Whole-body vibration does not influence knee joint neuromuscular function or proprioception

Running title: Acute whole-body vibration

Ricci Hannah[1], Claire Minshull[1], Jonathan Folland[2]

[1]**School of Science & Technology, Nottingham Trent University, Nottingham, UK;**

[2]**School of Sport, Exercise & Health Sciences, Loughborough University, Loughborough, UK**

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Correspondence:

Mr Ricci Hannah, School of Science and Technology, Nottingham Trent University, Nottingham, UK, NG11 8NS

Telephone: +44 (0) 115 848 8081

Fax: +44 (0) 115 848 6680

E-mail: ricci.hannah@ntu.ac.uk

Abstract

This study examined the acute effects of whole-body vibration (WBV) on knee joint position sense and indices of neuromuscular function, specifically strength, electromechanical delay and rate of force development. Electromyography and electrically evoked contractions were employed to investigate neural and contractile responses to WBV. Fourteen healthy males completed two treatment conditions on separate occasions: (1) 5 x 1 minute of unilateral isometric squat exercise on a synchronous vibrating platform [30 Hz, 4 mm peak-to-peak amplitude] (WBV); (2) a control condition (CON) of the same exercise without whole-body vibration. Knee joint position sense (joint angle replication task), and quadriceps neuromuscular function were assessed pre-, immediately-post and 1h post-exercise. During maximum voluntary knee extensions peak force (PF_V), electromechanical delay (EMD_V), rate of force development (RFD_V) and EMG of the quadriceps were measured. Twitch contractions of the knee extensors were electrically-evoked to assess EMD_E and RFD_E. Results showed no influence of WBV on knee joint position sense, EMD_V; PF_V and RFD_V during the initial 50, 100 or 150 ms of contraction. Similarly, electrically-evoked neuromuscular function and neural activation remained unchanged following the vibration exercise. A single session of unilateral WBV did not influence any indices of thigh muscle neuromuscular performance or knee joint proprioception.

Key words: explosive strength, joint stability, contractile properties, muscle activation, sensorimotor performance

Introduction

Neuromuscular function is a key determinant of sports performance as well as dynamic joint stability and thus injury prevention (Shultz and Perrin, 1999). In addition to maximum voluntary force, electromechanical delay (EMD) and the rate of force development (RFD), are important indices of neuromuscular function that may influence the performance of explosive movements such as vertical jumping (de Ruiter et al., 2006; Vos et al., 1990) and determine the capability for muscular stabilisation of joints during periods of unpredictable loading (Blackburn et al., 2009; Minshull et al., 2007). Effective neuromuscular control of skilled tasks and dynamic joint stability also requires precise proprioceptive information including an accurate sense of joint position (Riemann and Lephart, 2002). Any intervention that changes neuromuscular function (strength, RFD, EMD) and proprioception (joint position sense) might be expected to influence athletic performance as well as dynamic joint stability and the risk of injury.

Vibrating platforms are a popular training device used by elite athletes and recreationally active individuals. Whole-body vibration (WBV) exercise typically entails performing exercises such as squats whilst standing on a vibrating platform. WBV has been suggested to acutely enhance voluntary force and power production by influencing the neural processes important for neuromuscular function (Cardinale and Bosco, 2003). For example, where the vibrational stimulus is principally focussed on the agonist, the resultant reciprocal inhibition of the antagonist muscle (Martin et al., 1986) could, in theory, enhance net force production. Vibration is also a potent stimulus for activating the muscle spindle Ia afferents (Burke et al., 1976), and an increased sensitivity of the stretch reflex could facilitate volitional force generation by enhancing the reflex contribution to muscle activation (Cardinale and Bosco, 2003). An alternative consequence of greater Ia afferent sensitivity could be disruption of the conscious perception of joint position sense (Proske, 2005); disturbed position sense and illusory movements have been reported in response to vibration applied directly to the distal tendon of a muscle (Goodwin et al., 1972). These disruptions to joint position sense have been reported to last for several minutes following the cessation of direct muscle vibration (Rogers et al., 1985). However, to date, no research has investigated knee joint position sense subsequent to WBV.

The possibility that strength and power are acutely enhanced following WBV has received some scientific attention [see Rehn et al., (2007) for a review]. Improvements in vertical jump height after a bout of WBV have been found (Bosco et al., 2000; Cochrane and Stannard, 2005; Cochrane et al., 2008; Torvinen et al., 2002a), but research findings of maximum isometric knee extensor strength are equivocal, with reports of acutely increased (Torvinen et al., 2002a), decreased (Colson et al., 2009; de Ruiter et al., 2003; Erskine et al., 2007) and unaffected strength performance (Jordan et al., 2009; Torvinen et al., 2002b) after WBV. Furthermore, during explosive voluntary contractions, the acute effect of WBV on temporal force characteristics, such as EMD and RFD remain relatively unexplored; limited evidence suggests a preservation of RFD capabilities despite reductions in maximum strength (de Ruiter et al., 2003; Erskine et al., 2007). Typically these studies involved participants performing a bilateral squat during the WBV. Neural drive to the quadriceps muscle is greater during unilateral squatting with WBV compared to bilateral (Roelants et al., 2006). A unilateral squat on a vibrating platform might, therefore, be expected to provide a more potent WBV stimulus and help elucidate any changes in neuromuscular function.

