EFFECTS OF WHOLE BODY VIBRATION ON SPINAL PROPRIOCEPTION OF HEALTHY SUBJECTS AND PATIENTS WITH LOW BACK PAIN

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CERTIFICATE OF ORIGINALITY

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Lee Tin Yan (Name of student)

ABSTRACT

Low back pain (LBP) is a common health problem with a high recurrence rate. Current treatments are not that effective. As patients with LBP are often found to be proprioception impaired, new proprioception exercises are required. Whole body vibration (WBV) stimulates proprioceptive receptors on the muscles, causing an alternation in muscle recruitment and hence modifying the muscle stiffness and joint stability. Its potential to improve muscle function and proprioception has been shown in athletes. Sinusoidal alternative WBV was shown to be able to relieve pain in patients with LBP after a long term application. However, the underlying mechanism has not been investigated. Another study has demonstrated that short term WBV had an immediate effect on improving pelvic repositioning ability on normal individuals. As spinal proprioception facilitates spine positioning and movement and computes self-coordination under both static and dynamic conditions, it is essential to investigate the effect of WBV on lumbo-pelvic stability, coordination and repositioning ability to justify whether WBV has a beneficial effect on spinal proprioception. In this study, the immediate and carryover effect of a 5-min 18Hz WBV on spinal proprioception were investigated.

The study was divided into two stages. In the first stage, twenty young normal individuals were recruited and the effects of WBV in standing and seated postures on spinal proprioception were determined and compared. In the second stage, the effect of WBV on spinal proprioception was evaluated in eight individuals with LBP, with age matched with those in the healthy group, in seated posture. The results were compared with the healthy subjects receiving WBV in seated posture. In addition to quantifying body alignment, repositioning

ability of participants before and after WBV, postural stability and phasic relationship between the lumbar and pelvis segments were investigated in terms of maximum reaching distance and lumbo-pelvic coordination using Dynamical Systems Theory approach. Assessments were conducted before, immediately after, 30 minutes after and 1 hour after 5 minutes of WBV (18Hz, 6mm p-p amplitude). Multivariate analysis of variance was used to study the changes of each variable and LSD criterion was adopted for post-hoc comparisons.

In the first stage, it was shown that WBV in both standing and seated posture had significant beneficial effect on maximum reaching distance, dynamic lumbo-pelvic coordination and repositioning ability without significant group difference. Significant carryover effect of WBV was also shown. In the second stage, immediate improvement of postural control, lumbo-pelvic coordination and repositioning ability were observed for the LBP group. However, the effect seemed to be less long-lasting.

There were limitations in the study. The effect of vibration intensity and learning effect have not been fully investigated. As analysis was limited to the sagittal plane, the effect of WBV on spinal motor control in other planes was not known.. In conclusion, 5 minutes of 18 Hz WBV was shown to have significant positive effect on lumbo-pelvic stability, coordination and repositioning ability without any apparent adverse effect in both normal and LBP individuals. The effects were more apparent and long-lasting when WBV was applied to healthy individuals than patients with LBP. Further clinical study on patients with LBP undergoing similar or different WBV protocol is recommended to confirm its clinical application on improving spinal proprioception.

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Chapter 1. Introduction

Low back pain (LBP) is a common musculoskeletal disorder in the world. Most of the LBP cases are benign musculoskeletal problems probably attributable to muscle atrophy and fatigue (Henschke et al. 2009). The lifetime prevalence of an individual having low back pain ranges from 60 to 80% (Long et al. 1996). The subsidence period is around 2-3 months and it is common for the pain to recur (Hides et al. 1996). Around 5-10% of patients with LBP, the problem will become chronic (Indahl et al. 1995). Because of the high prevalence and recurrence of LBP, it has posed an enormous economic burden on individuals, families, communities and governments (Meng et al. 2014).

