

Acute effects of whole-body vibration on peak isometric torque, muscle twitch torque and voluntary muscle activation of the knee extensors

M. Jordan, S. Norris, D. Smith, W. Herzog

Human Performance Laboratory, The University of Calgary, Calgary, Alberta T2N 1N4, Canada

Corresponding author: Matthew J. Jordan, Human Performance Laboratory, The University of Calgary, 2500 University Drive NW, Calgary, Alberta T2N 1N4, Canada. Tel: 403 714 4655, Fax: 403 284 4815, E-mail: mjordan@ucalgary.ca

Accepted for publication 16 April 2009

The purpose of this investigation was to compare the acute effects of whole-body vibration (WBV) with a static squat on resting muscle twitch torque, peak isometric torque and voluntary muscle activation of the knee extensors during an isometric maximal voluntary contraction (MVC). Twenty-four healthy, strength-trained males were recruited for this randomized, cross-over design investigation. The WBV treatment consisted of three sets of 60 s of vibration (30 Hz, ± 4 mm) while standing in a semi-squat position. Voluntary muscle activation, peak isometric torque during MVC and resting muscle twitch torque (RTT) through percutaneous femoral nerve stimulation were obtained

before and following the treatment. Change in peak isometric torque, voluntary muscle activation and the RTT were calculated as the difference between pre- and post-treatment values. There was no observable post-activation potentiation of muscle twitch torque or enhancement in voluntary muscle activation or peak isometric torque. However, decreases in the peak isometric torque ($P = 0.0094$) and voluntary muscle activation ($P = 0.0252$) were significantly smaller post WBV interventions compared with the control treatment. Based on the current data, it is unclear whether or not this was attributable to the effects of WBV but further research into this possibility is warranted.

The use of strength and power exercise to augment the subsequent performance in a movement has been investigated extensively (Hodgson et al., 2005). This phenomenon has been termed post-activation potentiation (PAP) and there are several proposed mechanisms by which PAP may occur. They include one that is muscular (myogenic) in nature and can be quantified using muscle twitch force, and other mechanisms that are neural (neurogenic) in nature.

The type of strength and power exercise used to elicit PAP has included mostly traditional movements such as squatting exercise with additional load (Hodgson et al., 2005). However, whole-body vibration (WBV) has gained attention as another exercise modality that may elicit acute improvements in performance for various strength, jumping and running related tasks (Jordan et al., 2005; Rehn et al., 2007). Administration of vibration has been shown to lead to acute improvements in power output of the elbow flexors (Bosco et al., 1999), increased power output from the leg and hip extensors (Bosco et al., 2000) and increased vertical jump height (Cormie et al., 2006). Acute administration of WBV has also been shown to positively influence jumping and running performance in elite skeleton athletes

(Bullock et al., 2008) and jumping performance in field hockey players (Cochrane & Stannard, 2005). Despite the positive findings, several investigators have also shown no improvement in performance measures following acute WBV and this has led many investigators to question the value of this training stimulus (de Ruiter et al., 2003; Erskine et al., 2007; Torvinen et al., 2002).

Despite the mixed findings in the scientific literature and the recent popularity of WBV as a training method for athletes, very little is known about the physiological mechanisms underlying WBV (Jordan et al., 2005). It is clear that skeletal muscle is highly responsive to vibration, specifically the primary afferent (Ia) ending of the muscle spindle. For example, the administration of vibration elicits a reflex muscle contraction known as the tonic vibration reflex (TVR) (Bishop, 1974; Burke et al., 1976a, b; Desmedt & Godaux, 1978; Bongiovanni & Hagbarth, 1990; Bongiovanni et al., 1990), and in the post-vibratory period the stretch reflex is potentiated for a period of several minutes (Arcangel et al., 1971). In addition, WBV at a frequency of 30 Hz has been shown to elicit the greatest muscle activity from the vastus lateralis muscle (Cardinale & Lim, 2003). However, many of

these findings were based on vibration applied to isolated muscle and not WBV.