The influence of WBV on muscle activation during maximum isometric force production has been investigated with the interpolated twitch technique (ITT) and similarly equivocal findings of decreased (de Ruiter et al., 2003) and unchanged muscle activation (Colson et al., 2009; Jordan et al., 2009) have been reported. The ITT is not suited to evaluating muscle activation at the onset of rapid muscle contractions. In this context electromyography (EMG) may be a more appropriate technique, especially if expressed relative to the maximal compound muscle action potential (*M-max*) thereby controlling for changes in muscle membrane excitability and electrode impedance which could influence the EMG amplitude independent of any changes in neural drive (Gandevia, 2001). Furthermore, to date no research has used EMG to assess possible alterations in agonist and antagonist activation which, given the proposed neural responses to WBV, could contribute to any changes in maximum or explosive strength. Systematic investigation of the neuromuscular responses to WBV, including EMG and measurement of the muscle contractile properties via electrically-evoked contractions, may to help clarify the equivocal findings in the literature and elucidate the neural (activation) or peripheral (contractile) mechanisms underpinning any changes in function.

Given the prevalence of WBV as a training method and potential warm-up modality prior to athletic activities (Cochrane et al., 2008; Rittweger, 2010), the effects of WBV on neuromuscular function and proprioception are of considerable interest because of their relevance to sports performance and joint stabilisation. The aim of this investigation was to examine the effects of an acute bout of unilateral whole-body vibration exercise, of greater intensity than previous investigations, on neuromuscular function and proprioceptive acuity of the knee joint, specifically strength, EMD, RFD and joint position sense. Neural and peripheral contributions to any changes in function were investigated by means of EMG and electrically evoked responses.

Materials & Methods

Participants

Fourteen healthy, recreationally active (up to three sessions of aerobic activity per week and not involved in systematic strength or power training), male volunteers (22 ± 3 years; 176 ± 5 cm; 73.6 ± 12.5 kg) provided their written informed consent to participate in this study. All were free of musculoskeletal injuries specific to the ankle, knee and hip joints at the time of assessment. Participants refrained from strenuous physical activity for 36 h prior to each laboratory visit. Assessment protocols were approved by the University Human Ethical Review Committee.

Experimental Design

Participants visited the laboratory on three separate occasions. The first session was used to familiarise participants with all the measurements and the unilateral squat exercise. Participants did not experience WBV during the familiarisation. Thereafter, a cross-over design was employed so that individuals completed two conditions in a randomised order, each separated by 48 h. Measurements of the dominant leg were performed pre, immediately-post and 1 hr post either: a unilateral (dominant leg) whole-body vibration exercise session (WBV); or a control condition of equivalent exercise performed without the application of vibration (CON). Assessments at each time point were conducted in the following order: knee joint position sense; electrically-evoked contractions and then maximum voluntary contractions (MVCs) of the quadriceps femoris. These were performed ~2, 7 and 10 minutes after the cessation of exercise, respectively. In addition, MVCs of the hamstrings were completed immediately following quadriceps MVCs for the normalisation of antagonist muscle activation (detailed below). The duration of the assessments immediately following the WBV and CON treatments (17 min 45 s ± 3 min 12 s vs. 16 min 31 s ± 2 min 20 s [mean ± SD]) was not significantly different ($t_{(13)}$ = 1.66, P = 0.122).

Exercise protocol

The exercise consisted of a static unilateral squat at 140° knee joint angle (where 180° = full extension) performed on the vibration platform in both conditions (Next Generation, Pro5 Air™, Power Plate®, London, UK; Figure 1a). This extended knee joint position is typical of those used for squatting exercise during WBV (Cochrane et al., 2010; Hopkins et al., 2009; Melnyk et al., 2008), and approximates the angle selected for assessing knee joint position sense and neuromuscular function (150°, see below). During pilot testing, unilateral squatting at 150° with WBV elicited some discomfort associated with excessive transmission of vibration to the head. Therefore we selected a slightly more flexed knee joint angle which elicited minimal discomfort. Initial and final knee joint angles were as measured using a manual goniometer. During the CON condition no vibration was administered (the platform was switched off); for the WBV condition it produced synchronous vibrations at 30 Hz frequency and 4 mm peak-to-peak amplitude. The exercise was performed without shoes to minimise the attenuation of the vibration. Furthermore, neural drive to the quadriceps muscle has been demonstrated to be greater without shoes (Marin et al., 2009) and during WBV at 30 Hz (Cardinale and Lim, 2003) and 4 mm amplitude (Marin et al., 2009) compared to 40 or 50 Hz and 2 mm amplitude. Participants completed 5 x 1 minute bouts of exercise with 1 minute of relaxed standing between each bout.