LBP is characterized by pain or discomfort appears in the lumbar region, which generally happens below the costal margin and above the gluteal fold that could possibly affect the thigh (Chou et al. 2007). LBP can be originated from any spinal structures, such as vertebral bodies, muscles and ligaments, intervertebral discs and facet joints. LBP is classified into three categories according to individual's clinical history and results of physical examination: 1) LBP associated with a specific cause in the spine, 2) LBP associated with spinal stenosis, or 3) LBP with a nonspecific cause (Chou et al. 2007). For the first two diagnoses, they have defined etiology because the pain has a specific cause such as congenital, neoplastic, inflammatory, infectious, metabolic, traumatic, degenerative or functional. But for the third type, non-specific LBP, the cause is generally unknown (Burton et al. 2006), since it is very difficult to find out the exact origin (Balagué et al. 2012). Non-specific LBP is regarded as LBP that could not be classified with a recognizable or known specific pathology, such as infection, tumor, osteoporosis, structural deformity, Cauda equina syndrome etc (Balagué et al. 2012). There are many potential risk factors that would cause LBP, such as: age (Watson et al. 2003), gender (Watson et al. 2003), race (Chou et al. 2007), transportation travelled for school (Onofrio 2010), growth spurt (Feldman et al. 2001, Poussa et al. 2005), long periods of seating (Sjolie et al. 2004), child work (Fassa et al. 2005), psychosocial barriers (Jones et al. 2009) and body mass index (Shiri et al. 2010).

A wide range of interventions, including surgery, drug therapy and physical interventions has been introduced for the treatment of LBP (van Middelkoop et al. 2011). However, the effectiveness of these treatments varies among individuals (van Middelkoop et al. 2011, Hutchinson et al. 2012, Aladro-Gonzalvo et al. 2013, Balthazard et al. 2012).

Exercise therapy (Smeets et al. 2006) which consists of a series of physical training for better physical health, educational and skills acquisition program (Ribeiro et al. 2008), physiotherapy education (Goldby et al. 2006), transcutaneous electrical nerve stimulation (Ghoname et al. 1999), low level laser therapy which generates light rays with mono-wavelength without inducing heat effect (Soriano et al. 1998), relaxation therapy (Hernandex-Reif et al. 2001), acupuncture massage (Franke et al. 2000), superficial heat or cold treatment (French et al. 2006), antidepressants (Urquhart et al. 2008), manual therapy (Balthazard et al. 2012), application of traction using lumbar supports (Borman et al. 2003), therapeutic ultrasound (Ebadi et al. 2014) have been used to treat LBP patients. However, in the above studies and reviews, no significant reduction of pain intensity and disability in comparison with conventional physiotherapy treatment could be found due to poor-experimental design, inadequate randomization of the experimental protocol, un-blinded assessors blinded, insufficient sample size and/or high patients' drop-out rate. Moreover, there were studies using insole (Sahar et al. 2009) and total disc replacement through surgical procedures to minimize LBP reoccurrence and relieve pain. However, the former was found to be not effective and the latter was too invasive. Hence, there is still a need to explore effective treatment for LBP.

Chapter 2. Literature Review

2.1 Spinal Proprioception and Its Function

Proprioception is a sense of the position of the body and changes in related physical parameters such as muscle length or tension, joint angles and angular velocity of the joints (Magnusson et al. 1997). It is provided by sensory inputs from the mechanoreceptors: 1) Muscle spindles in the muscles in the active musculoskeletal systems and; 2) Joint receptors passive musculoskeletal systems. All the signals received from the sensory inputs will then be transmitted and processed in the cerebellum of the central nervous system (also called the neural feedback system), which acts as a feedback for movement modulation. The active and passive musculoskeletal subsystems (Panjabi 1992) co-operate with the neural feedback system to provide intact proprioception for intact spinal motor control. In essence, spinal proprioception is a feedback mechanism which critically facilitates spine positioning and movement during tasks performance (Taimela et al. 1999) and computes self-coordination under both static and dynamic conditions (Berthoz et al. 2001).

