Effects of resistance training with whole-body vibration on muscle fitness in untrained adults

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Accepted for publication 17 May 2011

The effects of resistance training (RT) combined with whole-body vibration (WBV) on muscle fitness, particularly muscle hypertrophy and neuromuscular performance, are not well understood. We investigated the effects of WBV in healthy, untrained participants after a 13-week RT course by performing magnetic resonance imaging and by measuring maximal isometric (with electromyography) and isokinetic knee extension strengths, isometric lumbar extension torque, countermovement-jump, knee extension endurance, and sit-ups. Thirty-two individuals (22–49 years old) were randomly assigned to RT groups with (RT-WBV, n = 16) or without WBV (RT, n = 16). Following the RT course, significantly higher increases in the cross-sectional areas of m. psoas major (vs baseline values) and erector spinae muscle (vs the RT group) were observed in the RT-WBV group (+10.7%, P < 0.05; +8.7%, P < 0.05) compared with the RT group (+3.8%, P = 0.045; 0.0%). Higher increases from baseline were also observed in maximal isometric force, concentric knee extension torque, countermovement-jump, and maximal isometric lumbar extension torque in RT-WBV (+63.5%; +76.7%, +15.0%, and +51.5%, respectively; P < 0.05) than in those of RT (+25.6%, P = 0.001; +17.8%, P = 0.18; +11.3%, P = 0.001; and +26.4%, P < 0.001, respectively). The WBV-induced increases in muscle hypertrophy and isometric lumbar extension torque suggest a potential benefit of incorporating WBV into slow-velocity RT programs involving exercises of long duration.

Recently, resistance training (RT) combined with whole-body vibration (WBV) has become popular among untrained middle-aged people. Although it has been suggested that RT with WBV enhances muscle strength, particularly in untrained adults (Marin & Rhea, 2010), the efficacy of WBV when incorporated into RT programs for improving muscle mass, strength, power, and endurance compared with the identical training without WBV is less clear. Among six recent studies, only Delecluse et al. (2003) found that WBV led to significant additional increases in muscle strength and power, as the other studies did not detect any additional effects resulting from the addition of WBV to RT programs (de Ruiter et al., 2003; Ronnestad, 2004; Kvorning et al., 2006; Carson et al., 2010; von Stengel et al., 2010). However, two studies reported that exercise combined with WBV significantly increased the cross-sectional area (CSA) of thigh muscles in older individuals (> 60 years of age) (Bogaerts et al., 2007; Machado et al., 2010). Although these represent the only findings to suggest that WBV training stimulates morphological changes in muscles, an identical exercise group in the absence of WBV was not included in the evaluations. Therefore, further examination of the effects of WBV training on muscle hypertrophy is needed.

To date, a standard WBV training program has not been established. The degree of muscle stimulation during WBV exercise is dictated by the amount of force generated by the vibration platform (actuator) that is transferred to the human body (resonator) (Rittweger, 2010). It was demonstrated previously that the acceleration of vibration platforms increases under weight-loaded conditions (Pel et al., 2009; Osawa et al., 2011b). If the actuator produces a larger force, the degree of response in the resonator would be expected to correspondingly increase. However, as a few studies did not detect any additional muscle strength or power gains with heavy-loading RT regimens combined with WBV [e.g., eight repetitions of 8–10 repetition maximum (RM) or 10 repetitions of 75–90% 1 RM], conventional RT regimens do not appear suitable for WBV training programs (Ronnestad, 2004; Kvorning et al., 2006; Carson et al., 2010). Therefore, longer exposure to vibration during muscle contractions may be necessary to elicit WBV per se effects on neuromuscular systems. This speculation is supported by a study of Bongiovanni et al. (1990), who found that...
reductions of electromyographic activity, motor unit firing rates, and contraction force were observed after 30-s muscle contractions with locally applied vibration. This may have been due to vibration-induced pre-synaptic inhibition and/or transmitter depletion in Ia excitatory pathways. In consideration of these reports, we anticipated that an intentional slow-velocity RT program that increases the time muscles are under tension would be suitable to combine with WBV. In addition, slow-velocity RT also involves less momentum, resulting in a more evenly applied muscle force throughout the range of motion and is amenable to the addition of lighter external loads than conventional training regimens, even when progressive overloading is needed to overcome strength-gain plateaus (Westcott et al., 2001; Tamimoto & Ishii, 2006). Here, we hypothesized that slow-velocity RT combined with WBV would lead to increases in muscle mass, strength, power, endurance, and neuromuscular activities.

The aim of this study was to investigate the effects of 13-week RT combined with WBV on muscle hypertrophy, strength, power, neuromuscular activity, and local muscle endurance compared with the identical training lacking WBV in untrained, healthy adults. Participants in both training groups were subjected to several performance tests, in addition to measuring the CSA of abdominal muscles, to assess the effects of WBV on the basis of changes in the pre-training and post-training measurements.