Knee joint position sense

Knee joint position sense (JPS) was obtained as an index of proprioceptive capabilities using a joint angle replication task (Paschalis et al., 2007). Participants were blindfolded and seated upright on a treatment table so that the popliteal fossa was ~5 cm from the edge of the table. A gravity-type goniometer (Leighton Flexometer Inc, Washington, USA) was secured to the ankle of the dominant limb just proximal to the lateral malleolus. A target knee angle of 150° was selected to represent a functionally relevant joint angle associated with maximal strain on the knee ligaments (Beynnon and Johnson, 1996). From a joint angle of ~90° the experimenter manually extended the knee of the participant to 150° and the participant was asked to actively maintain this position for 3 s before slowly returning the knee to the starting angle. After 5 – 10 s of rest the participant was asked to replicate the 150° joint position and to maintain it for 3 s while the position was recorded (Figure 1b). Participants were instructed to focus on accuracy, rather than speed, when replicating the target angle. Three trials were performed at the same target angle; the mean of the three attempts taken to describe performance. To minimise the effect that anticipatory knowledge of the target angle may have on performance, the experimenter passively extended the knee from 90° to 180° and back to 90° prior to each attempt. The absolute error (JPS-A) and relative error (JPS-R) scores were calculated (Paschalis et al., 2007). JPS-A and JPS-R were calculated as the difference in absolute and signed (+ or –) degrees respectively, between the target angle and the angle produced by the participant. Therefore, JPS-A and JPS-R represent the magnitude and direction [flexion (-) or extension (+)] of error, respectively.

Force measurements

Participants were secured in a custom built isometric dynamometer (modified from (Minshull et al., 2007)) with hip and knee joint angles of 110° and 150° (Figure 1c). Adjustable strapping across the shoulders, pelvis and thigh proximal to the knee localised the action of the involved musculature. The lever-arm of the dynamometer was attached to the dominant leg of the participant just proximal to the lateral malleolus by means of a padded ankle-cuff in series with a strain-gauge (615, Tedea-Huntleigh, Herzliya, Israel). The strain-gauge signal was sampled at 2000 Hz using an external A/D converter (1401, CED, Cambridge, UK).

Electrically-evoked muscle activation

Discrete electrical stimuli were delivered via percutaneous stimulation of the femoral nerve in the femoral triangle. Stimulation was achieved via a cathode stimulation probe (Electro Medical Supplies, Wantage, UK) pressed into the femoral triangle and maintained manually by the same experimenter (R.H.) throughout testing (Place et al., 2007). The surface of the anode, a 10 x 7 cm carbon rubber electrode (Electro Medical Supplies, Wantage, UK) was coated in electrode gel and positioned over the greater trochanter. Square wave pulses, of 1 ms in duration, were delivered via a constant current variable voltage stimulator (Model DS7AH, Digitimer, Ltd, Welwyn Garden City, UK). Stepwise increments in the current were delivered and separated by 10 s to allow for neuromuscular recovery (Moore and Kukulka, 1991), until a plateau in the amplitude of twitch force and compound muscle action potentials (*M*-waves) were reached. The stimulus intensity was increased by 25% beyond the value required to elicit a plateau to ensure supra-maximal stimulation (Place et al., 2007) and five discrete supra-maximal stimuli, each separated by 10 s were then delivered.

Maximum voluntary contractions (MVCs)

Following a series of warm-up contractions participants completed a series of three MVCs, each lasting ~ 3 s and separated from the next by 15 s rest. Participants attempted to extend their knee “as hard and fast as possible” on hearing an auditory signal (“go”), which was delivered randomly within a 1 – 4 s period during assessments of the quadriceps and hamstrings respectively. Strong verbal encouragement was given during all MVCs.

Electromyography (EMG)

Surface EMG data were recorded from the rectus femoris (RF), vastus medialis (VM), vastus lateralis (VL) and biceps femoris (BF; as a surrogate for the hamstring muscles) throughout the evoked ($_E$) and voluntary ($_V$) muscle activations. After preparation of the skin with shaving, light abrasion and cleaning with alcohol to yield an inter-electrode impedance <5 kΩ, bi-polar surface electrodes (self-adhesive, Ag-AgCl, 10 mm recording surface diameter, Unilect, Worcestershire, UK), were placed 3 cm apart over the distal aspect of the VM and mid-belly of the VL, RF and BF muscles, parallel to the presumed orientation of the muscle fibres. The reference electrode was 3cm lateral and equidistant from the recording electrodes. The raw unfiltered EMG signals were passed through a differential amplifier (1902 Mk IV; Cambridge Electronic Design, Cambridge, UK) with an input impedance of 10,000 MΩ, CMRR of 100 dB and at a gain of 1000. EMG data associated were digitally high and low pass filtered between 6 and 500 Hz using 2nd order Butterworth filter, prior to quantification of the root mean square amplitude (RMS) of the signal (see below).