2.2 Proprioceptive Deficit and Task Performance in Patients with LBP

Altered proprioception had been demonstrated to be associated with low back pain (LBP) (Gill et al. 1998; O'Sullivan et al. 2003; Newcomer et al. 2000a, 2000b, 2001; Georgy 2011). Deficit in proprioception would cause delayed protective muscle reflexes and coordination, which prevents muscle contraction from responding fast enough for excessive joint movement (O'Sullivan et al. 2003). Excessive loading would thus be transmitted to joint surfaces and would induce more pain to the patient (Forwell et al. 1996). Another view about LBP was that it might be caused by some initial damage in the spinal structure, which leads to muscular hypertonus and eventually insufficient circulation in the structure and proprioceptive impairment (Hirayama et al. 2006), thereby creating more and more pain. Hence, the recurrence rate of LBP was so high (Koes et al. 2006).

Proprioceptive deficit in patients with LBP would lead to altered motor control, hence motor control dysfunctions are common among chronic LBP patients (Hides et al. 1996). Spinal muscle endurance and proprioceptive impairment were observed in the lumbo-pelvic region of chronic LBP patients (O’Sullivan et al. 2000). Moreover, these patients have difficulty in adopting and maintaining static and dynamic lumbar spine postures (Lam et al. 1989), which makes their tasks performances comparatively different from normal individuals. Aberrant patterns of lumbo-pelvic motion had been reported both clinically (Fritz et al. 1998) and academically (Lamoth et al. 2002, Vogt et al. 2001) in patients with LBP. Correlation between the lumbar and pelvic angular motion in patients with LBP during trunk flexion was found to be lower for normal individuals (Shum et al. 2007, Lee et al. 2002). In addition, repositioning accuracy of patients with LBP was found to be lower (O'Sullivan et al. 2003) due to poorer proprioceptive sense, and they were found to have reduced lumbar flexibility and static balancing ability (Alexander et al. 1998, Brumagne et al. 2000).

2.3 Whole Body Vibration

Whole body vibration (WBV) has been proposed and investigated in many researches for its feasibility in treating LBP. Previous findings about the effects of WBV on humans are controversial. WBV could possibly lead to LBP depending on (1) the frequency of WBV (Pope et al. 1999); (2) the duration of WBV (Bongiovanni et al. 1990); and (3) the body posture adopted during the vibration (Rubin et al. 2003). Moreover, people who often drive vehicles and operated heavy machines are more prone to have LBP as a result of longer and higher amplitude of vibration to the spine that they experience (Joshi et al. 2010). Furthermore, industrial vibration has been shown to be a risk factor for LBP due to vibration with very low frequency (Yamazaki et al. 2002). Long term exposure to WBV should be prohibited since it would increase the chances of getting lumbar spine and central nervous system disorder (Bovenzi 2007). If an individual is exposed to WBV for a long time, the paraspinal muscles couldn’t generate a force that is large enough to oppose the compressive force induced by WBV, thus possibly resulting in muscle fatigue (Seidel et al. 1986), which would eventually increase the risk of spinal injury (Pankoke et al. 2001). This suggested that WBV with controlled duration is necessary when applied to humans.

2.3.1 Limitation when applying WBV

Other than duration, frequency is also a critical parameter for vibration propagation throughout the body. The resonant frequency of the spine should be around 7 Hz (Kong et al. 2003; Guo et al. 2009).

WBV at frequencies of 4-6 Hz had been implicated in the causation of LBP (Pope et al. 1992). Kasra (2006) had proved that around 5 Hz was a threshold frequency that disrupted protein metabolism. Also, it is necessary to avoid large transmission of vibration being delivered to the body. Large vertical acceleration (Panjabi 1986) and intervertebral movements (Pope et al. 1991) would be augmented when resonant frequency vibration is applied. If the induced motion is large, the spine and eventually the cervical part would be injured (Matsumoto et al. 2001). Transmissibility would be greatly reduced to 1/1—1/1000 when the applied frequency is lower than the resonant frequency (Matsumoto et al. 2001). Hence, choosing the suitable combination of amplitudes and frequencies of the applied vibration is also an important issue.

