Ankle Flexors Produce Peak Torque at Longer Muscle Lengths after Whole-Body Vibration

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Introduction: Whole-body vibration (WBV) has become a popular training method in recent years. This study investigated the effect of WBV on the length–tension relationship of the ankle dorsiflexors and plantarflexors as measured by a Biodex dynamometer (Biodex Medical Systems Inc, Shirley, NY).

Methods: Twenty healthy young adult males participated in this study and were exposed to two treatments. The first treatment (nonvibration) involved passive stretching of the plantarflexors at end range of motion (ROM) for five 1-min bouts. The second treatment involved the same passive stretch with superimposed WBV (frequency = 26 Hz) for five 1-min bouts on a rotary vibration plate (Galileo 900; Novotec, Pforzheim, Germany). Voluntary ROM, peak torque, and corresponding joint angle of the plantar- and dorsiflexors were recorded pre- and posttreatment. Within-treatment (before and after) and between-treatment (WBV and nonvibration) outcomes were assessed by repeated-measures MANOVA.

Results: No significant changes in the measures of ankle dorsiflexion were found within or between treatments. No significant changes in the measures of ankle plantarflexion were found after the nonvibration treatment. After WBV, however, there was a significant 7.1° shift in the angle (P = 0.001) of peak plantarflexor torque production corresponding to a longer muscle length.

Conclusion: This study shows that stretched human ankle plantarflexors respond to WBV by generating peak voluntary torque at longer muscle lengths. This has possible benefits for the rehabilitation of patients with neuromuscular disorders (e.g., stroke) who experience short ankle flexor resting lengths.

Key Words: Dynamometer, Isokinetic, Length–Tension, Torque

Whole-body vibration (WBV) has become a popular training method in recent years, with numerous studies having investigated its effect on the neuromuscular and cardiovascular systems of healthy adults. Investigations have reported gains in muscle strength and power (6,7), improved body balance (29), increased blood flow (19), and specific oxygen uptake (\(s\)\(\bar{VO}_2\)) (26) after WBV. Investigation of the mechanisms underlying the neuromuscular responses to WBV has shown that small, rapid changes in muscle length trigger reflex muscle activity (9) that is similar to the tonic vibration reflex caused by direct vibration of a muscle belly or tendon (4). The neural drive behind this activity is known to be caused by the activation of muscle spindle primary afferents operating through the spinal loop pathway (21). These findings suggest that vibration may alter the length–tension relationship of the homonymous muscle. No published study to date has investigated this hypothesis. The aim of this study, therefore, was to investigate the effect of WBV on the length–tension relationship of human skeletal muscle.

Most studies have investigated the short-term effect of WBV on the neuromuscular performance of healthy young adults. Significant increases in the performance of squat and counter movement jumps have been reported, suggesting improvements in lower body power, ability to recruit motor units, and explosive strength (10,13). Other work has found a significant increase in the concentric force generated by the biceps brachii musculature (coupled with a reduction in EMG-to-power ratio) for both athletic and untrained individuals, suggesting greater neural efficiency of the neuromuscular system after a single session of WBV (5,17). There is now some emerging evidence that WBV may be an effective exercise for elderly populations and
those with pathology (12,28,31). Short-term effects include improved dynamic stability in elderly females (12) and recovering stroke patients (31), increased isometric and isokinetic knee extension torque (28), and increased weight-shifting speed in recovering stroke patients (31).

Long-term WBV exposure is thought to lead to structural adaptations in muscle that enhance functional performance, whereas short-term exposure is thought to alter motor unit recruitment (25). Structural adaptations may be due to changes in the physiological cross-sectional area of muscle, resulting in increased force production, or changes in muscle length, leading to a shift in the length–tension relationship. It is well known that muscle training involving passive stretching or eccentric exercise over a restricted joint range of motion (ROM) can alter the length–tension relationship of a muscle (8,16). For example, eccentric training of lengthened hamstring musculature (i.e., extended knee angles) has been shown to change the length–tension property of the muscle where peak joint torque is generated at a longer muscle length (8). Thus, by controlling the joint angle and hence the muscle length over which vibration is applied, it may be possible to alter the length at which a joint produces peak torque.

The aim of this study was to investigate the effect of a single session of WBV on the length–tension relationship of the ankle flexors (dorsi- and plantarflexors) in young healthy adult males. It was hypothesized that the length–tension relationship would shift toward the length maintained during WBV. Past work has shown that WBV improves neuromuscular performance as evidenced by improvements in the ability to more rapidly activate leg musculature to produce greater power. If this study is able to show an acute change in the length–tension relationship of the ankle flexors, then future work may investigate the potential for a long-term shift in this relationship. The results of this investigation and future work may benefit populations who exhibit a reduced ability to rapidly generate peak torque at the ankle joint.