Materials and methods

Subjects

Figure 1 shows the flow of the study. Thirty-three untrained adults [6 males (M) and 27 females (F), 22–49 years old] volunteered for this study. Participants were recruited from local residents (n = 26) and from graduate school students of Keio University (n = 7) using posted advertisements. Power analysis was performed with the power set at 0.80 and an α-level of 0.05 under the hypothesis that RT with WBV would increase the CSA of m. psoas major as the primary outcome. The analysis setting with balanced data (equal number of participants in each group), and an expected effect size and standard deviation (SD) of 0.2% and 0.19%, respectively, revealed that a sample size of 14 participants in each test group was required for the detection of WBV effects. The eligibility criteria for participants were 20–49 years old, no experience with RT for at least 6 months before the study, could refrain from engaging in any regular vigorous activities, strength training, or stabilization training, and could maintain routine daily life throughout the trial. The health and medical history, current medical conditions, and signs and risk factors of cardiovascular or orthopedic diseases of each potential participant were evaluated using a self-administered Physical Activity Readiness Questionnaire (PARQ; Thomas et al., 1992). If an individual answered “No” to all questions, he or she was considered a suitable candidate and was entered into the study. The exclusion criteria were pregnancy, history of severe orthopedic abnormality, diabetes, or acute hernia. This study was approved by the local ethics committee of Keio University and written informed consent was obtained from all participants.

Randomization procedure

Participants were randomly assigned to either an RT with WBV (RT-WBV, n = 17) group or a non-WBV RT (RT, n = 16) group (Fig. 1). A restricted randomization (blocking and stratification) was used to allocate participants into one of the two groups. First, six matrices (age, 20s, 30s, or 40s; gender, female or male) were created to stratify the participants. Second, we prepared six envelopes for each stratified group, with each envelope containing 10 cards labeled with either “RT” or “RT-WBV” (RT-WBV:RT, 5:5). Finally, after the completion of all of the pre-training tests, each participant drew a card from the envelope corresponding to their stratified group, and was allocated to either training group as designated by the selected card.

Training programs

Vibration conditions

To deliver WBV to the RT-WBV group, a synchronous vibration device (Power Plate® Next Generation, Power Plate International, Northbrook, Illinois, USA) equipped with the platform pad provided by the manufacturer was used. We applied WBV at a frequency and amplitude of 35 Hz and 2 mm, respectively, throughout the trial because nearly all participants in a pilot study experienced discomfort in their head and chest regions when exercises were performed in supine and prone positions at higher frequencies or amplitudes, or without the platform pad. Mean acceleration magnitudes of the vibration platform device with and without weight loading were reported in a previous study (Osawa et al., 2011b).

RT program

After performing a standardized warm-up involving operating an ergometer for 5 min followed by stretching (e.g., modified hurdler’s stretch), participants, who wore socks, but no shoes, performed two exercises for lower extremities with their hands free (half squat, knee angle, 20°–90° (full extension = 0°); hip angle, 20°–30°, to 90° (full extension = 0°); Bulgarian squat, knee angle, 20°–90°; hip angle, 20°–30° to 90°) and six exercises for trunk muscles (roll back, trunk curl, hip walking, leg raise, back extension, and stabilization exercise) on the vibration platform either with (RT-WBV group) or without WBV (RT group) (Table 1). The position adopted in each exercise, including photographs, has been reported previously (Osawa & Oguma, 2011a). Although there is no well-established movement cadence for achieving optimal muscle fitness gains, here, we configured the training program to consist of a cadence of 4 s concentric phase (lifting), 2 s no-relaxing phase (isometric phase), and 4 s eccentric phase (lowering) to minimize momentum and to achieve a more evenly applied muscle force throughout the range of motion (Smith & Bruce-Low, 2004). Each exercise was performed for eight repetitions with the cadence with intermittent rest periods of 60 s between sets, with the exception of the roll back and hip walking exercises, which were performed continuously for 64 and 48 s, respectively, without any isometric phase. All cadences were strictly controlled using a metronome (SQ-77, Seiko, Tokyo, Japan). Weight loading was based on individual body mass (Table 1). As the g force produced by the Power Plate® increased with weight loading on the platform, the g force experienced by participants in the RT-WBV group and/or weight loading
intensity within the two groups would have varied if training intensity was decided by the maximum strength test. Therefore, we configured the weight loading based on the performance of a few individuals (e.g., not overly challenging and the degree of muscle soreness the day after training session) in pilot trials. As the laboratory was equipped with two Power Plate machines, training sessions were conducted with a maximum of two participants, who were strictly and closely supervised by the investigators. After each training session, participants ingested a multi-vitamin supplement (Nature Made, Otsuka, Tokyo, Japan) to provide the minimum reference dietary intakes recommended by the Japanese Ministry of Health and to minimize the effects of confounding related to insufficient food intake, particularly vitamins.
Magnetic resonance imaging (MRI)