2.3.2 Mechanism of WBV on proprioceptive receptors

During WBV, vibration is delivered to muscles and joints from vibration platform, proprioceptive receptors such as muscle spindles and joint mechanoreceptors are stimulated (Rittweger et al. 2000; Burke et al. 1976). This results in changing the proprioceptive sense of an individual. It was hypothesized that an illusion of muscle-lengthening is created during vibration (Goodwin et al. 1972). The proprioceptive organs detect the induced changes in muscle length (Rittweger 2010). The α-motor neurons are activated leading to muscle contractions similar to tonic vibration reflex (Rittweger et al. 2000) or an oscillatory stimulation to muscle. Throughout this stimulation process, increment of muscle activation leads to muscle contraction (McBride et al. 2010). Such increment is likely due to a larger number of type II muscle fibre recruitment and the absence of muscle fatigue or overexertion (Avelar et al. 2012). Through gamma efferent stimulation in the mechanoreceptors and the alternation of the muscle fibre recruitment, muscle stiffness and joint stability could be modified (Bogaerts et al. 2007). Thus, WBV may have potential for improving motor function (Ribot-Ciscar et al. 1998, 2002) and proprioception training (Johansson et al. 1991a,b).

2.3.3 Advantage of WBV

Rittweger et al. (2003) suggested that WBV at frequencies smaller than 20 Hz would reduce LBP by inducing muscle relaxation. WBV was also reported to be able to improve performance by enhancing motor function to increase muscle power in athletics (Bosco et al. 1999) and has been used as training exercises for athletes in different sports fields (Magnusson et al. 1996). WBV was found to be able to improve neuromuscular function (Abercromby et al. 2007) and increase muscle flexibility (Van der Tillaar et al. 2006; Jacobs et al. 2009). WBV was also shown to be able to improve muscle strength (Roll et al. 1980, Rauch et al. 2009), muscle power (Issurin et al. 1999) and balance (Delecluse et al. 2003). WBV has also been used as a warm-up exercise to maintain good muscle flexibility which could enhance physical performance and reduce the likelihood of musculoskeletal injury during sports activities (Shellock et al.. 1985).

Rittweger et al. (2002) believed that suitable vibration exercises could activate the neuromuscular system by improving neuromuscular performance and proprioception, which could be a possible therapy for LBP patients as these patients usually have disorders in their connective and neural systems (Issurin et al. 1994; Torvinen et al. 2002; Fontana et al. 2005). It was shown that vibration could also be used to relieve low back pain for patients (Rittweger et al. 2002).

Passive warm-up or voluntary exercises such as stretching could not recruit type II muscle fibres in the working muscles but WBV could, since the stimulus provided by WBV facilitated neuromuscular coordination (Kelly et al. 2010), and triggered a greater activation of the mechanoreceptors and the tonic vibration reflex, which acted predominantly on α-motor neurons (Delecluse et al. 2003). It was also believed that stimulation of the somatosensory system could promote brain plasticity. However, its underlying mechanism is still unknown (Johansson et al. 2000).

2.4 Related study about WBV and knowledge gap

The effects of WBV on spinal proprioception have been investigated in many studies (Rittweger et al. 2002, Brumagne et al. 2000, Fontana et al. 2005, Belavý et al. 2008, Bosco et al. 1999). However, it is difficult to compare among these studies as different protocols and vibration parameters were used. Local vibration applied to paraspinal muscle was shown to be able to improve position sense of LBP patients (Brumagne et al. 2000). A study demonstrated the trunk neuromuscular response of chronic LBP patients after WBV was not significantly from that of healthy individuals and decreased EMG existed after WBV during full trunk flexion, stating that WBV could improve the neuromuscular performance of the LBP patients without disturbing the spine stability (Boucher et al. 2013).

