Does whole body vibration training affect knee kinematics and neuromuscular control in healthy people?

BORJA SAÑUDO¹, ADRIAN FERIA¹, LUIS CARRASCO¹, MOISÉS DE HOYO¹,
RUI SANTOS^{2,3}, & HUGO GAMBOA^{2,3}

¹University of Seville, Department of Physical Education and Sport, Seville, Spain, ²Plux Wireless Biosignals, Lisbon, Portugal, and ³Universidade Nova de Lisboa, Department of Physics, Lisbon, Portugal

(Accepted 13 July 2012)

Abstract

This study aimed to investigate the effect of whole body vibration (WBV) training on the knee kinematics and neuromuscular control after single-legged drop landings. Surface electromyographic (sEMG) activity of the rectus femoris and hamstring muscles and knee and ankle accelerometry signals were acquired from 42 healthy volunteers. Participants performed three pre-test landings and after a recovery period of three minutes, they completed one set of six bouts of WBV each of one minute duration (30 Hz – 4 mm), followed by a single-leg drop landing. After the WBV intervention no significant changes were observed in the kinematic outcomes measured, although the time to stabilise the lower-limb was significantly lower after the vibration training ($F(8,41) = 6.55$; $P < 0.01$). EMG analysis showed no significant differences in the amplitude of rectus femoris or hamstring muscles after WBV training, however, significant differences in EMG frequency of the rectus femoris were found before ($F(8,41) = 7.595$; $P < 0.01$) and after toe-down ($F(8,41) = 4.440$; $P < 0.001$). Finally, no significant changes were observed in knee or ankle acceleration after WBV. Results suggest that WBV can help to acutely enhance knee neuromuscular control, which may have clinical significance and help in the design of rehabilitation programmes.

Keywords: knee, proprioception, drop landings, injury prevention, electromyography, vibration training

Introduction

Whole body vibration (WBV) is considered an effective training method by which improvements in muscle strength, power or balance (in addition to other physiological benefits) can be obtained (Cardinale & Lim, 2003; Marín & Rhea, 2010a, 2010b). However, there is currently no clear consensus on the mechanisms by which WBV enhances muscle strength or muscle power (Marín & Rhea, 2010a, 2010b). It is hypothesised that the WBV induced strength gains are mainly due to neural factors, such as an increase in the sensitivity of the stretch reflex, which in turn initiates muscle contractions (Rehn, Lidström, Skoglund, & Lindström, 2007). When it is considered that the neuromuscular factors that contribute to knee stability include: active muscle stiffness (Riemann & Lephart, 2002), muscle coactivity (Jordan, Norris, Smith, & Herzog, 2005) and reflexive muscular activation (Dhaheer, Tsoumanis, Houle, & Rymer, 2005), it is reasonable to hypothesise that WBV training could be an effective

somatosensory stimulus; as proprioception has been shown to affect all these variables (Cardinale & Bosco, 2003).

It is accepted that efficient neuromuscular control is essential to maintain dynamic joint stability; and this plays an important role in injury prevention (Blackburn, Bell, Norcross, Hudson, & Engstrom, 2009). Further the effects of WBV on power and strength have been clearly demonstrated, showing positive changes in healthy individuals for muscle strength and electromyographic (EMG) activity (Adams et al., 2010; Bazett-Jones, Finch, & Dugan, 2008; Bullock et al., 2008; Cardinale & Lim, 2003; Jacobs et al., 2009; Jordan, Norris, Smith, & Herzog, 2010; Lamont et al., 2010; Rhea et al., 2009; Roelants, Verschueren, Delecluse, Levin, & Stijnen, 2006; Rønnestad, 2009; Stewart et al., 2009; Wirth, Zurfluh, & Müller, 2011). Torvinen et al. (2002), who investigated the acute residual effects of a single bout of WBV intervention in young subjects also suggested that it was possible to induce transitional positive acute residual effects on muscle performance

and body balance and stated that these improvements were due to a neurogenic adaptation (an increased motoneurons firing rate and a better synchronisation of motor unit activation), which may have occurred in the lower extremities muscles in response to the vibrations. Recently Salmon, Roper, & Tillman (in press) aimed to determine the effects of a single session of WBV on the physical performance of individuals with knee osteoarthritis and it was suggested that neuromuscular enhancement may have occurred in the muscles of the lower extremities in response to vibration, and may also be a primary factor in improving physical performance. However, knowledge of the effectiveness of WBV on sensorimotor function in terms of joint stabilisation is limited and the scientific support for the effects of WBV training on knee proprioceptors is just emerging. The effects of WBV on power and strength have been demonstrated; however, in addition to the acute vibration exercise effects upon knee stabilisation, only Moezy, Olyaei, Hadian, Razi, & Faghihzadeh (2008) compared the effects of WBV training and conventional therapy on knee proprioception and postural stability in people who had anterior cruciate ligament (ACL) reconstruction suggesting that vibration training can be helpful in the rehabilitation after replacement of the ACL by enhancing the accuracy of knee joint proprioception.