MRI was performed using a 1.5 T imager (Intera 1.5 T, Phillips Medical Systems, Best, the Netherlands). As it has been suggested that soft tissues, joints, or items such as shoes and pads dampen the vibration magnitude (Rittweger, 2010), we anticipated that exercises performed in prone and supine postures would maximize the vibration efficacy on trunk muscles, which would be in direct or close contact with the platform, when compared with the effects of standing exercises on thigh and leg muscles. Thus, we decided to configure the RT exercise program to target mainly trunk muscles and investigate the additional WBV effects on muscle hypertrophy using MRI only in trunk muscles due to budget restraints. The CSA of m. psoas major, m. rectus abdominis, m. anterolateral abdominal (IABD; obliquus internus abdominis–obliquus externus abdominis+transversus abdominis), multifidus, erector spinae muscle, and quadratus lumborum muscle were determined from lumbar axial MRI images, which were obtained parallel to the L4–L5 disc space level. A single 10 mm axial slice was obtained using a T1-weighted image. The other MRI parameters were as follows: TR, 450 ms; TE, 20 ms; FA, 90°; NA, 1; matrix, 256 × 256; FOV, 400 × 400 mm; pixel size, 1.56; scan time, 11.3 s (SENSE mode); and TSE factor, 6. A body coil was used to image abdominal sections (SENSE-Body Coil, Philips Medical Systems). The DICOM images obtained were analyzed with ZedView 3.1 software (Lexi, Tokyo, Japan). Segmenting the CSA of muscle was based on the brightness of the MR value, and if a part of the CSA delineation was unclear, a free hand area calculation was performed (Arai et al., 2004). The average of the CSA of each left and right muscle was used for further statistical analysis.

All MRI measurements were performed by a radiologist (M.R.I.) and a medical software programmer (CSA measurements), who had no knowledge of the study design (e.g., purpose of the present study, participants’ information, and grouping), except that the CSA measurements were supplemented by an investigator for five women’s data and all the CSA of multifidus, erector spinae muscle, and quadratus lumborum muscle with free hand area calculation using the DICOM viewer software OsiriX ver 3.9 (http://www.osirix-viewer.com). Intraclass correlation coefficient (ICC) tests were also evaluated within one week of all of measurements for four participants and one investigator: \( r = 0.99 \) (m. psoas major), \( r = 0.98 \) (m. rectus abdominis), \( r = 0.91 \) (IABD), \( r = 0.94 \) (multifidus), \( r = 0.97 \) (erector spinae muscle), and \( r = 0.96 \) (quadratus lumborum muscle).

Performance tests

After the standardized warm-up described in the RT program section, the following performance tests (listed in the order they were conducted) were evaluated before (Pre), after 7 weeks of training (Mid), and after the completion of the 13-week training period (Post). Participants performed light stretches between tests.

Countermovement-jump test for muscle power

As the recruitment of participants was divided into two periods, and the instrument used for the muscle power test was only available during the second recruitment period, only 23 participants (RT-WBV, M: 1, F: 11; RT, M: 1, F: 10; 38.6 ± 8.2 years old) performed countermovement-jumps while wearing a Myotest® accelerometer on the waist (Myotest, Royal Oak, Michigan, USA) (Casartelli et al., 2010). The Myotest® automatically calculates jump height from the obtained flight time (\( t \)) by estimating the height of the rise of the body center of gravity (\( h \)) during countermovement-jump (\( h = 1/2 g t^2 \), where \( g \) = 9.81 m/s²). In a standing position, participants first made a downward movement by bending their knees and hips, and then jumped as high as possible while keeping their hands on their waist. After returning to a standing position, the participants were permitted a short intermittent rest of a few seconds between each jump. The jump was repeated five times, and the mean value of countermovement-jump height (cm) was recorded. The test was conducted twice, with an interval of 3 min, and the highest mean jump height was used for further analyses. The ICC for test–retest reliability of the countermovement-jump test was \( r = 0.96 \).

Maximal knee extension strength and endurance tests

Maximal voluntary isometric force and isokinetic knee extension torque, and local muscular endurance power and work were measured on the right side using a Kin-Com® KC500H device (Chattecx, Hixson, Tennessee, USA). During the tests, the right upper leg, ankle, and the hips were stabilized with safety belts. After gravity correction was performed in accordance with the manufacturer’s guidelines, participants were seated with a hip joint angle of 80° and arms crossed in front of the chest, and maximal isometric 5-s contractions were then measured at a knee angle of 60°. Maximal isokinetic concentric and eccentric knee extension torque was measured at knee angles of 80°–20° and a velocity of 60°/s. The local muscle endurance test, consisting of 30 consecutive concentric knee extensions, was performed at knee angles of 80°–20° and a velocity of 60°/s. Total work (\( W \)) and average power (\( P \)) during local muscular endurance test were measured. The measurements for all strength tests were repeated twice with 3-min rest intervals, and the peak force or torque obtained, which was normalized to body mass (N/kg, or N m/kg) for the maximal voluntary isometric and isokinetic tests, respectively, was used for further analyses. The ICC for test–retest reliability were \( r = 0.97 \) (isometric contraction), \( r = 0.86 \) (isokinetic concentric contraction), \( r = 0.91 \) (isokinetic eccentric contraction), and \( r = 0.79 \) (local muscular endurance).