Indices of neuromuscular function

M-max was defined as the peak-to-peak amplitude (mV) of the supra-maximal compound muscle action potentials recorded in the VM, VL and RF. Electromechanical delay during voluntary (EMD_V) and evoked contractions (EMD_E) was computed as the time delay between the onset of EMG and the onset of force. Onsets of EMG and force were defined as first point at which the myoelectric and force signals consistently exceeded the 95% confidence limits formed around the mean background noise. These indices were calculated for the VM, VL and RF muscles respectively. As a measure of true electromechanical delay, maximum EMD during voluntary and evoked contractions (EMD_V max; EMD_E max) was calculated as the longest EMD value among the VM, VL and RF muscles (Zhou et al., 1995).

Peak force (PF_V) and peak twitch force (PF_E) were recorded during volitional and evoked muscle activations. Time to peak tension (TPT_E) was measured as the time from the onset of force to PF_E. Half relaxation time (HRT_E) was defined as the time from PF_E to half peak twitch force on the descending slope of the force-time curve. Maximum rate of force development ($MRFD_E$), defined as the peak slope on the ascending limb of the force-time curve over a 5 ms interval was measured in absolute terms and normalised to the amplitude of force response, i.e. $MRFD_E/PF_E$. Absolute rate of force development during MVCs was also calculated as the average slope of the force-time curve over time intervals of 0 – 50, 0 – 100 and 0 – 150 ms from the onset of force (RFD_V 0 – 50, RFD_V 0 – 100 and RFD_V 0 – 150 ms).

During the knee extension MVCs the root mean square (RMS) EMG from the individual agonist (VL, VM, RF) and antagonist (BF) muscles was calculated at PFv and during the initial phase of the MVCs. Specifically EMG at PFv was measured over a 200 ms window (100 ms either side of PFv), and during the early phase of the voluntary contractions the RMS of the EMG data was calculated over time intervals of 0-50, 0-100 and 0-150 ms from the onset of electrical activity. EMG values from the agonists were then expressed as a percentage of the respective *M-max* to obtain $RMS:M^{-1}$ for each muscle. Any change in the RMS without a change in the *M-max* can be used to indicate alterations in voluntary muscle activation (Lepers et al., 2002). The mean value for the three quadriceps muscles was calculated to produce mean quadriceps $RMS:M^{-1}$. Antagonist (BF) EMG activity during the knee extension MVCs was expressed as a percentage of maximal EMG during maximal knee flexion contractions (Kubo et al., 2004), defined as the root mean square (RMS) calculated over a 200 ms window surrounding peak force (100 ms either side).

Indices of joint position sense (JPS-A; JPS-R) are reported as the mean of three trials. Indices of neuromuscular function are reported as the mean of five (evoked) and three (voluntary) discrete muscle activations, except PF_V where the highest value was taken as the representative figure for that occasion.

Statistical Analyses

Descriptive and outcome statistics are presented as mean ± standard deviation. Statistical significance was set at the $p < 0.05$ level. Separate two-way repeated-measures (condition [WBV; CON] x time [Pre; Post; Post-1h]) ANOVA were used to analyse each index of neuromuscular function and joint position sense. Post-hoc comparisons with a Bonferroni corrected paired t-test were performed when a significant effect was detected.

The experimental design offered an approximate 0.80 power of avoiding a Type II error when employing a least detectable difference for the following variables of: JPS-A, 1.4°; JPS-R 1.7°; PF_V, 21 N; EMD_V max, 3 ms; RFD 0-50, 292 $N.s^{-1}$; RFD 0-100, 281 $N.s^{-1}$; and RFD 0-150 ms, 192 $N.s^{-1}$.

Results

Joint-position sense

No significant interaction or main effects were revealed for absolute (JPS-A) or relative (JPS-R) errors in joint position sense (Figure 2), which suggests that proprioception performance was unaffected by either the WBV or CON treatment conditions.

Indices of voluntary neuromuscular function

There were no significant interaction or main effects on EMD_V max, RFD_V during the first 150 ms of the knee extension MVCs (interaction effects: $0.38 < P < 0.92$; Table 1)

Similarly there were no changes in neural drive (normalised EMG) of the agonist or antagonist muscles at peak force or during the first 150 ms of knee extension MVCs (interaction effects: $0.46 < P < 0.74$) (Table 1, antagonist muscle data not shown).