It seems that WBV exercise can enhance power output if applied in the correct dose (6 sets of 60 seconds), (Da Silva-Grigoletto, de Hoyo, Sañudo, Carrasco, & García-Manso, 2011). However, it has also been reported that a single exposure to WBV at the frequency and peak to peak displacements commonly used for strength training, had little or no effect on joint position sense at the ankle or knee and no effect on standing balance, in young healthy people (Pollock, Provan, Martin, & Newham, 2011). Others have also found that WBV does not affect performance during more simple balance tasks in young healthy individuals (Rittweger, 2010). Conversely after short-term WBV training programmes lasting 6 weeks or less, muscle strength was reported to be improved, particularly for knee extensor muscles (Colson, Petit, Hébreard, Tessaro, & Pensini, 2009). Mechanical oscillations also seem to improve single-limb standing balance (Melnyk, Kofler, Faist, Hodapp, & Gollhofer, 2008) as neural adaptations in the tibialis anterior muscle have been reported after a single WBV session (Mileva, Bowtell, & Kossev, 2009). Contradictory conclusions regarding the effectiveness of WBV training programmes have been reported in the literature and, to date, only a limited number of studies have investigated the effects of WBV training on knee extensor muscle activation. The findings of these studies are interesting to note. De Ruiter, van der

Linden, van der Zijden, Hollander, & de Haan (2003) and Colson et al. (2009) for example reported that WBV training did not improve voluntary muscle activation, while Jordan et al. (2010) reported decreased voluntary muscle activation of the knee extensors following WBV training. Although one may argue that WBV affects the reflex activity of the lower-limb muscles and thus the neuromuscular control of the knee joint, the likelihood of neural adaptations of the knee extensor muscle after multiple sessions of WBV remains unclear (Petit et al., 2010). Therefore, the aim of the current study is to investigate whether WBV training influences lower-limb muscle activity and knee kinematics and hence the joint stability. We hypothesised that the exposure to WBV would result in increased activation of the agonist and antagonist muscles (i.e. greater stiffness) and therefore decreased vertical ground reaction forces (GRFs) and knee flexion angles. We also hypothesised that there would be lower knee and ankle acceleration following WBV and therefore increased knee joint control.

Methods

Participants

Fifty-one students from the University of Seville were invited by mail and by word of mouth to participate in the study. Nine were excluded from the study due to schedule incompatibility (7), anterior cruciate ligament injury (1) or recent arthroscopic surgery (1), therefore forty-two healthy volunteers (age: 23 ± 3 years; weight: 71.93 ± 11.33 kg; height: 1.74 ± 1.06 m) were recruited for this study. Medical histories were reviewed by a physician to assess suitability for the study. Subjects with musculoskeletal conditions (including fracture or injury) were excluded. After being fully informed about the purpose of the experiments, each participant gave written informed consent. All procedures were approved by the University of Seville's Research Ethics Committee.

Outcome measures

Surface electromyographic activity. EMG signals of the dominant leg were collected in accordance with the guidelines of SENIAM (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles) Project (Hermens et al., 1999). To acquire the rectus femoris signal, self-adhesive bipolar surface electrodes (diameter: 1.5 cm, inter-electrode distance: 3 cm; Blue Sensor, Medicotest A/S, Olstykke, Denmark) were placed half way along the line from the anterior superior iliac spine to the superior part of the patella. For recording the hamstrings EMG signals, the

electrodes were placed approximately half the distance from the gluteal fold to the back of the knee (semitendinosus/semimembranosus muscles). The reference electrode was placed over the patella. Signals were acquired using surface EMG sensors (emgPLUX, PLUX- Wireless Biosignals, S.A., Lisbon, Portugal), with a passing band between 25 Hz and 500 Hz. The sensors were connected to a wireless signal acquisition unit (PLUX- Wireless Biosignals, S.A., Lisbon, Portugal).

EMG signals (sampled at 1000 Hz) were first processed removing the y axis offset, by subtracting its mean value. A band-stop filter was applied centred on 50 Hz, with a stop band of 2 Hz, to remove possible noise due to electronic devices interference. The signals were then rectified and normalised to the respective maximum value. A smoothing filter with a moving average window of 400 ms was then applied. Activation areas were determined as those where the resultant signal had an amplitude bigger than 10% of the maximum of the EMG signal prior to rectification.