Proposed mechanisms for the acute improvements in performance following exposure to vibration have included improved intramuscular coordination (Liebermann & Issurin, 1997; Issurin & Tenenbaum, 1999) and enhanced neuromuscular efficiency (Bosco et al., 1999, 2000), but these explanations were not based on systematic scientific investigation. Furthermore, improvements in leg power following acute administration of WBV have been associated with a relative decrease in electromyographic (EMG) activity in the quadriceps muscles (Bosco et al., 2000). This finding may suggest the possible involvement of non-neurogenic factors such as potentiation of muscle twitch force, as this may improve the rate of force development during explosive activity (Sale, 2002). Based on the PAP literature, it would appear that there is the involvement of both neurogenic and myogenic factors in PAP (Hodgson et al., 2005), and this may provide a clue to the mechanisms underlying the acute effects of WBV on performance.

The aim of the present investigation, therefore, was to compare the acute effects of WBV with a static squat on voluntary muscle activation, resting muscle twitch torque and peak isometric torque of the knee extensors during a maximal voluntary contraction (MVC) of isometric knee extension. It was hypothesized that the WBV treatment would result in increased peak isometric torque during the MVC, which could be attributable to either the potentiation of RTT and or increased voluntary muscle activation.

Materials & methods

Subjects

Twenty-four male subjects provided written informed consent to participate in this investigation. Subjects were recruited from the Faculty of Kinesiology at the University of Calgary. All subjects were healthy, former athletes at the National or intercollegiate level, and had been involved in regular strength training for a minimum of two years before the start of the investigation. The subject characteristics were as follows (mean \pm SD): age, 28.1 ± 3.3 years; height, 180.0 ± 6.7 cm; and body mass, 82.8 ± 7.6 kg. The experimental protocol was approved by the Conjoint Faculties Research Ethics Board at the University of Calgary.

Study design

The testing week was preceded by a 2-week familiarization period. The purpose of the familiarization period, a standardized workout regime, was to control for the effects of outside physical activity. Furthermore, 2 days before each testing session, the subjects rested, abstaining completely from any physical activity. Subjects performed the testing protocol twice over a 1-week time period: once with the vibration treatment and once with the control treatment. Subjects were randomly divided into one of two groups with the treatment order

Table 1. Layout of the cross-over design

Group	Testing day 1	1-week washout	Testing day 2
Group I (n_{12})	Vibration	–	Control
Group II (n_{12})	Control	–	Vibration

reversed for the second group (Table 1). The first group received the vibration treatment in the first testing session and the second group received vibration treatment in the second testing session.

Pre-testing procedure

Before the testing session, subjects were familiarized with the testing procedures. This included familiarization with the vibration platform and the maximal isometric knee extension on the Biodex dynamometer (Biodex System 3, Model Number: 835-110, Shirley, New York, USA). Upon arrival, subjects were prepared for testing; this included preparation of the subject's skin, fastening of the electrodes, and adjustments were made to the Biodex dynamometer in preparation for the MVC. Subjects performed a series of warmup isometric knee extension contractions, which included five submaximal repetitions at 50% effort, five submaximal repetitions at 75% effort and three near-maximal repetitions at 90% effort. Subjects were then allowed a 10-min rest while the electrical stimulation electrodes were fastened to the skin.

Subject preparation

Subjects were seated in the Biodex dynamometer with the lateral epicondyle of the femur aligned with the axis of rotation of the dynamometer. Subjects were strapped to the dynamometer with two belts crossing the chest and one belt crossing the hips. The knee angle was set at 90° of flexion using full knee extension as the 0° reference angle. The proximal and distal regions of the thigh were shaved and cleaned with isopropyl alcohol.

Electrical stimulation

Standard carbon-impregnated rubber electrodes (4.5×10 cm) were coated with a conductive gel. One electrode was secured to the skin with adhesive tape just over the femoral nerve, and the second was secured distal on the skin in the distal third of the quadriceps muscle. The voltage eliciting maximal resting twitch torque was determined using an incremental stimulation protocol and this voltage was maintained throughout the testing session. A doublet twitch square wave pulse with an interpulse interval of 8 ms was administered using a Grass S88 Muscle Stimulator in combination with an isolation unit approved for human use (Quincy, Massachusetts, USA). The torque resulting from the electrical stimulations was sampled at 2000 Hz using an analog-digital board, and was monitored and stored for further data analysis on an IBM personal computer (Armonk, New York, USA).