Indices of evoked neuromuscular function

PF_E, TPT_E and *M-max* for the three superficial quadriceps muscles were not statistically different across time and conditions (interaction effects: $0.07 < P < 0.48$; Table 2). HRT_E was shorter immediately post-exercise (ANOVA, $F_{[2,26]} = 11.73$, $P < 0.001$; Bonferroni, Pre vs. Post $P = 0.007$, Post vs. Post-1h $P = 0.005$); however, the improvements observed were similar between conditions (~8%; Table 2). Absolute $MRFD_E$ remained unchanged, but normalised $MRFD_E$ increased immediately post-exercise in both conditions (Bonferroni, Pre vs. Post $P = 0.001$), with values returning to baseline at post-1h (Bonferroni, Pre vs. Post-1h $P > 0.05$), but with no difference between WBV and CON (Table 2).

Maximum EMD_E (EMD_E max), i.e. the longest electromechanical delay of the three quadriceps muscles, was always observed in the RF muscle. A significant main effect for time (ANOVA, $F_{[2,26]} = 3.409$, $P = 0.048$) was observed for EMD_E data (Table 2); however, *post hoc* tests revealed no differences between measurement time points ($P > 0.05$). A time by condition interaction (ANOVA, $F_{[2,26]} = 4.043$, $P = 0.030$) suggested a difference between conditions in the recovery of EMD_E max from immediately post-exercise to post-1h

(Table 2). EMD_V max values were 104% - 125% greater than EMD_E max values across all time points and treatment conditions.

Discussion

The present study found no influence of WBV on proprioceptive acuity and voluntary neuromuscular function. Knee joint position sense, voluntary isometric strength, rate of force development and electromechanical delay were unaffected by either the control or whole-body vibration interventions. Similarly there were no differences in voluntary muscle activation or intrinsic contractile properties, as assessed by EMG and electrically-evoked contractions, following the two exercise conditions. Of note is the fact that the current results were obtained following unilateral WBV, which likely reflects a more intense WBV stimulus by comparison to bilateral squat exercise (Roelants et al., 2006) used in previous investigations and yet no substantive effects were observed.

Knee joint position sense

Accurate proprioceptive information is integral to efficient movement execution and prospective studies have highlighted the importance of superior proprioceptive capabilities on the amelioration of injury risk (e.g. Caraffa et al., 1996; Wedderkopp et al., 1999). Given that direct vibration has been shown to impair proprioceptive acuity (Goodwin et al., 1972; Rogers et al., 1985) one might have anticipated a deleterious effect of WBV on position sense at the knee, with potential negative implications for injury risk. The present results indicated that knee joint position sense, both in terms of the absolute magnitude and direction of error, remained unchanged during both treatment conditions (WBV; CON). As such, the data demonstrate that the WBV exercise protocol used in the current study does not seem to influence joint position sense in the same way as direct muscle vibration. The mode of vibration in the current study reflects the manner in which vibration is most commonly applied in an exercise setting (e.g. Bosco et al., 1999; Bosco et al., 2000; de Ruiter et al., 2003; Jordan et al., 2009; Torvinen et al., 2002a; Torvinen et al., 2002b). During WBV, the vibration stimulus is applied to the feet, and is likely attenuated by the foot, ankle and shank before reaching the knee and surrounding musculature (de Ruiter et al., 2003), potentially minimising any effects at the knee. Given the proximity of the ankle joint and shank muscles to the vibration stimulus during WBV, future studies may wish to examine the influence of WBV on position sense at the ankle.

Previous studies have investigated the effect of WBV on closed-chain postural control (Torvinen et al., 2002a; Torvinen et al., 2002b), which reflects a global and integrated measure of sensorimotor performance. A strength of the current study is that a deliberate attempt was made to avoid the potentially confounding effects of afferent information from the vestibular system and other joints in order to highlight the influence of WBV on proprioceptive acuity at the knee joint. Therefore, position sense was assessed using an open-chain joint-repositioning task. The current method of assessment of proprioceptive acuity was also selected on the basis of its routine use as an outcome measure both in clinical practice and in related sports medicine literature (see {{219 Riemann,B.L. 2002;}}for a review). Efforts were made to ensure precision and accuracy of measurement; however, it is possible that very small differences in joint positioning may have been rendered undetectable as evidenced by the variability of the responses within the group (Figure 2).

Indices of neuromuscular function

The current study used a combination of electrically-evoked contractions, EMG and voluntary contractions, to try and clarify, firstly the influence of acute WBV on neuromuscular function, and second also distinguish between contractile and neural aspects of any changes. This combination of methods has not been employed in the context of WBV. However, we found no evidence for functional, contractile or neural changes occurring after WBV.

Electromechanical delay is considered to be an important determinant of successful performance in tasks where the time available for the development of force is limited, for example, jumping (Vos et al., 1990) and dynamic joint stabilisation (Shultz and Perrin, 1999). The present results indicated that EMD_V max remained statistically unchanged throughout the duration of the study. There appeared to be a subtle difference in the recovery of evoked EMD after the two treatments, but the mean values overall the time points were tightly grouped (range, 13.0 – 13.7 ms). In agreement with previous studies we found voluntary EMD to be ~ 100% greater than evoked EMD (Minshull et al., 2007; Zhou et al., 1995) suggesting that voluntary neural activation is an important determinant of voluntary EMD (Zhou et al., 1995).