For both rectus femoris and hamstrings, EMG signal pre-activation periods (pre2500; beginning 2500 ms prior to toe-down), and post-activation periods (pos1500; beginning 1500 ms after toe-down), were defined. The duration of those periods was set to 500 ms. In each drop the Root Mean Square (RMS) of the EMG signals, were computed in each period. After obtaining the signal frequency spectra, by applying the Fast Fourier Transform algorithm, the respective mean frequency values were also calculated.

Acceleration. Tri-axial accelerometers (xyzPLUX, PLUX-Wireless Biosignals, S.A., Lisbon, Portugal) were used to measure accelerations of each participant's ankle and knee, within a range of ± 3 g. These sensors were connected to a wireless signal acquisition unit (PLUX- Wireless Biosignals, S.A., Lisbon, Portugal). Acceleration signals were sampled at 1000 Hz. Accelerometers were placed onto the skin at lateral condyle level and at the lateral malleolus level, orientated so their x axes were pointing upward. Acceleration signals provided information related to participants' knee and ankle oscillations. Signals were pre-processed to exclude the influence of gravity. In order to consider only vibration-induced muscle displacements, the signals provided by the accelerometer were low-pass filtered by the application of a smoothing filter with a moving average window of 10 points. Medial-Lateral (ML) and Antero-Posterior (AP) axis acceleration signals were considered for both knee and ankle joints. After computing the maximum values of each signal, in both axes, acceleration periods (60 ms) from knee and ankle signals were defined in both axes after

these maximums (AP_pos60 and ML_pos60). Signals were rectified and then the mean values were computed.

Drop landings. Participants performed 3 single-legged drop landings from a 30-cm platform onto a force plate (MuscleLab, Ergotest, Langesund, Norway), set at a sampling rate of 600 Hz. The force plate was used to measure vertical GRFs and to indicate time phases of initial ground contact (PF1) with the maximum vertical GRF (PF2) acting as key reference points for kinematic analyses. The force plate was also used to determine the time to stabilise the lower-limb (defined as the eccentric contact time). Peak GRF during landing was defined as the highest value attained from the force-time record for the landing phase (Ebben, Vanderzanden, Wurm, & Petushek, 2010). Participants, who wore no shoes to avoid possible influence on the landing phase, were required to cross their arms over their chest and begin each trial in single-limb stance on the dominant leg. They then dropped off the platform and landed on the force plate using the same leg. Data were sampled and processed using a dedicated PC system (MuscleLab, Ergotest, Langesund, Norway).

Whole body vibration procedures. All participants were familiarised with the vibrating platform (Power Plate, Amsterdam, Netherlands) and the proper positioning. During the test the participants were instructed to stand with bent knees and hips on the platform (with a 100° knee flexion) controlled by an electronic goniometer (Biometrics Ltd., Newport, United Kingdom). WBV stimulus was induced to the plantar surfaces of the feet at a frequency of 30 Hz and a peak-to-peak displacement of 4 mm, considered the optimal combination for muscle activation response (Da Silva-Grigoletto et al., 2011).

Joint kinematics. Three reflective markers were placed over the lateral malleolus, lateral condyle and greater trochanter. The two-dimensional sagittal-plane-projection angle of knee was measured during all tasks. A digital video camera (sampling frequency of 50 Hz) was placed at the height of the participant's knee, at a distance of 2 m from the participant's landing target and aligned perpendicularly to the sagittal plane. The digital images were imported into a digitising software program (Quintic 4, Quintic Consultancy Ltd., United Kingdom). Knee flexion angles were calculated during touch-down (angle 1) and when the maximal GRF was reached (angle 2).

Procedures

All measurements were conducted at the same time of the day (± 1 h) by the same research assistant.

All participants performed a habituation and testing session, they were also instructed on, and provided with a demonstration of, the correct performance of the drop exercise to be assessed during the test session (all with the dominant leg). All tests were preceded by a 5-min warm-up consisting of cycling on a cycloergometer (Ergoline 900, Ergometrics, Bitz, Germany) at 60 W (60 rpm). The warm-up was followed by 5 counter-movement jumps (CMJ) of increasing intensity and then repeated jumps were executed until they demonstrated the correct performance of the technique, in order to control motor learning effects. As illustrated in Figure 1 the experiment was developed in two phases.

