefly, three to five maximal trials separated by 3–5 min of rest were used to determine individual 1RM for each resistance exercise. The heaviest weight successfully pressed was recorded as the 1RM. A previous study reported a CV value of 1.6% for 1RM leg press in previously untrained adults (30).

Evaluations of muscle endurance

Muscular endurance testing was based on the procedure detailed in a previous study (29) and was determined by assessing the number of repetitions to lift a weight at 70% of pretraining or posttraining 1RM for the leg press exercises prior to failing. Any repetition that lacked the full range of movement was not counted. The maximal number of repetitions multiplied by the weight of 70% 1RM for the leg press (weight × repetition) was used as the measure of muscular endurance. A CV of 9.6% has been reported for the evaluation of muscular endurance (31).

Blood sample collection and analysis

Blood samples were collected from the antecubital vein. Then, the samples were stored at 4°C and centrifuged at 1500 rpm for 30 min within 2 h of sampling. The serum samples were sent to the clinical laboratory for further assays. [La] levels were estimated using an automated analyzer Dimension RxL Max Integrated Chemistry System (Siemens Healthcare Diagnostics Inc, Deerfield, IL, USA). The analyzer was used according to the manufacturer's instructions.

Statistical analyses

All data in this paper are expressed as mean ± standard error (SE). An independent t test was used to compare the RPE values between the groups. The effects of acute exercise and training on the two groups were assessed using repeated measures analysis of covariance (ANCOVA), using the pre exercise values as covariates. As indicated by Jamieson (32), when groups are assigned at random, ANCOVA is considered an adequate method for comparing changes between groups. Pre- and post-exercise within-group differences were analyzed with Bonferroni corrected paired *t*-tests. Statistical significance was set at $p < 0.05$ for all tests.

Results

Acute responses

The independent t test indicated that mean RPE values during exercise for the WBV + BFR group (6.52 ± 0.30) were significantly higher than those for the WBV group (4.82 ± 0.40; $t = 3.38$, $p < 0.01$).

Figure 2 illustrates the acute changes in [La] level before and after the initial exercise for both groups. The paired t test revealed that the [La] level increased significantly after the initial exercise compared with before the exercise in both the WBV + BFR and WBV groups ($p < 0.05$ for all participants). In addition, ANCOVA revealed that the increase in [La] value was significantly higher ($p < 0.05$) in the WBV + BFR group than in the WBV group.

Chronic Responses

The participants in the WBV + BFR group exhibited significantly increased thigh muscle mass (3%, $p < 0.05$) after the training period, but thigh muscle mass was unaltered in the WBV group ($p > 0.05$) after the training period (Table 1). ANCOVA showed that the increase in thigh muscle mass was significantly greater in the WBV + BFR group than in the WBV group (Table 1).

The 1RM leg press load significantly increased in the participants in both the WBV + BFR group (11%, $p < 0.05$) and the WBV group (4.5%, $p < 0.05$) after the 8-week training period (Table 1). ANCOVA indicated that the increase in 1RM leg press was significantly higher in the WBV + BFR group than in the WBV group (Table 1).

Muscular endurance was evaluated as the maximal number of repetitions multiplied by the 70% load of the 1RM leg press. Muscular endurance significantly increased in both groups after training (Table 1), but the improvements were significantly higher in the WBV + BFR group than in the WBV group, as determined by ANCOVA ($p < 0.05$; Table 1).

Discussion

The current study was able to replicate the findings from previous research that used a similar protocol and documented that external BFR manipulation in WBV exercise has an additive effect with respect to eliciting RPE and [La] production responses in people (22). However, our study extended these acute results by employing an 8-week WBV training regimen with or without BFR to compare the training responses. The improvements in muscle mass, 1RM leg press and muscle endurance after WBV + BFR, along with the improvements in 1RM leg press and muscle endurance after WBV (table 1), were greater than the CV of the respective tests (28, 30, 31) as described earlier, indicating an acceptable probability of true change in muscle fitness. Furthermore, the current study determined that participants who engaged in the WBV + BFR exercises had an increase in thigh muscle mass after their training. We also found that regular WBV training with BFR can lead to improved maximal strength and muscle endurance in previously untrained adults.