Twitch interpolation technique

The twitch interpolation technique used in this investigation has been described elsewhere (Suter et al., 1998). Briefly, three doublet twitches were given to the relaxed muscle. The average

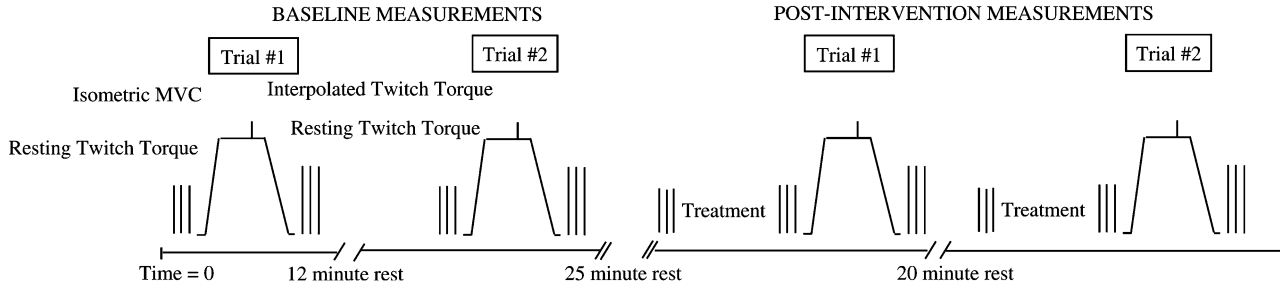


Fig. 1. Overview of the testing protocol.

torque produced by these three twitches represented the RTT.

$$RTT = (RTT_1 + RTT_2 + RTT_3)/3$$

The subject then performed an MVC that was held for 7s. The subject was provided with verbal encouragement to ensure a maximal effort was given for the MVC. At the fourth second of the voluntary contraction, when a steady-state torque had been reached, another doublet twitch was applied eliciting the interpolated twitch torque (ITT). The ITT typically exceeded the maximal voluntary force by a few percent. Following the MVC three additional doublet twitches were given to the relaxed muscle. Voluntary muscle activation during the MVC was calculated as follows:

$$\text{Voluntary muscle activation(\%)} = [1 - (ITT/RTT)] \times 100$$

The presence or absence of PAP following the treatment conditions was calculated by dividing the post-treatment resting muscle twitch torque (RTTpost) by the pre-treatment resting muscle twitch torque (RTTpre). This value was then multiplied by 100% and subtracted from 100.

$$PAP = (RTT_{\text{post}}/RTT_{\text{pre}} \times 100) - 100$$

MVC of isometric knee extension

Peak isometric torque from the knee extensor muscles was measured using a Biodex dynamometer. Peak isometric torque was calculated as the average torque over 500 ms immediately before the application of the interpolated twitch stimulation. Torque signals were sampled at 2000 Hz using an analogue-to-digital board, and data were monitored and stored on an IBM personal computer for analysis. Subjects were all well-trained strength athletes, and were very familiar with performing MVCs. The subjects were also provided with verbal encouragement throughout the MVC to ensure that a maximal effort was given in each trial.

Whole-body vibration treatment

The WBV treatment was administered using a commercially available WBV platform (NEMES-LC, SN: LC-0056). The WBV platform provided a sinusoidal vibration at a frequency of 30 Hz and an amplitude of ± 4 mm. Thirty hertz was chosen as this frequency has been shown to result in the greatest activation of the quadriceps muscle group (Cardinale & Lim, 2003).

Protocol

Baseline measurements (i.e. peak isometric torque during MVC, resting muscle twitch torque and voluntary muscle activation) were recorded with a 12-min rest interval separat-

ing each test (Fig. 1). The 12-min rest interval was chosen to ensure that all the potentiation resulting from the MVC was gone before beginning the second measurement. A 25-min rest interval separated the baseline measurements and the post-intervention measurements, and a 20-min rest interval separated the two post-intervention measurements. The longer rest interval was selected to ensure that the subjects had sufficient neural recovery between trials so that a maximal effort could be given for each MVC. For both the baseline measurements and the post-intervention measurements, the trials with the greatest peak isometric torque during the MVC were used for further data analysis.