In phase one participants performed the first single-leg drop landing onto a squared zone (50 x 40 cm) delimited into the force plate. After 1 min recovery this action was repeated twice (again with 1 min recovery between trials). After 3 min recovery participants were placed on the vibrating platform and completed one bout of 1 min WBV (30 Hz – 4 mm). Immediately after the vibration participants again performed the single-leg drop landing. During the second phase participants repeated the drop landing five times after the same WBV training, to complete the aforementioned one set of six bouts.

Statistical analysis

Normality of the data was checked and subsequently confirmed using the Kolmogorov–Smirnov test. Means and standard deviations (s) were calculated for each variable. Changes in the dependent variables over time within groups and differences between groups at the same time points were evaluated using repeated-measures analysis of variance (ANOVA) with corresponding post hoc Bonferroni corrected t-tests. Statistical significance was assumed at $P < 0.05$.

Results

Kinetic and kinematic analysis

Participants reached PF1 values between 1657.10 ± 534.25 N and 1973.14 ± 734.19 N while the PF2 was between 4884.81 ± 1420.47 and 5235.81 ± 1625.48 N (Table I). Two-way ANOVA testing revealed no significant differences with respect to vertical GRFs (All $P > 0.05$). No significant changes were observed for any of the angles measured ($P > 0.05$; Table I).

The time to stabilise the lower-limb was significantly lower after the vibration training ($F(8,41) = 6.55$; $P < 0.01$) but significant time effects were

Figure 1. Schematic illustration of testing protocol.

Table I. Vertical ground reaction forces and the correspondent kinematic data during 30-cm drop landing before and after WBV.

	Pretest1	Pretest2	Pretest3	Bout1	Bout2	Bout3	Bout4	Bout5	Bout6
PF1 (N)	1809.64 (602.99)	1711.36 (666.57)	1878.74 (778.49)	1973.14 (734.19)	1733.02 (658.42)	1678.94 (674.64)	1811.90 (719.07)	1657.10 (534.25)	1857.03 (648.96)
PF2 (N)	5235.81 (1625.48)	5043.19 (1452.27)	4980.90 (1623.68)	5011.09 (1660.51)	5016.90 (1483.67)	4984.07 (1481.54)	4884.81 (1420.47)	4965.45 (1456.01)	4992.55 (1769.79)
T _{stab} (s)	1.97 (0.61)	1.94 (0.63)	1.96 (0.56)	1.70 (0.46)	1.72 (0.62)	1.58 (0.40)	1.53 (0.37)	1.68 (0.59)	1.43 (0.31)
Angle1 (°)	31.21 (7.52)	33.60 (9.11)	34.93 (11.28)	32.33 (7.67)	33.62 (10.30)	35.83 (6.96)	33.22 (8.50)	34.69 (7.64)	34.33 (6.91)
Angle2 (°)	53.02 (8.55)	53.86 (6.83)	54.05 (8.69)	54.14 (8.06)	54.36 (8.00)	51.02 (16.79)	53.55 (8.04)	54.69 (8.87)	52.69 (8.24)

Data are reported as Mean (s); PF1 = First peak vertical force value; PF2 = Second peak vertical force value; T_{stab} = Time to stabilise the lower-limb; Angle1 = Knee flexion angle in touchdown; Angle2 = Knee flexion angle when the maximal vertical ground reaction force was reached.

observed mainly in the third ($P = 0.004$), fourth ($P < 0.001$) and sixth bout ($P < 0.001$) as reported in Figure 2.

EMG activity and acceleration in the lower-limb

EMG analysis showed that there were no significant differences in the mean rectified amplitude of rectus femoris and hamstring signals between pre and post-tests either before or after activation. When repeated measurements were performed there were no significant differences in RMS after WBV in any of the attempts (Table II). However, significant differences in the EMG frequency of rectus femoris were found before ($F(8,41) = 7.595$; $P < 0.01$; Figure 3) and 1500 ms after to toe-down ($F(8,41) = 4.440$; $P < 0.001$; Figure 4) although this response could not be found in the hamstring muscles. This EMG

Figure 2. Time to stabilise the lower-limb (s). * $P < 0.05$.

Figure 3. EMG frequency 2500 ms prior to toe-down in RF. * $P < 0.05$.

Figure 4. EMG frequency 1500 ms after toe-down in RF. * $P < 0.05$.

Table II. EMG activity during 30-cm drop landing before and after WBV.