Evidence has suggested that WBV exercise using a static squat position can increase thigh muscle mass in older population (33). However, research conducted by Osawa, Oguma, and Onishi did not find significant changes in thigh muscle mass among untrained young adults (26). Although no notable change was observed for thigh muscle mass among the participants in our WBV training program, an increase in thigh muscle mass was significant when participants engaged in WBV combined with BFR. This is the first study to demonstrate that WBV + BFR training can improve muscle mass. The current findings also support the notion that exercise combined with BFR can yield greater gains in muscle mass than engaging in the same exercise modalities without BFR (3, 6, 7, 17-20). How BFR training induces this muscle hypertrophy is not clearly understood, but it seems that the ischemic/hypoxic environment achieved through BFR magnifies metabolic stress, which is thought to play a prominent role in the induction of muscle hypertrophy (1, 4, 5). [La], which is a component of metabolic stress response, was augmented in the WBV + BFR group in the present study and can thus partly explain our observations. In addition, greater muscle activation, which is typically estimated via surface electromyography (EMG), is a critical factor for BFR training–induced muscle hypertrophy (34). Although we did not compare EMG amplitude between the WBV and WBV + BFR groups, a previous study using a similar protocol found that WBV + BFR exercise yields greater EMG amplitudes in quadriceps muscles (22). This may also help explain our finding of increased thigh muscle mass. Compared with previous research that included untrained adults as participants, increase in thigh muscle mass induced by WBV + BFR exercise (3%) observed in our study appear to be slightly greater than BFR combined with cycling (muscle mass: 1.15%; thigh cross-section area [CSA]: 2.45%) (19). However, due to methodological differences, the magnitude of improvement in our findings cannot be directly compared with other BFR exercise studies that used only the quadriceps or thigh muscle thickness for assessing hypertrophic effect (3, 7, 17, 18, 20). These BFR modalities used nonresistance-trained populations or older people found that an increase in quadriceps CSA induced by BFR + resistance training was 6.6%–8.0% (3, 6, 7) and induced by BFR + elastic band training was 6.9% (17). The increases in quadriceps volume induced by BFR + walking were 4.1% (18), and the increases in thigh muscle thickness induced by BFR + NEMS were 3.9% (20).

The results of our study indicate that regular WBV training improves muscle strength, supporting the results published by Machado and associates (33). It has been suggested that the use of vibration that causes reflexive muscle contractions to enhance muscle strength has a similar mechanism, which consists of both neural and muscular adaptations, as resistance training (35). Given the increase in participants' muscle strength noted in our WBV protocol in the absence of increased muscle mass, the possible mechanisms of WBV that increased strength in the current study may be attributed to a neural factor. This factor is thought to be associated with activation of the muscle spindles, Iα-motoneurons, and Golgi tendon organ, which consequently initiates force development (35). As we determined in the present study, gains in strength were greater among the WBV + BFR group than among the WBV group. This is similar to the findings of other BFR resistance training studies that have indicated that low-load resistance training combined with BFR increases muscle strength more than the same resistance training without BFR does (6-8).

Additionally, research on BFR resistance training has suggested that the metabolic stress induced by BFR may magnify metabolic response (5), which may influence muscle fiber fatigue and lead to the gradual recruitment of fast-twitch motor units during training (36). The current study may provide a rationale for this interpretation because both fatigability and part of metabolic stress, respectively estimated by RPE and [La] level, were heightened in the WBV + BFR group. Furthermore, as noted earlier, the increased muscle mass may facilitate gains in muscle strength. Therefore, the increase in muscle strength observed in the WBV + BFR group may be attributable to a concomitant increase in muscle mass and neuromuscular adaptation derived from the metabolic changes. The improvements in leg press 1RM strength in the WBV + BFR group (11%) was somewhat lower than that reported in some studies (16%–33.4%) that used low-load resistance training and elastic band training plus BFR (6-8, 17). This can likely be explained by the various types of muscle contraction (voluntary dynamic vs. static vibration) utilized in the studies. Methodological differences, such as duration of treatment and exercise protocol, may have also played a role. Notably, even the WBV + BFR exercises only consisted of bending the knee and the working muscles were almost passively stimulated. However, the improvements in muscle strength appear to be greater than those attained using other modalities in nonresistance-trained populations. These include endurance-based training such as walking (leg press: 7.4%) (18), cycling (knee extension: 5.95%) (19), and involuntary NEMS (isokinetic contractions: 7.0%–8.3%) (20). The foregoing suggests that WBV + BFR may provide greater benefits than nonresistance-type modalities.