For the post-intervention measurements, RTT was recorded immediately before the treatment (Fig. 1). This value served as the reference for the post-intervention RTT measurement and allowed for evaluation of the effects of the treatment on RTT. Following the baseline measurement of RTT, the subject was released from the Biodex dynamometer and stepped onto the vibration platform. The subject maintained a quarter squat position (knee angle measured at 130° of knee flexion) with the heels slightly elevated for three sets of 60 s of vibration (30 Hz, amplitude ± 4 mm) with a 60-s rest interval. Following the treatment, the subject was returned to the Biodex dynamometer and the RTTpost was measured at the 1-min mark post-treatment. The remainder of the twitch interpolation technique was performed as described above.

Control treatment

For the control treatment, the subjects stood on the vibration platform in the same position as for the vibration treatment, except that in this instance, no vibration was administered. All other aspects of the protocol for the control treatment were identical to the protocol described above.

Statistical analysis

The statistical analysis used to evaluate the treatment effects has been described in detail by Armitage, Berry and Matthews (2002). Briefly, the outcome measure for peak isometric torque, voluntary muscle activation and RTT was calculated by the change in the pre-treatment score and the post-treatment score. The difference between the change on Day 1 and Day 2 was calculated. The mean score for Group 1 and Group 2 was then compared using the two-sample *t*-test method. This method was used to evaluate the effects of vibration on the following variables: change in voluntary muscle activation, change in peak isometric torque and the effects of the treatment on RTT. The level of significance was set at $P \leq 0.05$.

Table 2. Mean (SE) baseline and post-treatment values for peak isometric torque, resting muscle twitch torque (RTT), interpolated twitch torque (ITT)/RTT ratio and voluntary muscle activation

Treatment	Baseline peak isometric torque (Nm)	Post-treatment peak isometric torque (Nm)	Baseline RTT (Nm)	Post-treatment RTT (Nm)	Baseline ITT/RTT ratio and voluntary muscle activation (%)	Post-treatment ITT/RTT ratio and voluntary muscle activation (%)
Vibration	248.6 (± 9.9)	244.3 (± 11.3)	289.0 (± 7.7)	271.8 (± 6.3)	0.135 (± 0.017) 86.5 (± 1.7)	0.136 (± 0.015) 86.4 (± 1.6)
Control	260.8 (± 11.5)	241.3 (± 14.4)	294.1 (± 6.4)	273.9 (± 5.4)	0.116 (± 0.017) 88.4 (± 1.7)	0.155 (± 0.018) 84.5 (± 1.8)

Table 3. Mean (SE) values for changes in voluntary muscle activation and peak isometric torque, and post-activation potentiation (PAP) of resting muscle twitch torque (RTT) following vibration and control treatment

Treatment	Change in voluntary Muscle activation (%)	Change in peak isometric torque (Nm)	PAP of RTT (%)
Vibration	0.1 (± 1.5)*	-4.4 (± 3.9)*	-5.5 (± 1.6)
Control	3.9 (± 1.3)	-19.5 (± 4.6)	-6.6 (± 1.3)

*Statistical significance as compared with control ($P < 0.05$).

Results

The baseline and post-treatment values for peak isometric torque, voluntary muscle activation and RTT are summarized in Table 2. There was no PAP present following WBV; in fact, RTT decreased following the WBV treatment and the control treatment (Table 3). RTT decreased by $-6.6 \pm 1.3\%$ (mean \pm SE) following the control treatment and $-5.5 \pm 1.6\%$ following the WBV. A comparison of these changes was not significantly different ($P = 0.5703$).

Voluntary muscle activation decreased following the WBV treatment and the control treatment. The mean change (\pm SE) in voluntary muscle activation was $3.9 \pm 1.3\%$ following the control treatment and $0.1 \pm 1.5\%$ following the WBV (between group $P = 0.0252$).