Surface electromyography (sEMG)

sEMG signals from the vastus medialis (VM) and vastus lateralis (VL) muscles of the right leg were recorded using a TeleMyo 2400 T V2 system (Noraxon Inc., Scottsdale, Arizona, USA) with disposable Ag/AgCl snap electrodes (EM-272, Noraxon Inc.) during the Bulgarian squat exercise with or without WBV and the isometric knee extension force test. The figure eight-shaped adhesive area of the electrodes was 4 × 2.2 cm, the two circular conductive areas were 1 cm in diameter, and the inter-electrode distance was 2 cm. After the skin over the respective muscle belly was lightly abraded, the electrodes were fixed in accordance with the Surface Electromyography for the Non-Invasive Assessment of Muscles guidelines (Hermens et al., 1999). After the electrodes were attached, the participants sat on a chair for at least 5 min to aclimatize the skin with the electrodes. The sEMG signals were sampled at 3000 Hz and subsequently band-pass filtered (15–500 Hz).

The processing of sEMG data was performed using MyoResearch XP software, Master Package ver. 1.06.74 (Noraxon Inc.). As suggested previously by Abercromby et al. (2007), raw EMG signals obtained during exercise with WBV include motion artifacts caused by the WBV source. Thus, we applied band stop filter analyses at \( f_c \), where \( f_c \) is the vibration frequency, and the stop-band was equal to \( f_c ± 0.5 \) Hz (i.e., 0.5$f_c$, 1$f_c$, 2$f_c$, ..., 14$f_c$). The raw EMG signals obtained from
the isometric contraction test were converted to an average root-mean square (EMGrms) with 0.5 s smoothing windows to compare the RT-WBV and RT groups. The 0.5 s time epochs around the isometric contraction force peak, which were identified using a Kin-Com® KC500H device, were used for further analyses.

**Trunk muscle strength and endurance**

We measured back extensor torque with an isometric lumbar extension machine (MedX, Orlando, Florida, USA) using testing positions that were standardized following the manufacturer’s guidelines. After the participant was seated in the lumbar extension machine, the pelvis was stabilized, and while the participant rested against the upper back pad (the angle of full extension was 0°), a counterweight was adjusted to neutralize gravitational force on the head, torso, and upper extremities. Maximal isometric lumbar extension torque was then measured in the sitting position through a 72° arc of lumbar motion (at 72°, 60°, 48°, 36°, 24°, 12°, and 0° of trunk flexion). The ICC for test–retest reliability of each angle ranged from \( r = 0.83 \) to 0.94. The maximal isometric lumbar extension torque at 60° of trunk flexion was used for further analyses, because the position gave the highest reliability in our laboratory (\( r = 0.94 \)) and in a previous report (\( r = 0.96 \)) (Graves et al., 1990).

Abdominal muscle endurance was evaluated by the total number of sit-ups performed in 30 s. We applied the sit-up test used in the New Japan Fitness Test formulated by the Japanese Ministry of Education, Culture, Sports, Science, and Technology, which is nearly identical to that used in the Eurofit Fitness Testing Battery, with the exception of arm position. A detailed explanation of the testing procedure was reported previously (Osawa et al., 2011b). The ICC for test–retest reliability of the sit-up test was \( r = 0.91 \).

**Physical activity and nutritional assessment during the trial**

The food intake of participants was assessed by a food frequency questionnaire based on Food Groups (FFQg) software version 2.0, which is an optional software of “Excel Eiyukun” (Kenpaku-sha, Tokyo, Japan) that conforms to the Fifth Edition of Standard Tables of Food Composition in Japan compiled by the resources research committee of the Science and Technology Agency (Tokyo, Japan) (Takahashi et al., 2001). The FFQg was conducted before, after the seventh week of training, and during the last training week.

Physical activity of each participant was assessed using a uniaxial accelerometer (LifeRecorder EX, Suzuken Co. Ltd., Nagoya, Japan) for at least 1 week, including 5 weekdays and 2 weekend days, once before the trial and again around the time of the last training week. Mean total step counts per day were used for further analyses.

**Statistical analyses**

Group differences in age, body mass, BMI, total physical activity, and the results of the FFQg at baseline were determined by the unpaired \( t \)-test. Normality and equal variance assumptions were performed using the Kolmogorov–Smirnov and Levene tests, respectively. If normality and equal variance were assumed, longitudinal changes in all outcomes were compared within the groups using two-way ANOVA (group time) with repeated measurements; otherwise, the percentage change from baseline values was tested using either the unpaired \( t \)-test or one-way ANOVA. If an \( F \)-value was found to be significant, preplanned contrast analyses (Bonferroni correction) were performed to evaluate the significance of time effects and differences between groups. A selective bivariate relationship (between percent change in muscle force/torque, muscle CSA, and EMG amplitude) was investigated using Pearson’s correlation coefficient. PASW software version 18.0 for Macintosh (SPSS Inc., Tokyo, Japan) was used for all statistical analyses. The level of significance was set at \( P < 0.05 \), and all values are presented as the mean ± SD.

**Results**

**Participant baseline characteristics**

The characteristics of the participants are summarized in Table 2. No significant differences between the RT-WBV and RT groups at baseline were observed in any of the evaluated characteristics, except the CSA of erector spinae muscle. In addition, with the exception of six individuals (RT-WBV, M: 2, F: 2; RT, M: 1, F: 1) who had once engaged in regular RT as part of a college sports team, all participants were novices for RT.