It had also suggested WBV below 20 Hz could reduce LBP by inducing relaxation of the back muscles since LBP is somehow related with spinal muscle spasm (Fischer et al. 1985). Rittweger et al. (2002) found that patients had significant pain reduction and a gain in lumbar torque after receiving 18 Hz WBV for three months with gradually increasing amplitude from 2-6mm amplitude for duration up to 7-minute in the final vibration session, although the latter effect was not significantly related to pain relief. In a study by Fontana et al. (2005), 18Hz WBV was applied to healthy subjects for 5 minutes with amplitude around 2mm and it was found that the repositioning ability of pelvic tilting was improved after WBV. It was also found that lumbar multifidus muscle function could be stimulated by WBV at about 20 Hz for 8 weeks and could be used to prevent the paraspinal muscle from atrophy (Belavý et al. 2008). Hence In this study, 18 Hz WBV was chosen because of its positive findings from previous studies (Rittweger et al. 2002, Fontana et al. 2005). For the 6 mm amplitude, it was adopted according to Rittweger et al's study. For the duration, it was decided according to the study of Fontana et al. 2005 and the averaged value used in Rittweger et al. 2002. The reason for investigation the effect of short term WBV on proprioception is that generally WBV is applied to individuals in long sessions, it will be interesting to find out whether WBV has the ability to cause any immediate effect on the spinal proprioception. Provided that the improvement existed, it will be necessary to figure out why WBV causes such beneficial effect.

The effects of WBV on dynamic motor control of the lumbar spine have not yet been investigated. In this study, spinal proprioception was assessed using the Dynamical Systems Theory approach in terms of functional spinal coordination and stability [Kurz et al. 2004, Stergiou et al. 2006]. Dynamical Systems Theory is an area of mathematics used to describe the behavior of complex dynamical systems usually by employing differential equations. As the attenuation of WBV had been found to occur at the knee level when the frequency of vibration was larger than 15 Hz [Pollock et al. 2010], transmissibility of the vibration would likely be affected [Rubin et al. 2003] around this frequency if the participants adopted a standing posture during WBV. Hence, other than the traditional standing posture, we proposed application of WBV in seated posture could deliver vibration to the spinal region with less attenuation, which may bring a different effect to the proprioception of an individual under the same frequency. In addition, participants might have the probability of losing balance during WBV if they are not allowed to hold a hand-bar throughout the vibration.

As vibration of certain frequency has been shown to have adverse effect on the spine, study of prolonged effect of vibration is not encouraged. Thus, the purpose of the study was to explore the beneficial effect of WBV on LBP and only a single bout of WBV was applied to the participants. The finding of the current study would provide evidence whether it is worthwhile to investigate the WBV protocol in long-term. In addition, the vibration dosage delivered to the subject in this study was quite large according to the ISO 2631 and BS 6841 standard, so it is better to explore whether the combination of frequency and amplitude of WBV used in this study is instantaneous beneficial effect. . If improvement of proprioception after instantaneous WBV could be demonstrated in this study, it would help us to understand more about the mechanism of WBV on spinal proprioception and encourage the possibility of using WBV to treat LBP in longer terms.

Hence, this study was divided into two stages. In the first stage, we hypothesized that 18Hz of 6mm peak to peak WBV would improve spinal proprioception of normal individuals though the repetitive stimulation of the mechanical receptors of the spinal muscles, and it was hypothesized that such improvement could be reflected though the performance of dynamics task and seated repositioning test. In addition, alternation of body alignment might be resulted. It was also hypothesized that the effects of WBV was different when it was applied with the subjects in seated and upright standing postures.

Chapter 3. Methodology

3.1 Experimental Design

In the first stage of the study, normal subjects were recruited and evenly divided into two groups to undergo WBV of the same frequency and duration but in different postures: standing and seated postures. Assessments were performed before, immediately after, 30 minutes after and 60 minutes after receiving WBV for evaluating the immediate and short-term carryover effects of WBV. In the second stage of the study, the effects of WBV spinal proprioception were investigated in patients with LBP. Seated WBV was applied to the patients and the results were compared with those of the normal individual undergone seated WBV in the first stage of the study.

Three tests were used to evaluate the effects of WBV, namely body alignment measurement, repositioning test, and functional reach test. Participants were asked to perform the assessments in the above order to minimize the effect of muscle fatigue. For the body alignment measurement, spinal curvature and the lower limb angulations were documented. For the repositioning test, repositioning error was quantified in terms of constant error (CE), variable error (VE) and absolute error (AE). For the functional reach test, maximum reaching distance (MRD) of the participants was firstly determined. The participants were then asked to perform dynamic reaching task and their lumbo-pelvic coordination was quantified in terms of mean absolute relative phase (MARP) and deviation phase in both forward and backward motions. Since there is no study at present investigating the effect of WBV on inter-segment coordination in any kind of assessment, MARP was thus set as the primary outcome of this study.