Peak isometric torque during MVC decreased compared with baseline values for both the WBV and the control treatment conditions. The mean change (\pm SE) in peak isometric torque was -19.5 ± 4.6 Nm (8.9%) following the control treatment and -4.4 ± 3.9 Nm (1.9%) following the WBV treatment (between group $P = 0.0094$).

Discussion

The results of the present investigation did not indicate the presence of PAP of RTT, enhanced voluntary muscle activation of the knee extensors or increased peak isometric torque from the knee

extensors during MVC following acute administration of WBV. In fact, following WBV, peak isometric torque and voluntary muscle activation of the knee extensors decreased. These results are consistent with the findings of similar investigations that have evaluated the acute effects of WBV on an MVC of isometric knee extension (Torvinen et al., 2002; De Ruiter et al., 2003; Erskine et al., 2007). Erskine et al. (2007) reported a significant decrease in peak isometric torque during MVC following 10 min of WBV compared with no change following a static squat without WBV in seven healthy males. However, in the present investigation, a comparison of the decrease in voluntary muscle activation and peak isometric torque following the WBV treatment and the control treatment was significantly different. Although the decrease in voluntary muscle activation and peak isometric torque was minimal for both conditions the change was significantly less following WBV. It is believed that this change was not due to environmental or psychological variables such as motivation as the conditions for each trial were carefully controlled, the subjects were all very familiar with performing MVCs and they were also provided with feedback and verbal encouragement for each trial to ensure a maximum effort was given. If the decrement in performance was not a result of psychological or environmental factors, then this result may provide evidence of a compensatory effect of WBV.

There are findings in the scientific literature that support the concept of a compensatory effect of vibration in a fatigued state (Bongiovanni et al., 1990). An investigation on the effects of vibration during fatiguing resistance exercise for the elbow flexors found that following vibration, the median power frequency of the elbow flexors was elevated in comparison with control, suggesting a potentiation of the higher threshold motor units that may have allowed fatigued motor units to recover (McBride et al., 2006). This acute post-vibratory effect has also been documented in other vibration-related investigations (Bongiovanni & Hagbarth, 1990; Bongiovanni et al., 1990; Martin & Park, 1997). It is unclear whether or not the significantly smaller decline in voluntary muscle activation following

WBV that was observed in the present investigation was a vibration-related effect but based on the literature it would seem that this finding is novel and further investigation of this possibility is warranted.

To the authors' knowledge, the present investigation was unique in that it was the first to investigate the acute effects of WBV on RTT. The specific WBV used in this study did not result in PAP. However, it is critical to consider the possibility that the treatment and testing protocol used in this investigation induced sufficient fatigue to abolish any observable PAP, as PAP and fatigue are factors that can co-exist following exercise (Hodgson et al., 2005). It is also possible that the 1-minute time delay that occurred between the subject stepping off the vibration platform and back into the Biodex strength testing machine affected the observation of PAP as PAP is time sensitive (Sale, 2002) and other post-vibration-induced neuromuscular changes appear to be time sensitive as well (Arcangel et al., 1971).

While there was no observable PAP of RTT following WBV, vibration has been shown to potentiate the stretch reflex (Arcangel et al., 1971). It is likely that dynamic movements involving a stretch-shorten cycle, such as jumping and running, would be enhanced to a greater degree by a vibration-induced potentiation of the stretch reflex than would isometric contractions, as were used here. A recent investigation on the acute effects of WBV on muscle strength and power lends support to this claim as WBV resulted in an acute improvement in vertical jump height but not strength during an 'isometric squat (Cormie et al., 2006). It has been postulated by other investigators that potentiation of reflex mechanisms may underlie the acute improvements in performance in dynamic movements that have been observed following WBV (Cormie et al., 2006; Bullock et al., 2008).