MATERIALS AND METHODS

Twenty healthy young adult males participated in this study (mean age = 21.2 yr, SD = 1.1 yr; mean stature = 175.4 cm, SD = 2.0 cm; mean mass = 76.8 kg, SD = 4.4 kg). Subjects were recruited from The University of Melbourne and from the local community and were screened for contraindications to WBV (i.e., recent musculoskeletal injury, neuromuscular dysfunction). Ethical approval was obtained from the Human Research Ethics Committee of The University of Melbourne. Written informed consent was provided by each subject in accordance with the committee’s guidelines.

Study design. This study used a single-group, randomized crossover design with two treatments: WBV and nonvibration (control). Subjects completed the treatments on two separate occasions, separated by a washout period of 3 d to eliminate carryover effects. One session involved WBV, with the ankle plantarflexors held in a lengthened position (maximal passive stretch). The other session involved the same position of the plantarflexors but with no vibration.

In the WBV condition, subjects were exposed to sinusoidal vibration delivered by a rotary vibration platform (Galileo 900, Novotec). Vibration was delivered at a frequency of 26 Hz, which has been shown to be the optimal frequency to produce a neuromuscular response (6,7,11). The peak-to-base amplitude of vibration was 0 mm at the ankle joint and reached 4–4.5 mm at the toes.

Protocol. The laboratory temperature was held at 22 ± 1°C throughout the study. Subjects wore shorts and T-shirt and were barefoot. Basic anthropometric measures of age, height, and mass were recorded. Subjects then completed a modified lunge test to establish the passive stretch end point of ankle dorsiflexion (3). Subjects were required to replicate this stretch to within 5° during each session, as verified with a goniometer. Before treatment, subjects were familiarized with the dynamometer and WBV systems. Subjects then completed a 5-min submaximal warm-up on a cycle ergometer (Repco Fitness) at a fixed rate of 50 rpm with 1 kgf resistance followed by a series of baseline measures. These included tests of ankle flexor voluntary range of motion (ROM) and maximum voluntary contraction (MVC) using a Biodex dynamometer (Biodex Medical Systems Inc, Shirley, NY). Leg girth measurements were completed after these tests.

Upon completion of the baseline measures, subjects were randomly assigned to one of two treatments. The vibration treatment consisted of five 1-min bouts of WBV (frequency = 26 Hz), with 1-min rest between each bout. Subjects stood on the vibration plate with feet positioned 2 cm apart (measured between medial malleoli) and with the ankle joint axes aligned with the rotation axis of the plate (Fig. 1). Once this was achieved, subjects leaned forward.

FIGURE 1—Body position on WBV plate.
while maintaining a straight knee to achieve maximal passive stretch of the plantarflexors (i.e., within 5° of lunge test performance), with the upper body supported by an adjustable plinth set to chest height. Subjects were required to keep approximately 80% of their body weight on the WBV platform. This was checked with electronic scales mounted on the platform before vibration. By adopting this position, the plantarflexors (comprising the biarticular gastrocnemius and monoarticular soleus muscles) were held in a lengthened position and the dorsiflexors in a shortened position. This made it possible to investigate the effect of muscle length on the muscular response to WBV. The nonvibration treatment required the subjects to maintain a passive stretch of the ankle plantarflexors as described above, but without WBV, for five 1-min bouts, with 1-min rest between bouts. Immediately after each treatment, voluntary ankle flexor ROM, MVCs and leg girth measurements were recorded.

**Accelerations.** WBV with an extended knee is known to increase the transmissibility of vibrations to the upper body (1). Therefore, as a safety measure, the mechanical vibrations applied to the body were monitored by an accelerometer (HOBOWare; Onset Computer Corp., Pocasset, MA) gripped between the teeth. Accelerations were recorded for one bout of vibration for each subject.