	Pretest1	Pretest2	Pretest3	Bout1	Bout2	Bout3	Bout4	Bout5	Bout6
RMS_pre2500_RF	0.006 (0.005)	0.006 (0.005)	0.007 (0.007)	0.011 (0.008)	0.013 (0.019)	0.009 (0.007)	0.009 (0.007)	0.010 (0.008)	0.013 (0.019)
Freq_pre2500_RF	177.710 (34.332)	179.553 (33.114)	176.359 (36.313)	151.490 (28.947)	148.456 (30.084)	154.725 (23.888)	157.030 (27.815)	149.118 (29.282)	153.083 (28.064)
RMS_pre2500_H	0.018 (0.021)	0.016 (0.013)	0.017 (0.017)	0.020 (0.014)	0.025 (0.035)	0.021 (0.019)	0.022 (0.022)	0.031 (0.033)	0.031 (0.037)
Freq_pre2500_H	135.579 (4.697)	135.375 (4.603)	135.551 (5.291)	135.083 (5.174)	134.757 (6.170)	135.909 (4.927)	135.266 (5.105)	135.451 (6.746)	136.752 (4.927)
RMS_pos1500_RF	0.0301 (0.019)	0.0362 (0.025)	0.0405 (0.034)	0.0595 (0.091)	0.0500 (0.039)	0.0417 (0.032)	0.0453 (0.038)	0.0441 (0.035)	0.0423 (0.030)
Freq_pos1500_RF	136.092 (13.985)	136.389 (13.421)	133.627 (16.320)	127.163 (14.752)	125.058 (13.641)	127.313 (13.435)	126.543 (10.576)	126.851 (13.444)	129.580 (14.965)
RMS_pos1500_H	0.047 (0.036)	0.071 (0.077)	0.069 (0.072)	0.086 (0.082)	0.085 (0.087)	0.070 (0.052)	0.069 (0.062)	0.077 (0.066)	0.074 (0.053)
Freq_pos1500_H	138.170 (8.932)	138.132 (5.699)	137.111 (6.751)	141.281 (16.017)	137.667 (6.904)	138.235 (5.643)	141.388 (19.705)	138.295 (5.411)	139.725 (12.735)

Data are reported as Mean (s); RMS_pre2500: pre-activation amplitude (2500 ms before to the toe-down); Freq_pre2500: pre-activation frequency values; RMS_pos1500: pos-activation amplitude (1500 ms after to the toe-down); Freq_pos1500: pos-activation frequency values; RF: Rectus femoris; H: Hamstrings.

frequency was significantly lower after WBV in all ($P < 0.05$) but the fourth bout ($P = 0.05$) 2500 ms before activation. Significant differences were also found in the second, fourth and fifth bouts. There were no significant differences regarding the frequency in hamstring muscles after WBV training.

Finally, no significant changes were observed for the acceleration of the knee or ankle in any of the bouts or axes (Table III).

Discussion

The role of neuromuscular training in knee motor control is well recognised although few authors have assessed the efficacy of acute vibration exercise effects. Therefore the aim of this study was to investigate the effect of a single exposure to a standard WBV training session on the knee stability of healthy athletes. The major findings of this study were that the time to stabilise the lower-limb was significantly lower after WBV and the EMG frequency signal of the rectus femoris before and after the ground contact was also significantly lower after WBV.

These results contrast with that previously reported by Pollock et al. (2011) indicating that a single exposure to WBV had little or no effect on joint position sense at the ankle and knee or standing balance. Although these authors did not find any meaningful change in balance after a single bout of WBV, authors such as Brunetti et al. (2006) showed that vibratory treatment based on sequences of sinusoidal mechanical oscillations improved the single-limb standing balance and Melnyk et al. (2008) also reported the positive effects of WBV on knee joint stability.

While it is beyond the scope of this study the results that have been found may be attributed to the activation of the sensory proprioceptive system following WBV training (Brunetti et al., 2006). Improvements in joint stability following WBV may

also be due to better central processing of afferent signals (Cardinale & Bosco, 2003). WBV seems to affect muscle spindle primary afferent fibres which in turn leads to better knee stability; this may be one of the possible explanations of our results. However, muscle twitch or reflex activity was not measured in this study; consequently we are unable to speculate further on the mechanism involved with improving stability following WBV in healthy subjects.

In the current study, in order to determine activation and neural adaptations, the surface EMG activity of agonist and antagonist knee muscles was assessed. Previous studies have demonstrated that reflex activity in the hamstring muscles in response to a perturbation of the knee may play an important role in stabilising this joint, suggesting a direct relationship between reflex activity and knee stability (Melnik et al., 2008). However in the current study the hamstring muscles did not benefit from the WBV stimulus. It is not easy to determine whether these EMG patterns can be attributed to an adaptation of the WBV or even to muscle fatigue. A possible explanation of these results could be that muscle fatigue resulted in decreased motor unit activity and consequently decreased surface EMG signal throughout a fatiguing contraction (Merletti, Rainoldi, & Farina, 2001). In fact, Rittweger, (2010) attributed these effects during vibration to high threshold motor units with depict rapid fatigue and which contribute largely to the inhibitory effects of vibration (pre-synaptic inhibitory mechanism). Although in the present study the role of muscle fatigue was not investigated, one cannot discount the possibility of fatigue occurring.