Finally, it should be mentioned that a systematic investigation into the neuromuscular response to WBV and isolation of the precise mechanisms that underlie the potential improvement or decrement in performance during the subsequent task is extremely challenging. By the nature of the generalized mechanical stimulus, WBV affects many muscle groups and biological systems simultaneously such as the neuroendocrine system, vestibular function, the circulatory system and muscle and skin sensory receptors, all of which have the capacity to affect the biological response to and subsequent performance following WBV (Jordan et al., 2005). This is contrasted with the literature on PAP, which typically involves movements with a more specific neuromuscular effect such as squatting or jumping exercise (Hodgson et al., 2005). Therefore, the complex biological response to WBV must be considered when comparing WBV with other more specific

forms of activity, which have been used in PAP investigations.

In conclusion, the WBV protocol used in this experiment did not improve voluntary muscle activation or peak isometric torque of the knee extensors during an MVC of isometric knee extension. Unexpectedly, the decrease in peak isometric torque and voluntary muscle activation following WBV was significantly smaller than following the control treatment. It is unclear whether or not WBV caused a compensatory effect but based on the scientific literature, further research into this possibility may be warranted. There was no observable PAP of RTT and although this may be attributable to fatigue or timing of the measurement, this finding may lend support to the idea that the potentiation of reflex pathways is partially responsible for the acute post-vibratory improvement in jumping and running tasks.

Perspectives

The use of traditional strength and power exercises to acutely enhance performance has been termed PAP (Hodgson et al., 2005). Several investigators have also evaluated the effectiveness of WBV to acutely enhance performance during strength, running and jumping tasks (Cochrane & Stannard, 2005; Cormie et al., 2006; Bullock et al., 2008); however, very little is understood regarding the physiological mechanisms underlying such improvements. Proposed mechanisms for PAP include those with a neurogenic and myogenic basis (Hodgson et al., 2005), and several investigators have proposed a neurogenic mechanism for a WBV-induced enhancement in performance. The results of the present investigation did not reveal an enhanced myogenic or neurogenic response of the knee extensors muscles following acute exposure to WBV. However, an unexpected finding was that the decline in voluntary muscle activation and peak isometric torque during an MVC was significantly less following WBV, which may provide evidence of a compensatory effect of WBV as this finding has been observed elsewhere in the scientific literature (McBride et al., 2006). There was no evidence of PAP, and while this may be due to the effects of fatigue or the timing of the measurement, this finding may lend support to the concept that other mechanisms, such as the potentiation of reflex pathways, are contributors to the post-vibratory improvement in performance that has been observed in dynamic movements such as jumping and running tasks (Bosco et al., 2000; Cochrane & Stannard, 2005; Bullock et al., 2008). While the data on WBV are mixed, it would appear that there is the potential for acute improvements in dynamic performance following WBV. While the results of the

present investigation failed to support the hypotheses, the findings are relevant to the body of scientific evidence on WBV as a systematic investigation was undertaken to evaluate the effects of WBV on two of the key mechanisms underlying PAP. Furthermore, this study provides a basis for the possible scenarios

in which WBV may be useful to enhance performance; however, further research into these possibilities is required.

Key words: post-activation potentiation, stretch reflex, compensatory effect, fatigue.