**Isokinetic dynamometry.** Maximal voluntary isokinetic unilateral ankle plantar- and dorsiflexions were performed on a Biodex System III Quick-Set dynamometer (Biodex Medical Systems Inc). For this study, the ankle joint angle–torque curve was defined by the torque, as a function of joint angle, produced by maximum voluntary activation of the ankle flexors during isokinetic shortening (8,27). Only the subjects’ preferred leg was tested. The preferred leg was taken to be the limb used to kick a ball (15). The Biodex (26) seat orientation (90°) and seatback tilt (80°) were adjusted so that subjects sat with their hips in 90° flexion with the leg fully extended. The test foot was placed on the dynamometer footplate and was secured to the attachment by Velcro straps over the metatarsal area and over the ankle to minimize heel movement. The lever arm was adjusted so the footplate axis of rotation was aligned with the rotation axis of the ankle, approximated by the fibular and tibial malleoli. A knee strap was used to limit knee flexion to less than 10°; this was verified by a goniometer. The subject’s body was firmly secured with dual crossover straps, a pelvic strap, and a thigh strap to restrict movement and involvement of proximal muscles. Subjects gripped handles on either side of the dynamometer to assist in maintaining a stable body posture.

Once subjects were secured in the Biodex chair, voluntary ROM was established. A rest period of 1 min was allowed after ROM calculation. Subjects were then instructed to perform ankle plantar- and dorsiflexions with maximal effort, pushing as hard and fast as possible. Verbal encouragement was given throughout the test. Seven isokinetic concentric MVCs at 30°s⁻¹ were completed.

The optimal speed is 30°s⁻¹ because it is slow enough to generate maximal torque over most of the range of ankle motion while not so slow as to cause significant fatigue. A quicker speed would result in too much of the ankle ROM being taken up with developing full muscle activation. The first and last contractions were excluded from the analysis because they were found to be less consistent. Ankle ROM, peak torque and angle of peak torque were recorded for the plantar- and dorsiflexors.

**Leg girth.** It was expected that the vibration bouts may cause some minor muscle damage and delayed onset muscle soreness (DOMS), similar to that experienced after eccentric exercise (2). DOMS triggers an inflammatory response in the muscle, producing local swelling (2). In this study, muscle swelling of the ankle flexors was documented by taking leg girth measurements of the lower leg 15 cm below the middle of the popliteal fossa. Changes in gastrocnemius and soleus volume were expected to present as small changes in girth, bearing in mind that girth measurements included both the ankle plantar- and dorsiflexors.

**Soreness evaluation.** Over the 3 d after a treatment (WBV or nonvibration), each subject was required to rate the amount of lower leg soreness or tenderness in response to locally applied pressure and when standing up and walking. Subjects were asked to give a numerical value out of 10; 0 indicated “no soreness” and 10 indicated “the most muscle soreness that you can possibly bear” (8).

**Data analysis.** Ankle flexor torque, joint angle, and ROM were recorded by the Biodex system. From this information, the peak torque and the corresponding ankle joint angle were extracted. These measures were the dependent variables, with treatment (WBV and nonvibration) the independent variable. Statistical Package for the Social Sciences for Windows (version 14.0; SPSS Inc., Chicago, IL) was used to perform all statistical analyses. A one-way repeated-measures multivariate analysis of variance (RM MANOVA), with contrast testing, was used to compare baseline measures taken before each treatment. Separate RM MANOVA was used to compare measures before and after each treatment.

**RESULTS**

Each subject completed the study without any adverse side effects. All data met the assumptions of MANOVA testing. The descriptive and inferential statistics are listed in Table 1.

**Baseline measures.** The baseline measures recorded before each treatment (WBV and nonvibration) were not significantly different (Table 1).

**Plantarflexion.** No significant differences were found in plantarflexor ROM, peak torque, or joint angle of peak torque after the nonvibration treatment. On average, ankle plantarflexor ROM increased by 3.0°, peak torque by 0.6 Nm, whereas the angle of peak torque decreased by 0.4°. Figure 2A shows typical plots of the plantarflexor
angle–torque relationship, showing similar patterns before and after the nonvibration treatment.

No significant differences were found in the measures of plantarflexor ROM and peak torque after the WBV treatment. On average, ankle plantarflexor ROM increased by 2.0° and peak torque increased by 10.3 N·m after WBV. A significant 7.1° shift in the angle \( (P = 0.001) \) of peak plantarflexor torque production toward a longer muscle length was found after WBV. Figure 2B shows typical plots of the plantarflexor angle–torque curve before and after WBV, showing that the angle–torque relationship is shifted to the right after vibration (solid line).

**Dorsiflexion.** No significant differences were found in the outcome measures for the nonvibration treatment (Table 1). On average, ankle dorsiflexor ROM increased by 2.0°, angle of peak torque by 1.2°, whereas peak torque reduced by 1.5 N·m. Figure 3A shows typical plots of the ankle dorsiflexor angle–torque relationship, showing similar patterns before and after treatment.