The present study found no influence of WBV on voluntary RFD during the first 150 ms of contraction. In addition, the activation and co-activation of the agonist and antagonist muscles during these initial phases of contractions were shown to be unaffected by either WBV or CON interventions. Previous studies, which likely represented a lower intensity WBV stimulus (i.e. bilateral), have also reported no influence of WBV on voluntary RFD (de Ruiter et al., 2003; Erskine et al., 2007). The results of the current study provide further evidence that a session of WBV of this type is unlikely to alter the capacity for fast muscle activation and explosive force production.

Although there were small improvements in the speed of muscle contraction (normalised $MRFD_E$) and relaxation (HRT_E) post-exercise, there was no difference between conditions and as mentioned, these changes were not accompanied by improvements in voluntary RFD. These post-exercise enhancements in muscle contractile speed may have been due to an increase in muscle temperature (de Ruiter et al., 1999), as acute WBV has been shown to increase muscle temperature (Cochrane et al., 2008). The lack of concomitant changes in RFD_V may be because the changes in contractile speed were of insufficient magnitude to exert a detectable effect, or because RFD_V depends more on neural activation at the onset of contraction rather than the maximal muscle contractile speed (de Ruiter et al., 2004).

Knee extensor strength (PF_V) was unchanged following both the WBV and CON conditions. This finding is in agreement with other research that has found no differential effect of WBV and control exercise on knee extensor strength (Colson et al., 2009; Torvinen et al., 2002b), but in contrast with those reporting strength after WBV to be acutely increased (Torvinen et al., 2002a), decreased (Erskine et al., 2007) or preserved in comparison to a reduction observed with control exercise (Jordan et al., 2009). Whilst methodological differences may be a source of differential findings in some cases, four out of five studies (including the present experiment) found no increase in strength and one reported a very limited net benefit of 3%. It appears that there is little or no benefit to be gained from a bout of WBV with regards to any acute improvement in knee extensor strength. One potential limitation of the current study was the time frame within which the measurements were obtained. Whilst decrements in knee extensor strength following WBV have been reported to last up to 2h (Erskine et al., 2007), it is possible that short-lasting effects of WBV may have been undetected in the current study. For example, the logistics of the protocol dictated that measurement of voluntary neuromuscular function took place ~10 minutes following the cessation of the exercise treatments.

WBV has been suggested to influence subsequent voluntary force production by altering neural activation, specifically enhancing agonist muscle activation and reducing antagonist muscle co-activation (Cardinale and Bosco, 2003), but no previous investigation has measured agonist and antagonist activation following WBV exercise. The unaltered strength values in the present study mirrored the lack of change in agonist or antagonist muscle activation after WBV or control interventions. Furthermore, the similar PF_E and *M*-wave amplitudes after WBV and CON imply that sarcolemmal excitability and excitation-contraction coupling were not differently affected by the two conditions. Previous studies have also reported that knee extensor PF_E (Colson et al., 2009; Jordan et al., 2009) and muscle activation (Colson et al., 2009) were unaffected by WBV. Although one study reported twitch potentiation lasting at least 5 minutes following acute WBV (Cochrane et al., 2010), no attempt was made to investigate the effects on voluntary neuromuscular function. The present findings of unaltered agonist activation and antagonist co-activation during the voluntary contractions do not support the proposed influence of prior WBV on neural activation during maximum voluntary contractions.

In conclusion, 5 minutes of unilateral WBV exercise did not influence the knee joint position sense or the electromechanical delay, rate force development or peak force during maximal voluntary knee extensions. WBV did not differentially affect the muscle contractile properties or level of agonist and antagonist muscle activation when compared to the CON condition. Therefore, this study found WBV did not facilitate neuromuscular function or compromise proprioception.

Perspectives

Despite evidence that vibration can be detrimental to proprioceptive capabilities (Goodwin et al., 1972; Rogers et al., 1985) that appear to offer some protection from injury (Caraffa et al., 1996; Wedderkopp et al., 1999), the effects of acute WBV on proprioception had not previously been investigated. The present results suggest that an acute bout of WBV does not impair position sense at the knee and, though the risk of lower limb injury is likely multi-factorial, do not imply an increase in the immediate risk of knee joint injury. The current data also indicated that WBV does not induce acute changes in voluntary neuromuscular function (PF_V, EMD_V max, RFD_V) of knee extensors in a recreationally active male population. These findings therefore do not support the use of WBV as a warm-up modality for enhancing neuromuscular function prior to athletic activities.

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Conflicts of interest

The authors report no conflicts of interest.