The current study also demonstrated that muscle endurance was greatly improved in the participants in the WBV + BFR group. This finding supports previous studies that have used resistance training modalities plus BFR and have revealed that both trained and untrained populations made greater gains in muscle endurance compared with people who only engaged in non-BFR-treated resistance training (9-11). Although it is difficult to compare the magnitude of improvements in muscle endurance we found to these studies because of methodological differences in the examination of muscle groups and the nature of muscle endurance assessment, it is worth noting that muscle endurance was the most pronounced improvement among the muscle fitness parameters examined in the current study. This is very similar to the findings of Kacin et al. (9) that demonstrated an obvious increase in muscle endurance among the muscle fitness testing parameters examined after ischemic exercise. A significant increase in skeletal muscle capillarization is thought to contribute to increases in muscular endurance, which facilitates oxygen delivery within muscles (37). The adaptation of capillarization following exercise shows signs of angiogenic growth factors (e.g., VEGF) (38). Resistance exercise when combined with BFR pushes working muscles into a greater ischemic/hypoxic state, which in turn augments angiogenic gene expression, and has been speculated to elicit adaptations in muscle endurance (10, 11). Although angiogenic biomarkers were not acquired in the current study, the WBV + BFR protocol employed corroborates a study conducted by Wu et al. (21) that documented circulating VEGF elevation after acute WBV + BFR exercise. Collectively, this might be indicative of enhanced muscle endurance due to increased VEGF values.

Limitations regarding the interpretation of this study must be emphasized. First, setting a WBV training regimen in nature only reflects absolute intensity rather than the relative intensity felt by different participants. Although all participants were physically inactive, individual differences in response to exercise may exist, and a uniform absolute vibration intensity could have induced minor disproportionate increases in various muscle fitness parameters. Second, the ratio of male to female participants enrolled in the current study was 4 to 1. Although recent research indicated that sex has no major impact on resistance training-induced related muscle fitness outcomes (39), others reported that females were less likely to exhibit improvements in muscle fitness than males (40), which might have affected the overall improvement of the parameters. To provide a better generalization for adults regardless of gender, there appears to have been a greater number for females. Finally, the participants in this study were a sedentary population. The results might not be appropriate for extrapolation to populations who are physically active. Despite these limitations, our findings provide information on superior gains in muscle fitness after the WBV + BFR protocol.

In conclusion, the passive muscle contraction modality of the expose to WBV + BFR not only magnifies several acute physiological responses but also elicit greater thigh muscle mass and maximal strength, as well as muscular endurance when training regularly for a period of time as compared with that of WBV alone. If the untrained participants wish to enhance muscle fitness using WBV training, they can simply compress the proximal parts of the stimulated muscles with the appropriate pressure.

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Declaration of interest statement

The authors declare no conflict of interest.

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Table 1. Changes in the participants' muscle fitness after WBV or WBV + BFR training (mean ± SE)

		Pre	Post	Delta (%)	Between group difference
Thigh muscles (Kg)	WBV+BFR	15.31 ± 0.89	15.77 ± 0.82*	3	2.88‡
	WBV	16.25 ± 0.72	16.27 ± 0.76	0.12	
1RM leg press (Kg)	WBV+BFR	139.58 ± 6.86	155.08 ± 6.52*	11.1	6.7‡
	WBV	131.45 ± 9.02	137.20 ± 9.05*	4.4	
Muscular endurance (Kg)	WBV+BFR	2095.11 ± 215.85	3118.48 ± 364.60*	48.85	33.66‡
	WBV	2136.12 ± 226.50	2460.69 ± 213.18*	15.19	

*Significantly different from pretest values, as determined by Bonferroni corrected paired t-tests ($p < 0.05$). ‡Changes significantly greater than those in the WBV group, as determined by analysis of covariance ($p < 0.05$). WBV + BFR = whole body vibration plus blood flow restriction, WBV = whole body vibration, 1RM= one-repetition maximum.