No significant differences in all outcome measures were found after the WBV treatment. On average, ankle dorsiflexor ROM increased by 3.0°, angle of peak torque by 0.5°, whereas peak torque reduced by 0.5 N·m after WBV. Figure 3B depicts typical plots of the dorsiflexor angle–torque relationship before and after treatment. Again, the plots exhibit similar patterns.

**Accelerations.** An accelerometer was used to record maximal accelerations at the head. Accelerations due to WBV (additive to gravity) never exceeded 0.5 g (SD = 0.4 g), which falls below the ISO safety recommendation of 1.7 g (20).

**Leg girth.** There was no significant change in leg girth for each treatment. On average, leg girth increased by 0.25 cm after treatment.

**Muscle soreness.** Subjects did not report any muscle soreness immediately after WBV. However, all subjects reported some tenderness on the day after WBV (average rating = 1). This tenderness was no longer present 2 d after WBV.

### DISCUSSION

This study investigated the acute effect of WBV on the length–tension relationship of the ankle flexors in healthy young adult males. To examine this relationship, measures of ankle joint torque were recorded over a voluntary ROM by a Biodex dynamometer. This is the first study to report a significant shift \( (P = 0.001) \) in the ankle joint angle toward a longer muscle length for the generation of peak plantarflexor torque. Moreover, this shift was found to be dependent upon the muscle being fully stretched (i.e., lengthened) over the period of vibration. No shift in the angle–torque relationship was found for the ankle dorsiflexors. The ankle dorsiflexors were held in a shortened position during vibration.

In a recent study, Savelberg et al. (27) found that the angle at which the knee joint generates maximal knee

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**TABLE 1.** Descriptive and inferential statistics for each outcome measure before and after treatment.

<table>
<thead>
<tr>
<th>Outcome Measure</th>
<th>Pre</th>
<th>Post</th>
<th>( P )-value</th>
<th>Pre</th>
<th>Post</th>
<th>( P )-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leg girth (cm)</td>
<td>37.8 ± 5.0</td>
<td>38.0 ± 3.0</td>
<td>0.889</td>
<td>37.9 ± 5.0</td>
<td>38.2 ± 4.0</td>
<td>0.881</td>
</tr>
<tr>
<td>ROM (°)</td>
<td>49.0 ± 1.5</td>
<td>52.0 ± 1.5</td>
<td>0.061</td>
<td>49.0 ± 1.2</td>
<td>51.0 ± 1.2</td>
<td>0.077</td>
</tr>
<tr>
<td>Optimum angle (°)</td>
<td>18.4 ± 1.6</td>
<td>18.0 ± 1.5</td>
<td>0.563</td>
<td>17.5 ± 1.7</td>
<td>10.4 ± 1.5</td>
<td>0.001</td>
</tr>
<tr>
<td>Peak torque (N·m)</td>
<td>57.1 ± 6.6</td>
<td>57.7 ± 7.4</td>
<td>0.829</td>
<td>58.0 ± 6.5</td>
<td>68.3 ± 7.2</td>
<td>0.057</td>
</tr>
<tr>
<td>Dorsiflexion ROM (°)</td>
<td>8.0 ± 1.1</td>
<td>10.0 ± 1.4</td>
<td>0.077</td>
<td>8.0 ± 1.4</td>
<td>11.0 ± 1.5</td>
<td>0.065</td>
</tr>
<tr>
<td>Optimum angle (°)</td>
<td>29.0 ± 1.2</td>
<td>30.2 ± 1.2</td>
<td>0.689</td>
<td>29.6 ± 1.2</td>
<td>30.1 ± 1.3</td>
<td>0.138</td>
</tr>
<tr>
<td>Peak torque (N·m)</td>
<td>20.3 ± 1.2</td>
<td>18.8 ± 1.1</td>
<td>0.547</td>
<td>19.1 ± 1.1</td>
<td>18.6 ± 1.2</td>
<td>0.320</td>
</tr>
</tbody>
</table>

