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The effects of whole body vibration on humans: Dangerous or advantageous?

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The effects of whole body vibration (WBV) have been studied extensively in occupational medicine. In particular, it has been shown that when the body undergoes chronically to whole body vibrations spinal degeneration is likely to be one of the deleterious outcomes. Low back pain has been shown to be the leading major cause of industrial disability in the population under the age of 45 years and has been linked to whole body vibration exposure encountered in some industrial settings. Whole body vibration has been recently purposed as an exercise intervention suggesting its effectiveness in increasing force-generating capacity in lower limbs and low back. It has also been reported to be an effective non-pharmacological intervention for patients with low back pain. Relatively short exposure to whole body vibration has been also shown to increase the serum levels of testosterone and growth hormone. The combined effects on the neuromuscular system and endocrine system seem to suggest its effectiveness as a therapeutic approach for sarcopenia and possibly osteoporosis. Due to the danger of long-term exposure to whole body vibration, it is important to develop safe exercise protocols in order to determine exercise programs for different populations.

Keywords: whole body vibration, occupational medicine, spinal degeneration, testosterone, growth hormone

The shaking of the human body by means of vibration should be expected to cause complex physiological responses. Vibration applied to the body or parts of it is likely to produce a series of consequences due to the particular features of the human biological system. Those consequences are related to the fact that human body is able to perceive vibratory stimuli and respond in a highly specific manner to such stimuli. Vibrations can produce very different responses ranging from beneficial to dangerous. For a better understanding of vibrations, it is important to define the mechanical parameters

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characterising them. This is helpful in order to understand how each part of the body moves under vibrating stimuli, and how this motion can affect human's biological system.

Vibration is an oscillatory motion. The extent of this motion determines the magnitude of the vibration and the repetition rate of the cycles of oscillation determines the frequency of the vibration (measured in Hz (24)). Oscillatory motion can be produced in different forms: sinusoidal, multi-sinusoidal, random, stationary and transient. With all those parameters determining the vibration output, it is understandable how wide the possibility of studying the effects of whole body vibration exposure. Only with sinusoidal motion it is possible to analyse the effects of different vibration frequencies due to the deterministic characteristics of this motion.

Sinusoidal motion is a periodic motion, which repeats itself identically for a certain time interval termed period. The frequency of this motion is given by the reciprocal of the period and is expressed as cycles of motion per second. The S.I. unit currently utilised to define the frequency of a vibration is Hertz (Hz).

It is now important to distinguish between different types of vibrations based upon how they are applied. It is in fact possible to differentiate between whole body vibrations (WBV) and locally applied vibrations. The first is usually said to occur when the whole body is undergoing motion and the effect is not local. The second is said to occur when a single part of the body is undergoing motion (i.e. a specific limb). Vibration can produce a variety of effects.

The large effects of WBV are mainly due to the fact that the human body is a complex biomechanical and physiological structure characterised by rigid and wobbling masses, which are all affected by a sinusoidal motion (16). When the body undergoes WBV, all the internal organs, muscles and the skeleton are exposed to the vibratory stimulus. For this reason, specific physiological responses have been identified following different vibration stimuli. To date, WBV has been extensively studied in occupational medicine, since it has been shown to cause unwanted effects. However, it should be pointed that vibration is not always to be avoided. In fact, recent evidence seems to suggest the positive effects of WBV on musculo-skeletal interactions and opens interesting perspective for its application as an effective non-pharmacological intervention for the prevention and cure of sarcopenia and osteoporosis. The aim of this work was to review the danger and the positive effects of WBV analysing its possible use as an exercise intervention.

Whole body vibration and spinal disorders

Low back pain (LBP) is the leading major cause of industrial disability in the population under the age of 45 years. Work-related risk factors are important and thus have some potential for prevention (15). There is an extensive literature relating exposure to WBV to LBP and various spinal disorders (15, 21, 22, 37, 62). Dupuis and Christ (19) found that, of those with greater than 700 tractor driving hours per year, 61% had pathological radiographic changes of the spine, of those with 700–1200 hours, 68% were affected and with greater than 1200 driving hours, 94% were affected. Low back pain paralleled pathological changes. Hilfert et al. (30) found that in drivers of earth moving equipment, a clear trend of greater pathological changes on radiographs was seen in the exposed group. The prevalence increased with age. Similar trends were found by Barbaso (1) in bus drivers.