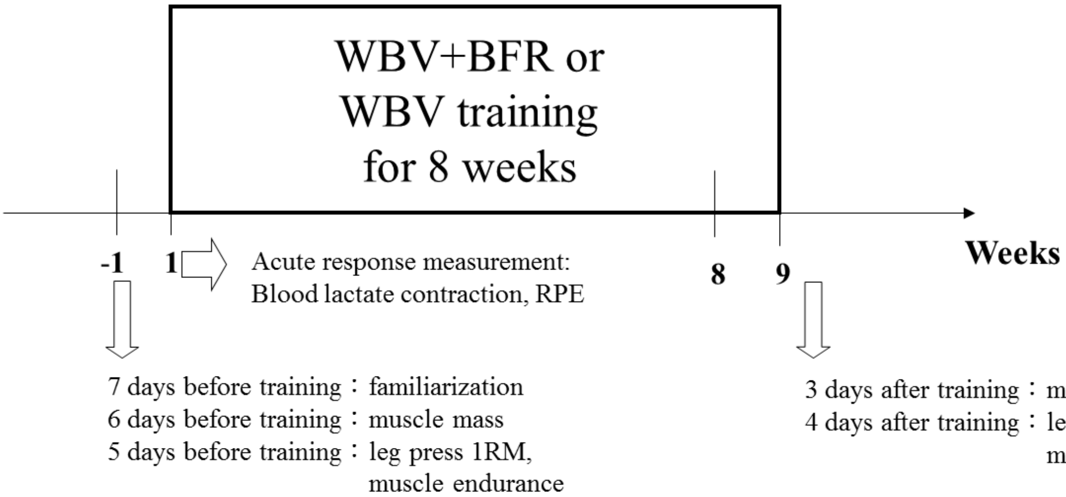

Figure 1. Schematic timeline of the experimental procedure. WBV + BFR = whole body vibration plus blood flow restriction, WBV = whole body vibration, RPE = rating of perceived exertion, RM = repetition maximum.

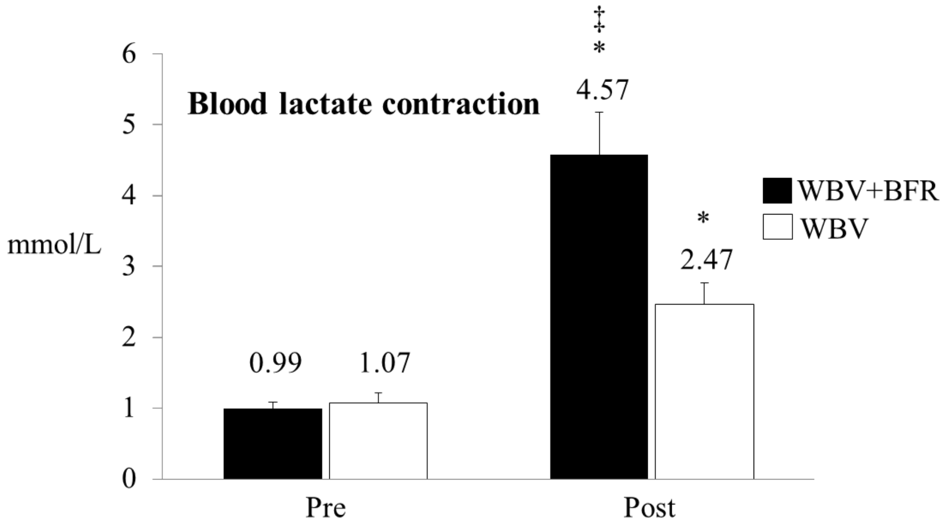

Figure 2. Blood lactate contractions before and after the acute exercise (mean ± SE). *Significantly different from the pretest values, as determined by Bonferroni corrected paired t-tests ($p < 0.05$). ‡Changes significantly greater than those in the WBV group, as determined by analysis of covariance ($p < 0.05$). WBV + BFR = whole body vibration plus blood flow restriction, WBV = whole body vibration.

Figure captions

Figure 1. Schematic timeline of the experimental procedure. WBV + BFR = whole body vibration plus blood flow restriction, WBV = whole body vibration, RPE = rating of perceived exertion, RM = repetition maximum.

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