Despite there being no effect observed in the EMG frequency of the hamstring muscles, the response in the rectus femoris was lower after WBV. EMG frequency analysis indicates how fast the myoelectric activity of muscle changes and therefore, any variation in motor unit activity indicates that WBV resulted in changes in conduction velocity or perhaps

Table III. Acceleration data during 30-cm drop landing before and after WBV.

	Pretest1	Pretest2	Pretest3	Bout1	Bout2	Bout3	Bout4	Bout5	Bout6
AP_pos60_Knee	1.734 (0.463)	1.620 (0.432)	1.597 (0.430)	1.692 (0.399)	1.665 (0.410)	1.674 (0.394)	1.649 (0.456)	1.657 (0.498)	1.540 (0.484)
ML_pos60_Knee	1.397 (0.350)	1.439 (0.377)	1.494 (0.441)	1.435 (0.450)	1.384 (0.430)	1.484 (0.472)	1.470 (0.436)	1.370 (0.412)	1.433 (0.412)
AP_pos60_Ankle	2.233 (0.468)	2.274 (0.457)	2.312 (0.366)	2.316 (0.419)	2.403 (0.412)	2.398 (0.395)	2.379 (0.415)	2.331 (0.532)	2.381 (0.528)
ML_pos60_Ankle	0.908 (0.299)	0.884 (0.274)	0.902 (0.290)	0.943 (0.314)	0.897 (0.265)	0.907 (0.267)	0.957 (0.295)	0.928 (0.258)	0.904 (0.305)

Data are reported as Mean (s); AP_pos60_Knee: Knee acceleration 60 ms after the ground contact for the Antero-Posterior axis; ML_pos60_Knee: Knee acceleration 60 ms after the ground contact for the Medial-Lateral axis; AP_pos60_Ankle: Ankle acceleration 60 ms after the ground contact for the Antero-Posterior axis; ML_pos60_Ankle: Ankle acceleration 60 ms after the ground contact for the Medial-Lateral axis.

synchronisation activity of rectus femoris. Our data may indicate that the underlying mechanisms responsible for the stabilisation mainly involved peripheral muscle adaptations. This is consistent with the enhancements in muscle strength and power observed after WBV as reported by Bosco et al. (2000). This can be attributed to more efficient neuromuscular coordination based on an increase in the synchronisation activity of the motor units which is consistent with the EMG activity reported in the present study. A possible explanation of our results after WBV might be due to a remodelling of the central balance control circuits but not to strength gains.

In addition, a novel finding of the current study is that no significant changes were observed for the acceleration signals in the AP and ML axes of the knee or ankle after any of the bouts of WBV. Although Myer, Ford, Brent, & Hewett (2007) found significant improvements in peak knee abduction torque in “high risk” athletes compared to in “low risk” athletes after a neuromuscular training programme, to our knowledge this is the first study analysing knee and ankle oscillations after a WBV session. Dynamic stability of the knee joint depends on the ability to react quickly to sudden situational changes (von Porat, Henriksson, Holmström, & Roos, 2007), and although this study has demonstrated that WBV training can improve knee stability more research is needed to determine the efficacy of WBV as protective mechanism to avoid excessive abduction displacement of the joint.

Different WBV settings can lead to different results; in fact high frequencies or durations of the vibration may impair proprioception (Weerakkody, Mahns, Taylor, & Gandeiva, 2007) and higher WBV frequencies seem to produce a higher EMG signal than others (Cardinale & Lim, 2003). The peak to peak displacement, frequency and duration used in the current study (30 Hz – 4 mm) were selected based on a recent manuscript of Da Silva-Grigoletto et al. (2011). This combination was considered to be the most appropriate vibratory training stimuli to obtain the greatest muscular response. This is in accordance with Marín and Rhea, (2010a, 2010b) suggesting that the higher the WBV frequency and peak-to-peak displacement, the greater the strength and power gains are. This study does have some limitations. First, the present study was performed in a controlled laboratory environment where participants knew exactly what to expect, the study therefore does not accurately simulate the athletic environment. Another limitation may be that the hip was not analysed; therefore prospective kinematic studies will help to clarify the importance of the hip in the athlete. Finally, the present study wanted to investigate whether WBV training may acutely

influence joint stability; however it is not clear how the changes found after the successive 1-min periods of WBV exposure can lead to training effects. Further study on the effects of neuromuscular training is important for the advancement of injury prevention and safe participation in athletics.