One male in the RT-WBV group dropped out of the study after the mid-training tests due to conflicts with his job; however, the other participants completed the 13-week training program and all of the evaluation tests (Fig. 1).

**Muscle activity during exercise**

sEMG signals from the VM and VL muscles recorded during Bulgarian squat exercise illustrate the differences in muscle activity for contractions performed in the presence and in the absence of WBV (Fig. 2). In the RT group, the EMG signals from VM and VL showed 44.6 ± 14.3% and 49.3 ± 21.4% maximal voluntary contraction (MVC), respectively, during exercise, while the total duration that the signals did not reach 40% MVC was 42 and 36 s, respectively, during the 80 s period that each exercise set was performed (Fig. 2a). In contrast, the EMG

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>RT-WBV, ( n = 16 ) (F:14, M:2)</th>
<th>RT, ( n = 16 ) (F:13, M:3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>36.8 ± 8.4</td>
<td>37.7 ± 9.5</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>161.2 ± 6.4</td>
<td>164 ± 5.9</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>55.3 ± 8.8</td>
<td>58.8 ± 9.0</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>21.1 ± 2.3</td>
<td>21.8 ± 2.3</td>
</tr>
<tr>
<td>Total physical activity (steps/day) *</td>
<td>10565 ± 2022</td>
<td>9248 ± 3772</td>
</tr>
<tr>
<td>Total energy intake (kcal/day)</td>
<td>1856 ± 366</td>
<td>2080 ± 470</td>
</tr>
<tr>
<td>Protein (%)</td>
<td>13.1 ± 1.3</td>
<td>13.9 ± 1.9</td>
</tr>
<tr>
<td>Fat (%)</td>
<td>29.9 ± 7.0</td>
<td>30.1 ± 4.4</td>
</tr>
<tr>
<td>Carbohydrate (%)</td>
<td>56.2 ± 5.6</td>
<td>56.0 ± 5.4</td>
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</tbody>
</table>

*Total physical activity was determined by the number of steps counts per day, as measured using a uniaxial accelerometer.

BMI, body mass index; RT, resistance training group; RT-WBV, resistance training with whole-body vibration group.
signals, which were recorded with a band-stop filter, from VM and VL in the RT-WBV group showed 48.9/11.7% and 52.4/20.9% MVC, respectively, while the total duration that the signals did not reach 40% MVC was 21 and 30 s, respectively, during the 80 s period that each exercise set was performed.

CSA of abdominal muscles
To assess the effect of WBV on muscle hypertrophy, participants of both training groups were subjected to MRI testing before and after the 13-week training period (Fig. 3). From the MRI images of the abdominal area, changes in the CSA of several target muscles were determined and compared between the two training groups. As shown in Fig. 4, a significant group \times time interaction was observed in the CSA of m. psoas major (P = 0.03), which significantly increased in both the RT-WBV (+10.7 ± 5.3%, P < 0.001) and RT groups (+3.8 ± 7.5%, P = 0.045). A significantly higher percent change increase in erector spinae muscle in the RT-WBV group was also detected compared with that of the RT group (P = 0.04, unpaired t-test). In addition, although no significant group \times time interactions were found in the CSA of m. rectus abdominis (P = 0.85) or IABD (P = 0.53), significant time effects were observed in both these muscles (P < 0.001 and P = 0.002, respectively). Finally, no significant group \times time interactions were detected in the CSA of quadratus lumborum (P = 0.94) or multifidus muscles (P = 0.86).

Countermovement-jump test
Changes in muscle power were evaluated using the countermovement-jump test, which revealed significant group \times time interactions in jump height
A comparison of the mean pre-treatment and post-treatment values revealed that significant increases in jump height occurred in both the RT-WBV \((115.0 \pm 10.5\%, P < 0.005)\) and RT groups \((11.3 \pm 8.2\%, P < 0.001)\).

Maximal voluntary isometric knee extension force

A significant group \(\times\) time interaction was also observed in maximal isometric knee extension force (Table 3), as marked increases in strength from pre-training levels were observed following the 13-week training in both the RT-WBV \((+63.5 \pm 53.9\%, P < 0.001)\) and RT groups \((+25.6 \pm 13.9\%, P = 0.001)\). Notably, maximal isometric knee extension force was significantly higher in the RT-WBV group than the RT group at both the mid-training and post-training evaluation points \((P = 0.009\) and \(P < 0.001\), respectively).

sEMG

To examine the intensity of muscle contractions under the two training conditions, sEMG signals from the VM and VL muscles were monitored during the maximal isometric extension force test. A significant group \(\times\) time interaction was observed in the EMGrms during isometric extension in VM \((P = 0.012)\) (Fig. 5). In addition, no group \(\times\) time interactions were detected in the EMGrms of VL \((P = 0.54)\); however, significant time effects were observed \((P < 0.001)\) between the pre-training and mid-training \((P = 0.014)\) and pre-training and post-training \((P = 0.01)\) sEMG measurements.