References

- Arcangel CS, Johnston R, Bishop B. The achilles tendon reflex and the H-response during and after tendon vibration. *Phys Ther* 1971; 51(8): 889–902.
- Armitage P, Berry G, Matthews JNS. *Statistical methods in medical research*, 4th edn. London: Blackwell Science, 2002.
- Bishop B. Vibratory stimulation: neurophysiology of motor responses evoked by vibratory stimulation. *Phys Ther* 1974; 54(12): 1273–1282.
- Bongiovanni LG, Hagbarth KE. Tonic vibration reflexes elicited during fatigue from maximal voluntary contractions in man. *J Physiol* 1990; 423: 1–14.
- Bongiovanni LG, Hagbarth KE, Stjernberg L. Prolonged muscle vibration reducing motor output in maximal voluntary contractions in man. *J Physiol* 1990; 423: 15–26.
- Bosco C, Cardinale M, Tarpela O. Influence of vibration on mechanical power and electromyogram activity in human arm flexor muscles. *Eur J Appl Physiol* 1999; 79: 306–311.
- Bosco C, Iacovelli M, Tarpela O, Cardinale M, Bonifazi M, Tihanyi J, Viru M, De Lorenzo A, Viru A. Hormonal responses to whole-body vibration in men. *Eur Appl Physiol* 2000; 81: 449–454.
- Bullock N, Martin DT, Ross A, Rosemond CD, Jordan MJ, Marino FE. Acute effects of whole-body vibration on sprint and jumping performance in elite skeleton athletes. *J Strength Cond Res* 2008; 22(4): 1371–1374.
- Burke D, Hagbart K, Lofstedt L, Wallin GB. The responses of human muscle spindle endings to vibration of non-contracting muscles. *J Physiol* 1976a; 261: 673–693.
- Burke D, Hagbart K, Lofstedt L, Wallin GB. The responses of human muscle spindle endings to vibration during isometric contraction. *J Physiol* 1976b; 261: 695–711.
- Cardinale M, Lim J. Electromyography activity of the vastus lateralis muscle during whole-body vibrations of different frequencies. *J Strength Cond Res* 2003; 17(3): 621–624.
- Cochrane DJ, Stannard SR. Acute whole body vibration training increases vertical jump and flexibility performance in elite female hockey players. *Br J Sports Med* 2005; 39: 860–865.
- Cormie P, Deane RS, Travis Triplett N, McBride JM. Acute effects of whole-body vibration on muscle activity, strength and power. *J Strength Cond Res* 2006; 20: 257–261.
- de Ruiter CJ, Van Der Linden RM, Van Der Zijden MJA, Hollander AP, de Haan A. Short-term effects of whole-body vibration on maximal voluntary isometric knee extensor force and rate of force rise. *Eur J App Phys* 2003; 88: 472–475.
- Desmedt JE, Godaux E. Mechanism of the vibration paradox: excitatory and inhibitory effects of tendon vibration on single soleus muscle motor units in man. *J Physiol* 1978; 285: 197–207.
- Erskine J, Smillie I, Leiper J, Ball D, Cardinale M. Neuromuscular and hormonal responses to a single session of whole-body vibration exercise in healthy young men. *Clin Physiol Funct Imaging* 2007; 27: 242–248.
- Hodgson M, Docherty D, Robbins D. Post-activation potentiation: underlying physiology and implications for motor performance. *Sports Med* 2005; 35(7): 585–595.
- Issurin VB, Tenenbaum G. Acute and residual effects of vibratory stimulation on explosive strength in elite and amateur athletes. *J Sport Sci* 1999; 17: 177–182.
- Jordan MJ, Norris SR, Smith DJ, Herzog W. Vibration training: an overview of the area, training consequences, and future considerations. *J Strength Cond Res* 2005; 19(2): 459–466.
- Liebermann DG, Issurin V. Effort perception during isotonic muscle contractions with superimposed mechanical vibratory stimulation. *J Hum Movem Stud* 1997; 32: 171–186.
- Martin BJ, Park HS. Analysis of the tonic vibration reflex: influence of vibration variables on motor unit synchronization and fatigue. *Eur J Appl Physiol* 1997; 75: 504–511.
- McBride JM, Porcari JP, Scheunke MD. Effect of vibration during fatiguing resistance exercise on subsequent muscle activity during maximal voluntary isometric contractions. *J Strength Cond Res* 2006; 18: 777–781.
- Rehn B, Lidstrom J, Skoglund J, Lindstrom B. Effects on leg musculature performance from whole-body vibration exercise: a systematic review. *Scand J Med Sci Sports* 2007; 17: 2–11.
- Sale D. Post-activation potentiation: role in human performance. *Exerc Sport Sci Rev* 2002; 30(3): 138–143.
- Suter E, Herzog W, Bray RC. Quadriceps inhibition following arthroscopy in patients with anterior knee pain. *Clin Biomech* 1998; 13: 314–319.
- Torvinen S, Sievanen H, Jarvinen TAH, Pasanen M, Kontulainen S, Kannus P. Effect of 4-min vertical whole body vibration on muscle performance and body balance: a randomized cross-over study. *Int J Sports Med* 2002; 23: 374–379.