3.2 Subjects Recruitment

All Subjects were recruited by posting posters within the university campus. Table showing the total sample size required for all parameters in future study were shown in Chapter 7.8.

All Subjects were recruited by posting posters within the university campus. All subjects were required to read and understand Chinese or English instructions, similar to the study by Rittweger et al. (2002). Subjects within 18-30 were considered only in this study. For the healthy individuals, all of them have regular exercises with normal BMI level. All of them were not drug users, regular smoker and alcoholics. Patients who suffered from specified vertebral osteoporosis, scoliosis, spinal tumors or metastases, acute vertebral disc herniation, recent fractures of the axial skeleton, inflammatory diseases of the spine, rheumatoid arthritis, osteogenesis imperfecta or other generalized bone diseases, tumor or inflammatory diseases, heart failure, recent abdominal surgery, lower limbs endoprothesis or other metallic implants, aortic aneurism, recent venous thrombosis were excluded. Moreover, subjects who had a history of any neurological disorders (vestibular disorders or cerebral trauma), inner ear infections, or hearing loss, which could affect balance and proprioception, were also excluded from the experiment. For LBP subjects invited in the second stage, they were only included if they had chronic non-specific LBP either continuously for more than 6 months or intermittently for more than 2 years.

All participants fulfilled the inclusion and exclusion criteria mentioned above and hereinafter. Ethical approval was acquired from the Ethics Committee (Appendix 7.7) and written informed consents from all of the participants were obtained before the study. Prior to the experiment, participants were required not to be involved in any other fitness/training program or any other back pain related therapy including pain reduction medication. To eliminate the possible effect of a distended abdomen on mechanoreceptor input from the abdominal region which could affect the results of repositioning error, the subjects were requested not to eat or drink for 2 hours prior to testing (Maffey-Ward et al. 1996).

3.3 Experimental Procedures

3.3.1 Markers Attachment and Data Acquisition

A total of nineteen 15mm spherical retro-reflective markers were used for different purposes in each of the tests. The markers were attached to the chin, C7, T2, T5, T7, T12, L1, L3, S1, bilateral anterior and posterior superior iliac spine and the right hand ulnar styled process after palpation (Appendix 7.3). Markers were also attached to greater trochanter, lateral condyle, lateral malleolus, second metatarsal head and heel of the right leg. The markers were located by palpation and were attached to the subjects by using double-sided adhesive tape with their bodies slightly flexed to minimize the effects from traction of the skin during motion (Swinkels et al. 1998). Paper surgical tape was used to further secure the markers during WBV. Relative movements between skin markers and the bony structure beneath were neglected. An eight-camera motion analysis system (Vicon Nexus, MXF40 cameras, Oxford Metric, UK) was used to monitor positions of the spherical markers. Subjects were only allowed to wear a pair of tight elastic shorts during the experiment for the ease of markers attachment, hence only males subjects were considered for this study. All data were sampled at 100 Hz and low-pass filtered at 3 Hz using residual analysis (Winter 2005) (Appendix 6.1). Static and dynamic calibrations of the motion analysis system were conducted prior to every experiment with mean average error less than 0.25mm.

3.3.2 Application of WBV

See-saw type WBV was delivered using a Galileo sport (teeterboard-like) platform (Novetec, Pforzheim, Germany) (Figure 1). This vibration platform works like a seesaw, producing side-alternating WBV with amplitude between 0-6 mm (equivalent to 0-12 mm peak to peak, medial to distal) and adjustable frequency from 0-40 Hz. The advantage of using side-alternating vibration instead of vertical vibration is that a rotary component is introduced to the lumbar spine, thereby reducing the vibration transmitted to the trunk and hence the head (Abercromby et al. 2007).