Maximal isokinetic strength tests

As was observed for isometric knee extension force, a significant group \(\times\) time interaction was also detected in maximal concentric knee extension torque (Table 3). A comparison of the pre-training and post-training strengths revealed a significant increase in the RT-WBV group \((+76.7 \pm 53.8\%, P < 0.001)\), whereas no significant changes were found in the RT group \((+17.8 \pm 27.8\%, P = 0.18)\). The analysis also demonstrated that maximal concentric knee extension torque was significantly higher in the RT-WBV group than the RT group after completion of the 13-week training program \((P = 0.007)\).

In contrast to concentric knee torque, no group \(\times\) time interactions were observed in maximal eccentric knee extension torque (Table 3); however, a significant time effect was found \((P < 0.001)\). Similar results were observed for the local muscle endurance, as no
Table 3. Effects of whole-body vibration on performance tests

<table>
<thead>
<tr>
<th></th>
<th>RT-WBV (n = 16)</th>
<th>RT (n = 16)</th>
<th>P-value</th>
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<tbody>
<tr>
<td>CMJ (cm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>24.5 ± 8.6</td>
<td>23.4 ± 7.0</td>
<td>*</td>
</tr>
<tr>
<td>Mid</td>
<td>26.9 ± 8.5</td>
<td>24.4 ± 7.4</td>
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<tr>
<td>Post</td>
<td>27.9 ± 8.6</td>
<td>25.8 ± 6.9</td>
<td></td>
</tr>
<tr>
<td>ISOM-K (N/kg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>5.7 ± 1.4</td>
<td>5.5 ± 0.8</td>
<td>***</td>
</tr>
<tr>
<td>Mid</td>
<td>7.6 ± 1.2</td>
<td>6.4 ± 1.3</td>
<td></td>
</tr>
<tr>
<td>Post</td>
<td>8.8 ± 1.1</td>
<td>6.8 ± 1.2</td>
<td></td>
</tr>
<tr>
<td>CON (N m/kg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>1.1 ± 0.2</td>
<td>1.3 ± 0.2</td>
<td>***</td>
</tr>
<tr>
<td>Mid</td>
<td>1.6 ± 0.4</td>
<td>1.5 ± 0.5</td>
<td></td>
</tr>
<tr>
<td>Post</td>
<td>1.9 ± 0.5</td>
<td>1.5 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>ECC (N m/kg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>1.9 ± 0.4</td>
<td>1.9 ± 0.5</td>
<td></td>
</tr>
<tr>
<td>Mid</td>
<td>2.2 ± 0.5</td>
<td>2.1 ± 0.5</td>
<td></td>
</tr>
<tr>
<td>Post</td>
<td>2.5 ± 0.6</td>
<td>2.2 ± 0.5</td>
<td></td>
</tr>
<tr>
<td>TW (J)</td>
<td>1036 ± 374</td>
<td>1213 ± 461</td>
<td>***</td>
</tr>
<tr>
<td>Mid</td>
<td>1126 ± 333</td>
<td>1266 ± 546</td>
<td></td>
</tr>
<tr>
<td>Post</td>
<td>1242 ± 445</td>
<td>1344 ± 478</td>
<td></td>
</tr>
<tr>
<td>MP (W)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>34.1 ± 11.9</td>
<td>36.9 ± 14.5</td>
<td></td>
</tr>
<tr>
<td>Mid</td>
<td>34.9 ± 10.7</td>
<td>42.4 ± 17.1</td>
<td></td>
</tr>
<tr>
<td>Post</td>
<td>39.8 ± 13.3</td>
<td>41.9 ± 15.2</td>
<td></td>
</tr>
<tr>
<td>ISOM-L (N/m/kg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>3.4 ± 1.2</td>
<td>3.4 ± 1.2</td>
<td>**</td>
</tr>
<tr>
<td>Mid</td>
<td>4.5 ± 1.4</td>
<td>3.8 ± 1.2</td>
<td></td>
</tr>
<tr>
<td>Post</td>
<td>4.9 ± 1.4</td>
<td>4.1 ± 1.2</td>
<td></td>
</tr>
<tr>
<td>Sit-up (times)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>15.0 ± 6.7</td>
<td>15.9 ± 5.4</td>
<td></td>
</tr>
<tr>
<td>Mid</td>
<td>20.9 ± 6.3</td>
<td>21.0 ± 7.7</td>
<td></td>
</tr>
<tr>
<td>Post</td>
<td>23.9 ± 7.0</td>
<td>23.6 ± 7.6</td>
<td></td>
</tr>
</tbody>
</table>

Significant group × time interactions are marked as follows:
• P < 0.05; ** P < 0.01; *** P < 0.001.

Pre, pre training program; Mid, post 7-week training period; Post, post 13-week training period; CMJ, countermovement-jump height; CON, concentric contraction; ECC, eccentric contraction; ISOM-K, isometric knee extension torque; ISOM-L, isometric lumbar extension torque; MP, mean power in endurance test; RT, resistance training; RT-WBV, resistance training with whole-body vibration; TW, total work in endurance test.

Significant group × time interactions were observed in total work (J) or mean power (W) (Table 3), although the time effects were found to be significant for both total work (P = 0.003) and mean power (P = 0.002) on comparison of pre-training and post-training levels.