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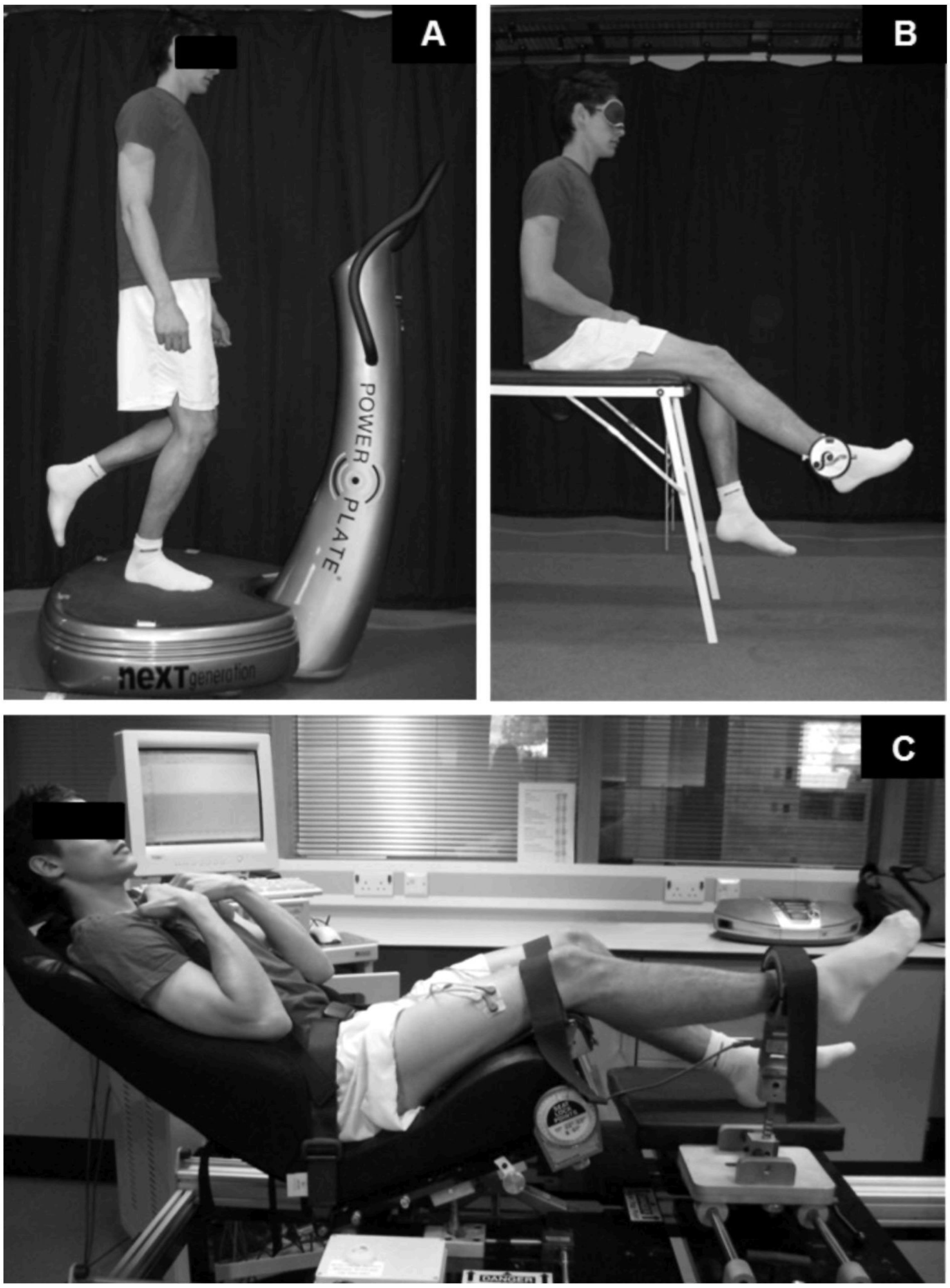

Figure 1. Participant orientation during: (a) WBV and CON exercise; (b) assessments of joint position sense; and (c) during assessments of neuromuscular function.