Pope et al. (50) studied the response to vibration, as measured by transducers rigidly fixed to the lumbar spinous processes. The outcome measure was the transmissibility and phase angle between the pin acceleration and that of the platform. In Pope et al. (51) tests are described in which a subject is placed in different controlled sitting postures, and the transmissibility and phase angle determined. It was found that there is a reproducible resonant frequency in the range of 4–5 Hz depending on posture. At the resonant frequency the forces in the spine have been shown to be higher.

The phasic activity of the erector spinae muscles were measured in subjects who were free of low back pain (67). The relationship of the electromyographic signal to a given torque demand on subjects was found by measuring EMG while performing an isometric pull. The signals were high-pass filtered, rectified and ensemble-averaged. The ensemble-averaged signals were then converted to torque using the EMG-torque calibration. From these data, the time lag between the seat vertical position and the peak EMG activity varied from 30 ms to 100 ins at 3 Hz, and 70 ms to 100 ms at 10 Hz. At 10 Hz there was a trend for the muscle contraction again becoming in phase (or 360° out of phase) with the input signal. At all other frequencies, it was out of phase.

A frequency shift, towards lower frequencies has also been shown as an effect of fatiguing contractions. The development of fatigue was studied through the analysis of the EMG signals from contracting back muscles (28, 40). EMG signals were recorded using surface electrodes, were amplified and filtered, and subjected to spectral analysis. To ensure muscular activity, the subjects sat in a forwardly bent position, carrying extra weight on the front of the chest. In this position, the subjects were exposed to 1) WBV of 5 Hz and 0.2 g root-mean-square (r.m.s.) acceleration, and 2) static sitting. Root-mean-square values and mean frequencies for each subject, and each exposure condition, were calculated. The mean frequency of the EMG signals obtained from the erector spinae muscles, at both the thoracic and lumbar level, decreased with time (28, 40). The decrease was accentuated by WBV at 5 Hz. Prolonged exposure to vibration has also been shown to determine structural changes to the spine. Spinal height changes were measured by means of a stadiometer (41). The column was equipped with supports for the head and the pelvis, as well as four pressure sensitive switches, which functioned as posture controls. The posture of the head was controlled. Height changes were measured in subjects exposed to static unsupported sitting and seated whole body vibrations. The WBV input was 5 Hz frequency and 0.1 g r.m.s. acceleration. Exposure time was five minutes, and the intermissions between the exposure periods were twenty minutes of lying supine. Each subject attended two sessions on different days. The effect of backrest inclination on spine height changes during seated WBV was tested (42). The backrest inclinations tested were 110° and 120°. Comparisons were made with the unsupported sitting in a previous study with the same subjects.

Height loss was demonstrated in all the subjects, and was significant for both WBV and static sitting but a larger height loss was demonstrated when the subjects were exposed to vibration. Backrest inclination angles of 110° and 120° caused significantly less height loss than upright unsupported sitting (42).

In another series of studies we measured biochemical changes due to WBV (52). The von Willebrand factor (vWf) is a complex protein whose release is a marker for endothelial damage; serum levels of its antigen (vWFAg) can be used as a marker for such changes. The hypotheses tested were that back discomfort and serum vWF levels would increase after WBV but would recover after a period of rest. Subjects acted as their own controls. We measured the levels of back discomfort and vWFAg in subjects following 25-min periods of (1) lying down, (2) sitting still, (3) vibrating whilst sitting at 5 Hz at 3.5 m/s^2 and (4) sitting still. The WBV exposure was at the level of the ISO 2631 fatigue decreased proficiency limit (33).

Back discomfort and vWF levels were significantly increased following sitting upright, compared with lying flat, and increased further following WBV. They fell thereafter with a period of sitting still upright. These results demonstrate that WBV has a significant effect in increasing back discomfort and the serum levels of vWFAg, and it is possible that WBV may induce vascular changes (52).