In summary, this study demonstrated that knee kinematics and neuromuscular responses can be improved with WBV, probably due to an increase in muscle synchronisation activity which has been suggested to reduce the rate of injuries in this particular joint. The results of this study may have clinical significance and be particularly important in the design of rehabilitation programmes.

References

- Abercromby, A. F. J., Amonette, W. E., Layne, C. S., McFarlin, B. K., Hinman, M. R., & Paloski, W. H. (2007). Variation in neuromuscular responses during acute whole-body vibration exercise. *Medicine and Science in Sports and Exercise*, 39, 1642–1650. 760
- Bazett-Jones, D. M., Finch, H. W., & Dugan, E. L. (2008). Comparing the effects of various whole-body vibration accelerations on counter-movement jump performance. *Journal of Sports Science and Medicine*, 7, 144–150. 765
- Blackburn, J. T., Bell, D. R., Norcross, M. F., Hudson, J. D., & Engstrom, L. A. (2009). Comparison of hamstring neuromechanical properties between healthy males and females and the influence of musculotendinous stiffness. *Journal of Electromyography and Kinesiology*, 19, e362–369. 770
- Bosco, C., Iacovelli, M., Tsarpela, O., Cardinale, M., Bonifazi, M., Viru, M., et al. (2000). Hormonal responses to whole-body-vibration in men. *European Journal of Applied Physiology*, 81, 449–454. 775
- Brunetti, O., Filippi, G. M., Lorenzini, M., Liti, A., Panichi, R., Roscini, M. et al. (2006). Improvement of posture stability by vibratory stimulation following anterior cruciate ligament reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy*, 14, 1180–1187. 780
- Cardinale, M., & Bosco, C. (2003). The use of vibration as an exercise intervention. *Exercise and Sport Sciences Reviews*, 31, 3–7. 785
- Cardinale, M., & Lim, J. (2003). Electromyography activity of vastus lateralis muscle during whole-body vibrations of different frequencies. *Journal of Strength and Conditioning Research*, 17, 621–624. 790
- Cochrane, D. J., Loram, I. D., Stannard, S. R., & Rittweger, J. (2009). Changes in joint angle, muscle-tendon complex length, muscle contractile tissue displacement, and modulation of EMG activity during acute whole-body vibration. *Muscle & Nerve*, 40, 420–429. 795
- Colson, S. S., Petit, P. D., Hébreard, L., Tessaro, J., & Pensini, M. (2009). Whole body vibration does not enhance muscle activation. *International Journal of Sports Medicine*, 30, 841–844. 800
- Da Silva-Grigoletto, M. E., de Hoyo, M., Sañudo, B., Carrasco, L., & García-Manso, J. M. (2011). Determining the optimal whole-body vibration dose–response relationship for muscle performance. *Journal of Strength and Conditioning Research*. In press. 805
- De Ruiter, C. J., van der Linden, R. M., van der Zijden, M. J., Hollander, A. P., & de Haan, A. (2003). Short-term effects of whole body vibration on maximal voluntary isometric knee extensor force and rate of force rise. *European Journal of Applied Physiology*, 88, 472–475. 810