Trunk muscle strength and endurance

The final performance tests measured isometric lumbar extension strength and abdominal muscle endurance. A significant group × time interaction was observed in the isometric lumbar extension torque, with both the RT-WBV and RT groups displaying marked increases in post-training muscle strength compared with baseline values (+51.5 ± 34.1%, P < 0.001 and +26.4 ± 17.5%, P < 0.001, respectively) (Table 3). The evaluation of abdominal muscle endurance revealed that both groups had significant increases in the number of sit-ups performed with respect to time (P < 0.001). However, the observed changes in abdominal muscle endurance did not represent significant group × time interactions (Table 3).

Anthropometry, physical activity, and nutritional assessment

No significant group × time interactions were observed in the body mass (P = 0.50), total energy intake per day (P = 0.83), or the ratio (%) of protein:fat:carbohydrate consumed during the trial; protein (P = 0.43), fat (P = 0.17), and carbohydrate (P = 0.41). In addition, no group × time interactions were observed in physical activity (P = 0.13); however, physical activity significantly differed between the pre-training and post-training levels (P = 0.01).

Correlation analyses

A significant correlation was observed between percent change in maximum isometric knee extension force and EMG activity in the RT-WBV group (r = 0.67, P < 0.001). However, no significant correlation was found between the percent change in muscle force/torque and CSA [lumbar extension torque and erector spinae muscle (r = 0.42,
Discussion

In our randomized controlled study composed of healthy, untrained adults, a 13-week slow-velocity RT program involving light external loading combined with WBV resulted in considerable gains in the CSA of abdominal muscles, and increases in maximal isometric knee extension force, isokinetic knee extension torque, isometric lumbar extension torque, countermovement-jump height, and EMG activities compared with the identical RT without WBV. The present results suggest that WBV has marked additional effects on muscle hypertrophy and strength in abdominal muscles, and may be suitable for combining with slow-velocity RT involving exercises of long duration (≥80 s).

The RT regimen used in this study consisted of eight different lower extremity and trunk muscle exercises performed for 80 s with slow velocity, with the exception of the roll back and hip walking exercises that were performed continuously for 64 and 48 s, during an approximately 60 min session. Marked effects on muscle strength and power were also reported in the study conducted by Delecluse et al. (2003), who utilized a 20 min WBV-RT program composed of 60 s body-weight exercises with 5 s intermittent rest periods over a 12-week period. In the RT regimens used by researchers who did not find any additional effects of WBV on muscle strength and power, either light exercises with low volume (5–8 min/session) or high-intensity training with short-exercise duration (approximately 30 s/set) were performed (de Ruiter et al., 2003; Ronnestad, 2004; Kvorning et al., 2006; Carson et al., 2010; von Stengel et al., 2010). These findings suggest that the additional effects of WBV may be dependent on the training regimen, particularly the duration of WBV exposure and the intensity of training.

In addition to including exercises of longer duration, our training regimen was designed to examine the influence of external weight loading and exercise position on the augmentation of WBV effects on muscle. Two studies have reported that the frequency and amplitude of vibration platforms or additional weight loading have effects on force generation (Pel et al., 2009; Rittweger, 2010). We confirmed previously that force generation increases when weight is loaded on the vibration platform (Osawa et al., 2011b). Our present results indicate the possibility that light external weight loading would be suitable for exercise protocols combined with WBV (frequency, 35 Hz; amplitude, 2 mm) in individuals with normal body mass. Furthermore, our training regimen mainly consisted of exercises performed in prone and supine positions, resulting in close proximity of the trunk muscles to the WBV source with minimal dampening. Although the optimal relationship between vibration parameters, weight conditions (total mass of body mass and additional weight), and exercise position remains unclear, these factors appear to be related with the marked muscle fitness improvements associated with WBV.

The observed effects of WBV on muscle hypertrophy may involve a number of physiological mechanisms. First, the exogenous stimulation of skeletal muscle with vibration may contribute to increases in muscle mass. This speculation is supported by the study of Xie et al. (2008), who found that daily (15 min/day) WBV exposure for 8 weeks (5 days/week) without any exercises or stretching led to increases of 24% and 29% in type I and II fibers, respectively, in soleus muscles compared with age-matched controls. Second, WBV might enhance the effects of RT on muscle hypertrophy by augmenting muscle activity. It has been suggested that WBV leads to increases in exercise-induced growth hormone responses via activation of the hypothalamus–pituitary axis by afferent signals from both muscle metaboreceptors and mechanoreceptors (Kjaer, 1992; Rittweger, 2010). It has also been proposed that WBV leads to muscle deoxygenation, which is associated with the production of free radicals and reactive oxygen species, stimulating satellite cells to regenerate muscle fibers (Anderson, 2000; Yamada et al., 2005). Although it is suggested that a continually generated MVC of >40% during exercises is necessary for muscle growth (Tanimoto & Ishii, 2006), we found that muscle contractions during exercise with WBV were occasionally <40% MVC after applying a band-stop filter. Although the application of band-stop filters will result in an underestimation of the true magnitude of neuromuscular responses to WBV, muscle activities with WBV after filtering of the EMG signals remained higher than those without WBV during exercise. In addition, a recent study measuring muscle length and EMG activity during exercise with WBV has shown that EMG changes precede muscle lengthening (Cochrane et al., 2009), suggesting that stretch reflex would occur on exposure to WBV. Although further studies are needed to provide mechanistic insights for the additional effects of WBV on muscle hypertrophy (e.g., protein turnover and/or intracellular anabolic signaling from muscle biopsies), our results suggest that WBV leads to additional gains in muscular CSA.