Beneficial vibrations

The possibility of using vibrations as an effective exercise intervention can be considered a recent idea. However, it should be pointed that already Whedon et al. (73) reported some positive effects of oscillating beds on plaster-immobilised patients. Mechanical vibrations applied to the whole body are a means for increasing the gravitational load imposed on the neuromuscular system. Mechanical vibrations have been applied to the whole body by means of vibrating platforms (3, 5–7) and locally by means of (26), vibrating dumbbells (4) and vibrating cables (34). WBV has been shown to determine specific neuromuscular and hormonal responses. In fact, only recently it has been shown that ten days of whole body vibration used as an exercise intervention can be beneficial to improve neuromuscular performance (3). A total exposure time of 100 minutes in ten days produced significant improvement in vertical jumping ability in well-trained young individuals. The early gains in force-generating capacity were ascribed to an increased neural drive and an improvement of the excitability of spinal reflexes (3).

Three sessions per week of vibration exercise for three weeks were able to enhance isometric torque in seventeen subjects with residual emiplegia (32). The training protocol consisted of five sets of 60s of WBV at 20 Hz with 60s rest between sets. The results showed an increase in isometric torque in uni- and bilateral knee extensions. A recently published randomised controlled trials conducted on fifty-six healthy sedentary volunteers showed significant enhancement of vertical jump and lower limb extension strength following 4 months of WBV exercise (69). In this experiment, the subjects were exposed to vibration exercise 4 minutes per day at a frequency of 25 Hz to 35 Hz. Finally, a chronic program of WBV has been shown to be effective in reducing pain sensation and pain-related disability in patients affected by chronic low back pain (57). Few studies have been currently conducted on long-term exercise programs using vibration, however most of the studies conducted on acute responses to WBV exposure suggest that vibration represents a strong simulation to the sensory-motor pathways. In particular, depending on the characteristics of the vibratory stimulus, it seems that force-generating capacity in human skeletal muscle can be acutely affected. Acute enhancement of force-velocity and power-velocity characteristics of lower limbs have been observed in well-trained female volleyball players undergoing WBV treatments at 30 Hz (5). Vertical jumping ability has been also observed to improve following a total exposure of ten minutes in parallel with increased testosterone and growth hormone production and acute depression of cortisol (7). However, vibration does not seem to be always effective in acutely enhancing performance. In fact, few studies have shown an acute decrease in force-generating capacity. Five sets of one minute each of WBV were shown to determine a 7% decrease in maximal voluntary contraction (MVC) of leg extensors muscles in sedentary subjects (18). A full recovery of MVC was observed after 3 hours. Seven bouts of one minute each of WBV were also shown to acutely decrease vertical jumping ability in well-trained individuals (6). A parallel decrease of Testosterone was also observed suggesting an acute impairment of the hypothalamus-hypophysis-gonads axis. Recently, Rittweger et al. (58) found that squatting while exposed to WBV produced more fatigue as compared to squatting in no-vibration condition. In their experiment, no difference in rate of perceived exertion (RPE) was observed between the treatments, however a marked difference in exercise duration was identified, suggesting that WBV impose more stress on neuromuscular structures.

The acute effects of vibration seem to be connected to the duration of the stimulation, the characteristics of the subjects (well-trained vs. untrained), and the magnitude of the vibration stimulus (amplitude, frequency and acceleration). Notwithstanding the above-mentioned differences identified in the literature, it seems clear that if the vibration stimulus is not too stressful, it is possible to determine an acute enhancement in force-generating capacity due to an improvement in the sensory-motor functions (11, 12). On the other side, prolonged exposure to vibration could determine a transient decrease in neuromuscular performance. The cardiovascular system is also affected by WBV. In a study by Rittwegger et al. (56), vibration up to exhaustion and vibration performing slow squatting with and without an extra weight showed an O_2 uptake of less than 50% of VO_{2max}. Kerschan-Schindl et al. (35) showed an increase by 200% in mean blood flow velocity in the popliteal artery following one bout of WBV exercise at 26 Hz on a commercial vibrating plate.

In light of these preliminary results it appears clear that vibration could represent an effective exercise intervention if the goal is an increase in strength and power performances. Also, the mild effects on the cardiovascular system presented by recent studies supports the idea that vibration exercise could be a beneficial exercise intervention for different populations.