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**FIGURE 2**—Left panel - Typical plots of the plantarflexion angle-torque curve showing similar patterns before (dashed line) and after the nonvibration treatment (solid line). Right panel - typical plots of the plantar flexion angle-torque curve before (dashed line) and after WBV (solid line).
extension torque is affected by the joint position during WBV exposure (27). When the extensors were held in a lengthened position (bent knee or squat posture), maximal torque was generated at a longer muscle length or 3.6° earlier after WBV. In contrast, when the extensors were held in a shortened position (straight knee), maximal torque was generated at a shorter length or 7.9° later after WBV ($P = 0.001$). These results are similar to the findings of the current study. When held in a lengthened position and vibrated, the ankle joint plantarflexors generated maximal joint torque 7.1° earlier ($P = 0.001$). On the other hand, when held in a shortened position and vibrated, the ankle joint dorsiflexors generated maximal joint torque 1.1° later. The difference in the magnitude of the outcomes between the two studies is most likely due to the extent of muscle stretch during vibration training. It is known that neuromuscular responses are different when a muscle is trained at different lengths, with the magnitude of response increasing as the muscle is lengthened (33). In the study by Savelberg et al. (27), the knee extensors were only partially stretched or shortened (knee flexion of 70° and 10°, respectively). However, in the current study, the ankle plantar- and dorsiflexors underwent full voluntary stretch and shortening, respectively.

It is unlikely that the shift toward a longer muscle in the joint angle of the ankle plantarflexors was simply due to muscle stretching. There was no significant change after the nonvibration treatment where the plantarflexors were fully stretched. It is also unlikely that the vibration altered the structural integrity of the ankle joint (e.g., damage to cartilage or joint capsule) because no adverse events were observed. The most plausible explanation probably involves some change in the musculotendinous unit. There was some minor muscle damage as indicated by the DOMS experienced by the subjects. DOMS is accompanied by microscopic muscle damage, with multiple areas of damage scattered throughout the muscle, but each confined to a single fiber. In 1999, Morgan and Allen (22) proposed that these areas of microscopic damage are caused by disruption of the weakest sarcomeres in a muscle. As these disrupted sarcomeres lie in series with still contracting sarcomeres in the muscle fiber, the series compliance of the muscle increases, leading to a shift in the length–tension relationship in the direction of a longer muscle length. It is possible that vibration of a stretched muscle similarly disrupts the weakest sarcomeres, causing a change in its length–tension properties.

This study shows that WBV can shift the position of the joint angle where peak plantarflexion torque occurs. This allows a person to generate plantarflexion torque more rapidly. This finding is important because it is well known that a rapid response by the lower limb musculature is critical for regaining balance after a perturbation (30). Although other treatments (e.g., stretching and eccentric exercises) have been shown to alter optimum muscle length (24), this study shows that WBV is more effective. Jones et al. (18) reported a 3.9° shift in optimum ankle joint plantarflexor angle after 2 h of eccentric exercise. Several studies have reported shifts of less than 4° in optimum ankle joint plantarflexor angle after passive stretching (14,32). Our study has demonstrated a larger 7.1° shift after a brief bout of WBV.

Although nonsignificant, the maximum joint torque generated by the ankle plantarflexors increased by 18% ($P = 0.057$), whereas maximum joint torque generated by the ankle dorsiflexors reduced by 3% after vibration training. Other studies have reported significant strength gains in the knee extensors after vibration training (17,27,29). A possible reason for the lack of significant change in our study may lie in the exercise training backgrounds of the subjects who participated in this study. Previous work has shown greater gains in measures of strength and power in weaker untrained individuals compared with well-trained individuals (25). Although their exercise background was not recorded, it is possible that the group of young male adults was drawn from a population of
well-trained individuals. However, recent work has shown that the degree of muscle length change is unaffected by training background (27).

This study shows that stretched human ankle plantarflexors respond to WBV by shifting the point of peak voluntary torque toward a longer muscle length. It is acknowledged that the shift found in this study was transient. However, past studies have reported lasting neuromuscular adaptations after long-term WBV exercise programs. It is reasonable, therefore, to propose that a lasting shift may occur after a long-term program that adopts the protocol used in this study. This is yet to be investigated.

This study investigated the acute effect of WBV on the length–tension relationship of the ankle plantarflexors in a group of young healthy adults. A significant shift ($P = 0.001$) in the ankle joint angle toward a longer muscle length for the generation of peak plantarflexor torque was found in this group of young adults. Future studies should involve populations that have a diminished ability to generate rapid ankle joint plantarflexion torque, such as the elderly and the pathological populations (e.g., stroke). It is well known that these populations have a reduced capacity to generate rapid ankle torque to proactively deal with or recover from known and unexpected perturbations such as a trip or a stumble. Changing the length–tension of the plantarflexors through WBV may be beneficial to these populations by quickening the onset of peak ankle joint torque production (23).

The Galileo vibration plate was kindly provided by Novotec, Pforzheim, Germany. The results of this study do not constitute endorsement by ACSM.

### REFERENCES

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