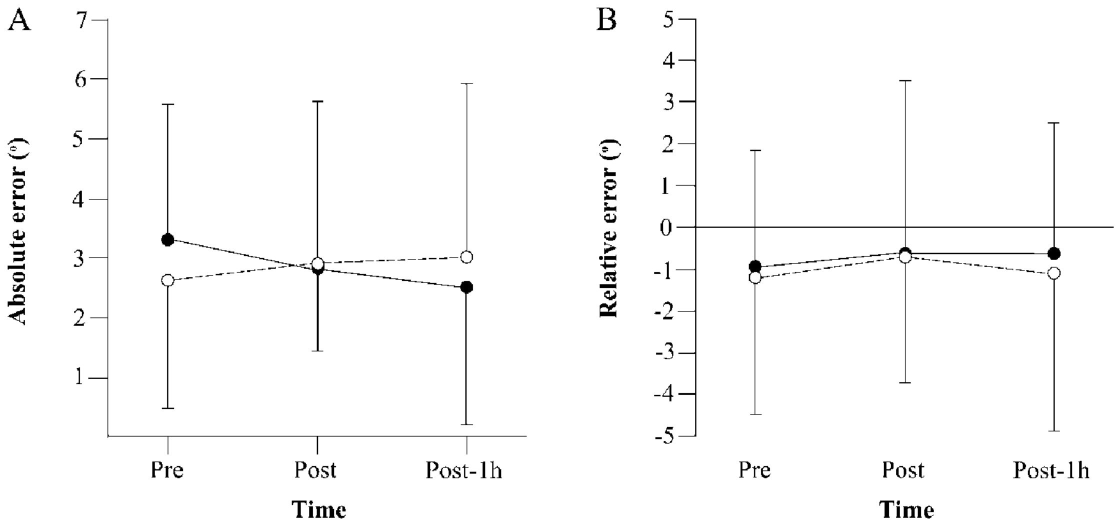

Figure 2. Effects of whole-body vibration (*closed circles*) and control (*open circles*) exercise on absolute (A) and relative (B) re-positioning errors during the assessment of knee joint position sense at 150°. Data are mean ± SD, n = 14.

Table 1. Indices of voluntary neuromuscular function before (Pre), immediately after (Post) and 1 hour after (Post-1h) the control and whole-body vibration exercise

Dependent variable	Whole-body vibration			Control			
	Pre	**Post**	**Post-1h**	**Pre**	**Post**	**Post-1h**	***P***
Electro-mechanical responses							
EMD_V max (ms)	27.6 (3.4)	28.2 (5.1)	27.7 (5.4)	28.8 (4.5)	28.7 (6.7)	28.7 (6.9)	0.62
Mechanical responses							
PF_V (N)	553 (109)	550 (110)	544 (141)	567 (133)	538 (102)	542 (118)	0.71
RFD_V 0-50 ms ($N{\cdot}s^{-1}$)	1853 (798)	1808 (923)	1804 (905)	2011 (1095)	1895 (934)	1929 (929)	0.92
RFD_V 0-100 ms ($N{\cdot}s^{-1}$)	2841 (861)	2827 (952)	2757 (927)	2872 (1022)	2794 (1057)	2895 (1036)	0.54
RFD_V 0-150 ms ($N{\cdot}s^{-1}$)	2481 (566)	2441 (636)	2380 (664)	2556 (798)	2481 (798)	2560 (886)	0.38
Electromyographic responses, mean quadriceps							
$RMS{:}M^{-1}$ at PF_V	7.0 (1.9)	6.5 (1.9)	7.0 (2.3)	6.9 (1.6)	6.0 (1.6)	6.5 (1.6)	0.57
$RMS{:}M^{-1}$ 0-50 ms	4.8 (2.8)	5.0 (3.7)	4.7 (3.0)	4.9 (2.6)	4.3 (2.3)	4.6 (2.6)	0.46
$RMS{:}M^{-1}$ 0-100 ms	5.9 (2.2)	5.6 (2.5)	5.4 (2.5)	5.7 (2.4)	5.2 (2.1)	5.4 (2.2)	0.63
$RMS{:}M^{-1}$ 0-150 ms	5.8 (2.0)	5.6 (2.5)	5.4 (2.5)	5.7 (2.2)	5.2 (1.9)	5.4 (2.0)	0.58

Values are mean (SD). n = 14. EMD_V max: electromechanical delay; PF_V: peak force; RFD_V 0-50, 0-100, 0-150ms: average rate of force development over those time intervals; Mean quadriceps $RMS{:}M^{-1}$: average root mean square of EMG activity expressed as a percentage of the M-wave of the VL, VM and RF muscles. *P* values refer to interactions from ANOVA analyses [condition (2) x time (3)].

Table 2. M-wave and twitch contractile properties before (Pre), immediately after (Post) and 1 hour after (Post-1h) the control and whole-body vibration exercise

	Whole-body vibration
Dependent variable	**Pre**
Electro-mechanical responses	
EMD_E max (ms)	13.5 (0.6)
Mechanical responses	
PF_E (N)	130 (38)
Absolute $MRFD_E$ ($N{\cdot}s^{-1}$)	2665 (792)
Normalised $MRFD_E$ ($PF_E{\cdot}s^{-1}$)	20.5 (2.6)
TPT_E (ms)	85.2 (9.2)
HRT_E (ms)	67.2 (7.9)
Electromyographic responses, mean quadriceps	
M-max (mV)	6.1 (1.7)

Values are mean (SD). n = 14. T: significant effect for time; I: significant interaction; EMD_E max: the longer electromechanical delay of the VM, VL and RF PF_E: peak twitch force; $MRFD_E$: maximal rate of twitch force development; TPT_E: time-to-peak tension; HRT_E: half-relaxation time; M-max: average M-wave amplitude for VM, VL and RF. *P* values refer to interactions from ANOVA analyses [condition (2) x time (3)].