In line with the induction of muscle hypertrophy resulting from WBV, maximal isometric and
concentric contractions, in addition to power, were also increased by incorporating WBV into the 13-week RT regimen. Notably, however, maximal eccentric contraction and local muscle endurance were not noticeably affected by WBV. The finding that additional WBV effects were observed only in a few muscle performance gains might be attributable to the higher sensitivity of the neuromuscular systems involved in isometric and concentric contractions, and countermovement-jump to WBV, leading to increased co-activation of α–γ motor neurons (Burke et al., 1978; Romano & Schieppati, 1987; Kouzaki et al., 2000; Fallon & Macfield, 2007). As an earlier study found that exercise with vibration significantly improved maximal force (+49.8%) after a 3-week training period, it has been suggested that RT combined with WBV would lead to increases in muscle strength primarily due to enhancement of neural factors (Issurin et al., 1994). We detected a significant correlation between elevated EMG amplitude and knee extension force gain in the RT-WBV group. The elevated EMG activity reflects increased recruitment and firing rate of motor units, and would contribute to increased muscle force (Suzuki et al., 2002). In contrast, we did not detect a correlation between the increase in the CSA of m. psoas major and countermovement-jump height improvement, which may have been due to the numerous skeletal muscles that contribute to the movement, or between the increase in the CSA of erector spinae muscle and lumbar extension torque gain. As we did not observe muscle hypertrophic effects on lower extremity muscles or on neural improvement in abdominal muscles, we could not provide solid evidence for the contribution of muscle hypertrophy on the observed strength gains. However, the present results suggest that the observed strength gains might be attributable to the stimulation of neural factors by WBV.

In the present study, weight loading was based on individual body mass due to safety concerns that untrained individuals could correctly perform the target exercises on the moving vibration platform with standardized weight limits. Under unstable conditions, there was also concern that certain participants might perform exercises without adequate training intensity, resulting in variations in muscle strength and power gains in the RT-WBV group. However, in both training groups, participants perceived the exercises as physically demanding and experienced fatigue, light to moderate delayed onset of muscle soreness following each training session, and improved muscle fitness. Thus, we have confidence that the training intensity was properly configured in this study, a speculation that is supported by the muscle fitness gains observed in both groups.

Several limitations of this study should be considered when interpreting and generalizing the findings presented here. First, we did not obtain MRI data from quadriceps muscles due to budget restraints. Second, EMG was not applied to the evaluation of antagonist muscles and the power and trunk muscle strength tests due to a lack of instruments for synchronizing muscle power and EMG signals, and because the waist pad of the lumbar extension machine was located at an identical level as the electrode positions. Finally, although the participants were randomly assigned to training groups stratified by age and sex, the study consisted predominantly of women with a relatively wide range of ages. As age and sex might be effect modifiers of muscle strength and power gains, a larger study size with a higher proportion of men and smaller age range is needed to confirm that the observed increases in strength are applicable to both males and females.

In conclusion, we have demonstrated that a 13-week RT program combined with WBV leads to considerable gains in the CSA of abdominal muscles, maximal isometric and concentric knee extension strengths, isometric lumbar extension strength, and countermovement-jump height over baseline values in untrained adults compared with the identical training lacking WBV. In particular, the WBV-induced increases in the CSA of m. psoas major and erector spinae muscle, and the maximal isometric lumbar extension strength gains, suggest that incorporation of WBV into RT programs may be beneficial for the prevention and rehabilitation of chronic low back pain.

**Perspectives**

Our findings confirm that intentional slow-velocity RT combined with WBV has marked training effects on muscle hypertrophy, strength, and power in healthy, untrained adults. The combined training method takes advantage of the force generated by the vibration platform (Rittweger, 2010) and stimulation of the tonic vibration reflex response in muscles (Hagbarth & Eklund, 1966). In future studies, it would be interesting to determine whether the efficacy of vibration is increased when combined with RT exercise protocols that subject muscles to increasing time under tension. In practical applications, the significant increases in the CSA of m. psoas major muscle and the ability to obtain higher maximal isometric lumbar extension torque with vibration may be beneficial for the prevention of sarcopenia and rehabilitation of low back pain, which is associated with the deterioration of these parameters (Cassisi et al., 1993; Barker et al., 2004).
As RT with WBV has also been shown to relieve chronic low back pain sensation in the elderly (Iwamoto et al., 2005), our promising results support the need to further investigate the effects of WBV on chronic musculoskeletal pain sensation and strength in young to middle-aged individuals.

Key words: muscle mass, vibration, novice, platform, trunk muscle, training program, neural adaptation.

Acknowledgement

This study was supported by the Keio University Doctoral Student Grant-in-Aid Program, 2009.

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This study was supported by the Keio University Doctoral Student Grant-in-Aid Program, 2009.