- Dhaher, Y. Y., Tsoumanis, A. D., Houle, T. T., & Rymer, W. Z. (2005). Neuromuscular reflexes contribute to knee stiffness during valgus loading. *Journal of Neurophysiology*, 93, 2698–2709.
- Ebben, W. P., Vanderzanden, T., Wurm, B. J., & Petushek, E. J. (2010). Evaluating plyometric exercises using time to stabilization. *Journal of Strength and Conditioning Research*, 24, 300–306.
- Hermens, H. J., Freriks, B., Merletti, R., Stegeman, D., Blok, J., Rau, G., et al. (1999). *European recommendations for surface electromyography, results of SENIAM project* (8th ed.). Enschede: Roessingh Research and Development.
- Jordan, M. J., Norris, S. R., Smith, D. J., & Herzog, W. (2005). Vibration training: An overview of the area, training consequences, and future consideration. *Journal of Strength and Conditioning Research*, 19, 459–466.
- Jordan, M. J., Norris, S., Smith, D., & Herzog, W. (2010). Acute effects of whole-body vibration on peak isometric torque, muscle twitch torque and voluntary muscle activation of the knee extensors. *Scandinavian Journal of Medicine and Science in Sports*, 20, 535–540.
- Marín, P. J., & Rhea, M. R. (2010a). Effects of vibration training on muscle power: A meta-analysis. *Journal of Strength and Conditioning Research*, 24, 871–878.
- Marín, P. J., & Rhea, M. R. (2010b). Effects of vibration training on muscle strength: A meta-analysis. *Journal of Strength and Conditioning Research*, 24, 548–556.
- Melnik, M., Kofler, B., Faist, M., Hodapp, M., & Gollhofer, A. (2008). Effect of a whole-body vibration session on knee stability. *International Journal of Sports Medicine*, 29, 839–844.
- Merletti, R., Rainoldi, A., & Farina, D. (2001). Surface electromyography for noninvasive characterization of muscle. *Exercise and Sport Sciences Reviews*, 29, 20–25.
- Mileva, K. N., Bowtell, J. L., & Kossev, A. R. (2009). Effects of low-frequency whole-body vibration on motor-evoked potentials in healthy men. *Experimental Physiology*, 94, 103–116.
- Moezy, A., Olyaei, G., Hadian, M., Razi, M., & Faghihzadeh, S. (2008). A comparative study of whole body vibration training and conventional training on knee proprioception and postural stability after anterior cruciate ligament reconstruction. *British Journal of Sports Medicine*, 42, 373–378.
- Myer, G. D., Ford, K. R., Brent, J. L., & Hewett, T. E. (2007). Differential neuromuscular training effects on ACL injury risk factors in “high-risk” versus “low-risk” athletes. *BMC Musculoskeletal Disorders*, 8, 39.
- Petit, P. D., Pensini, M., Tessaro, J., Desnuelle, C., Legros, P., & Colson, S. S. (2010). Optimal whole-body vibration settings for muscle strength and power enhancement in human knee extensors. *Journal of Electromyography and Kinesiology*, 20, 1186–1195.
- Pollock, R. D., Provan, S., Martin, F. C., & Newham, D. J. (2011). The effects of whole body vibration on balance, joint position sense and cutaneous sensation. *European Journal of Applied Physiology*. In press.
- Rehn, B., Lidström, J., Skoglund, J., & Lindström, B. (2007). Effects on leg muscular performance from whole-body vibration exercise: A systematic review. *Scandinavian Journal of Medicine and Science in Sports*, 17, 2–11.
- Riemann, B. L., & Lephart, S. M. (2002). The sensorimotor system, part I: The physiologic basis of functional joint stability. *Journal of Athletic Training*, 37(1), 71–79.
- Rittweger, J. (2010). Vibration as an exercise modality: How it may work, and what its potential might be. *European Journal of Applied Physiology*, 108, 877–904.
- Roelants, M., Verschueren, S. M. P., Delecluse, C., Levin, O., & Stijnen, V. (2006). Whole-body-vibration-induced increase in leg muscle activity during different squat exercises. *Journal of Strength and Conditioning Research*, 20, 124–129.
- Salmon, J. R., Roper, J. A., & Tillman, M. D. (in press). Does acute whole body vibration training improve the physical performance of people with knee osteoarthritis? *Journal of Strength and Conditioning Research*, Nov 29.
- Torvinen, S., Sievänen, H., Järvinen, T. A., Pasanen, M., Kontulainen, S., & Kannus, P. (2002). Effect of 4-min vertical whole body vibration on muscle performance and body balance: A randomized cross-over study. *Journal of Sports Medicine*, 23, 374–379.
- Trans, T., Aaboe, J., Henriksen, M., Christensen, R., Bliddal, H., & Lund, H. (2009). Effect of whole body vibration exercise on muscle strength and proprioception in females with knee osteoarthritis. *Knee*, 16, 256–261.
- von Porat, A., Henriksson, M., Holmström, E., & Roos, E. M. (2007). Knee kinematics and kinetics in former soccer players with a 16-year-old ACL injury—the effects of twelve weeks of knee-specific training. *BMC Musculoskeletal Disorders*, 17, 35.
- Weerakkody, N. S., Mahns, D. A., Taylor, J. L., & Gandevia, S. C. (2007). Impairment of human proprioception by high-frequency cutaneous vibration. *Journal of Physiology*, 15, 971–980.
- Wirth, B., Zurfluh, S., & Müller, R. (2011). Acute effects of whole-body vibration on trunk muscles in young healthy adults. *Journal of Electromyography and Kinesiology*, 21, 450–457.
- Wojtys, E. M., Wylie, B. B., & Huston, L. J. (1996). The effects of muscle fatigue on neuromuscular function and anterior tibial translation in healthy knees. *The American Journal of Sports Medicine*, 24, 615–621.