Acute and chronic responses to vibration: central and peripheral neuromuscular aspects

Due to its mechanical characteristics, the vibration stimulus produces fast and short changes in length of the muscle-tendon complex. This perturbation is detected by sensory receptors that modulate muscle stiffness through reflex muscular activation in order to damp the vibratory waves. Mechanical vibrations applied to the muscle belly or tendons have been shown able to elicit a reflex muscle contraction (26). This neuromuscular response has been named "tonic vibration reflex" (TVR) and has been shown to be mediated by mono and polysynaptic pathways (17, 45). Muscle spindle Ia afferents have been indicated as the major determinant of this vibration-induced neuromuscular activation leading to the TVR. It is not known whether it can be elicited by low superimposed vibration frequency (1–30 Hz), even if it has been suggested to occur (66). When vibration is applied to the whole body by means of vibrating plates, the anti-gravitary muscles are highly stimulated. In particular, the EMG activity of the muscles of the lower limbs has been shown to increase when the plate is vibrating (Cardinale and Lim, in press). Unpublished observations from our lab on the EMG activity of superficial muscles of the back have shown the occurrence of the TVR. This suggests that when the body undergoes to vibration, muscle activity is necessary for damping the vibratory waves. This particular feature of the neuromuscular system has been defined as muscle tuning (70). Whole body vibrations also affect balance even when the displacement is relatively small. Postural muscles then play an important role in stabilising the body during vibration. As supportive evidence, in a study by Roll et al. (61) it was concluded that foot sole input contributes to the coding and the spatial representation of body posture.

The sinusoidal characteristics of the vibration stimulus determine quick and fast changes in the muscle-tendon complex length of the anti-gravitary muscles. The reflex response to vibration stimulation has been mainly attributed to the activation of muscle spindles leading to an increased activity of the Ia loop (9, 60). Also a facilitation of the excitability of spinal reflexes has been shown to be elicited through vibration to quadriceps muscle (10). Lebedev and Peliakov (38) also suggested that vibration might elicit excitatory flow through short spindle–motoneurons connections in the overall motoneuron inflow. The primary endings are particularly sensitive to vibrations (10, 53, 59) as compared to secondary endings and Golgi tendon organs. However, when vibrations are applied to a muscle tonically contracted, also Golgi tendon organs have been shown to be highly sensitive (53). The position assumed on the vibrating plates and the activation of the target muscles needs to be considered when vibration treatments are administered. In fact, posture and state of vigilance have been shown to affect the activation of the myotatic pathway during vibration (39, 44). Since sensitivity to vibrations has been shown to increase when the target muscle is lengthening (20, 48, 54, 59) it is important to keep this in mind when vibration exercise programs are developed. Vibrations are not only perceived by neuromuscular spindles, but also by the skin, the joints and secondary endings. In fact, all these structures contribute to the facilitatory input to the γ-system (38, 68) which in turn affects sensitivity of the primary endings. Hollins and Roy (31) found that sinusoidal stimuli ranging from 10 to 100 Hz with a small amplitude applied to the left index fingerpad were perceived by Meissner and Pacinian afferents and were able to trigger spindle activation. High frequency vibratory stimuli at a frequency of 250 Hz have been shown to be perceived by Pacinian corpuscles (27). The modulation of neuromuscular response to vibration is than not only to be referred to spindle activation, but to all the sensory systems in the body. Exposing the body to vibration for a relatively short time can contribute to an increased sensitivity of the stretch reflex. Furthermore, vibration appears to inhibit activation of antagonist muscles through Ia-inhibitory neurons, thus altering the intramuscular co-ordination patterns leading to a decreased braking force around the joints stimulated by vibration. Vibration has been shown to facilitate strength production in isometric tasks in normal subjects (23) and in subjects with spinal cord injuries (55). Recent evidence also suggests that vibration is more effective on improving force-generating capacity when applied during concentric rather than isometric and isokinetic activations (72). This suggests the use of vibration as a facilitatory input acting on spatio-temporal summation of afferent feedback and central drive activating motor units not otherwise available (29). Bongiovanni and Hagbarth (2) found that muscle vibration did increase motor unit firing rate, force and EMG during fatiguing MVCs.

The influence of supraspinal structures is also of paramount importance. In fact, it has been shown that the primary and secondary somatosensory cortex, together with the supplementary motor area, constitutes the central processing unit of afferent signals (47). Vibration applied at different frequencies that is capable of producing kinaesthetic illusion has been shown to activate the supplementary motor area, the caudal cingulate motor area, and area 4a of the brain (47). The supplementary motor area of the brain that has been also shown to be activated early during self-initiated movements (14). In light of the above considerations, it seems clear that the acute enhancement in force-generating capacity observed following whole body vibration exercise could be due to the excitation of central and peripheral structures. It is necessary to evaluate the effects of chronic programs of whole body vibration exercise on muscle structure and function, even if the preliminary findings are extremely promising.

Whole body vibration and bone

The deleterious effects of chronic exposure to vibration on the spine have been already discussed previously. Vibration applied chronically to the body has been shown to cause diverse disorders. In particular, bone and joint injuries have been reported in various groups of vibration exposed workers (i.e. 8, 25). Mainly, the reported problems occur in workers using percussive pneumatic tools. The spine is without doubts the most important structure to be considered when the whole body is undergoing vibration since the vibratory waves are transmitted to the whole body through the spine. Whole body vibration can be one of the factors responsible for trauma to the spine. However, the negative effects of vibration also depend on the characteristics of the vibration stimulus, the posture assumed on the vibrating source and the predisposition of the individual. Currently the mechanisms are not clear and further studies are needed in order to identify the precise vibration intensity and exposure time causing spinal disorders.

WBV is causing dangerous outcomes if high frequencies are used and if humans are undergoing vibration for many hours per day. Low-frequency WBV applications seem to suggest its use for therapeutic purposes. In particular, the recently reported effects on bone remodelling and hormonal profile suggest the use of vibration as a non-pharmacological intervention for osteoporosis and low back pain. In particular the work from Clinton Rubin's group has suggested that vibratory stimulation could be osteogenic (63, 64). Low-level mechanical signals in the form of vibration have been shown to effectively counteract bone loss. Low-level vibration at 30 Hz for 20 minutes per day stimulated a 34% increase in the density of trabecular bone in the proximal femur of adult male sheep following one year of treatment (63). Preliminary evidence in adolescents with cerebral palsy (71) and children with low bone mineral density (49) seems to suggest that this intervention may have an anabolic effect on bone tissue. The magnitude of musculo-skeletal interactions is of paramount importance for the maintenance of bone integrity. Physical activity performed early in life has been shown to contribute to high peak bone mass (43). Some forms of exercise, in particular the ones producing high impact forces, seem to be able to reduce or reverse the age-related loss of bone (65). On the other side, a lack of weight-bearing activity could favour the likeliness of sarcopenia (46) reducing in this way signals critical to the maintenance of bone mass. Vibration represents a strong stimulus for musculo-skeletal structures due to the need to quickly modulate muscle stiffness to accommodate the vibratory waves (12). The current findings suggest that vibrations transmitted to the body by means of vibrating plates may be an effective alternative countermeasure to bone loss. However, it is our opinion that also some influence from hormones could influence the remarkable adaptive responses to vibration as an exercise intervention. Vibration has been in fact shown to acutely increase testosterone and growth hormone levels in healthy individuals (7) when the training protocol was relatively short. Taking into consideration the results of these preliminary studies it would not seem far-fetched; then, to suggest that the combination of low-frequency mechanical stimuli and hormonal responses provided by vibration could represent an anabolic signal to musculo-skeletal tissues. While these preliminary studies are promising, longer term, larger population scale studies must be performed in order to verify the effectiveness of vibration treatments on the spine and the lower limbs.

Conclusions

In conclusion, vibration represents a strong stimulus for musculo-skeletal structures. Muscles respond to vibration stimuli with an increased activation mediated by monosynaptic and polysynaptic afferent pathways. Chronic exposure to vibration has been shown to determine dangerous side-effects on the spine. On the other hand, WBV exercise interventions have been effective in enhancing strength and power performance and reduce low back pain. In particular, voluntary activation of skeletal muscle following vibration stimulation was shown to be affected by vibration due to central and peripheral neuromuscular mechanisms. Future studies are needed in order to clarify the influence of different physiological mechanisms in mediating acute and chronic responses to this novel exercise intervention. Moreover, long-term studies are needed in order to develop safe and effective vibration training protocols for different populations considering also the problems of chronic exposure to vibration stimuli highlighted in occupational medicine.

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