In the first stage of the study, subjects in the standing group underwent WBV at 18 Hz, 6mm peak to peak amplitude for 5 minutes while maintaining a normal standing posture on the vibrating platform with knees slightly flexed (Figure 2). Since Pollock et al. 2010 reported a simultaneous knee flexion on the subjects during WBV, where they were told not to lock their knees, the angle of flexion of the subjects in this study was asked to maintain about 15 to 20 degrees during WBV for standardization. Amplitude was adjusted to 6mm by setting foot distance approximately 33cm apart and equidistant from the central axis (Figure 3). Both feet should be positioned in parallel on the platform (Fontana’s et al. 2005) and made sure to be flat for even force distribution. The participants were allowed to hold the hand bar of the platform if needed. For the seated group, subjects were asked to sit in a relaxed posture on the WBV platform with their hands placed comfortably on the thighs (Figure 2). Subjects in both groups gazed horizontally during the vibration (Rittweger et al. 2002). The LBP subjects in the second stage of the study were also required to receive WBV in the same seated posture as those in the seated group.

Figure 1 Galileo Sport platform

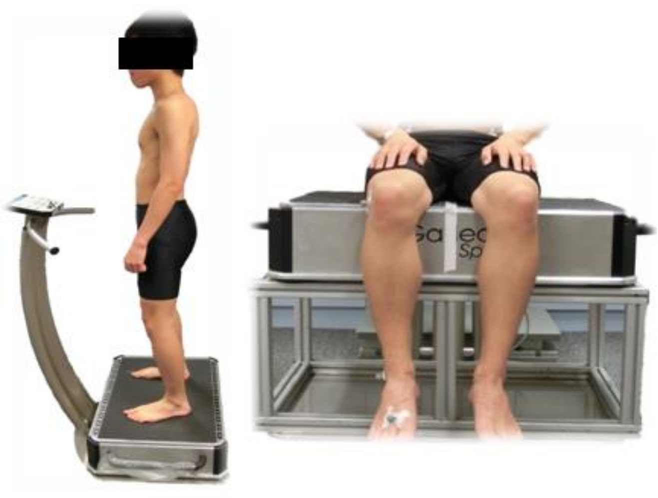

Figure 2 Subject under whole body vibration in standing (left) and seated (right) postures

Figure 3 Foot positions on the platform during standing WBV

3.3.3 Assessments

3.3.3.1 Spinal Curvature Test

Body alignment measurement included spinal curvature and lower limb posture documentation. Spinal curvature was measured using markers attached on the chin and the spinous processes of C7, T2, T5, T7, T12, L3 and S1 (Chow et al. 2007) (Figure 3). Pelvic tilt, knee and ankle angles were measured by markers attached bilaterally to the anterior superior iliac spines and posterior superior iliac spines as well as great trochanter, femoral condyle, lateral malleolus, heel and second metatarsal head (Figure 3). Subjects were instructed to stand in their normal upright stance with hands rested aside and feet separated at a comfortable distance. Feet positions were marked on the floor while subjects looked at a target two meters in front of them at eye level. The markers positions were recorded for 3 seconds in this position. The subjects were then asked to walk around a 6-meter loop, returning to the same position and upright stance for another 3 seconds for capturing marker position again. This process was repeated 5 times and the mean angles of the 6 trials were used as spinal curvature and body alignment measurements. Six trials were performed because the coefficient of variation and statistical power for the accuracy and precision of the variables were shown to become stable after this amount of trials (Allison et al. 2003). The definitions of all the angles were shown in Figure 4 and the names and abbreviations were summarized in Table 1.

Angles	Definitions of angles
CH-C7-T2	Neck flexion angle
C7-T2-T5	Upper thoracic flexion angle
T2-T5-T7	Middle thoracic flexion angle
T5-T7-T12	Lower thoracic flexion angle
T7-T12-L3	Upper lumbar extension angle
T12-L3-S1	Middle lumbar extension angle
L3-S1-Horizontal	Lower lumbar extension angle

Table 1 Definition of the angles measured as spinal curvature

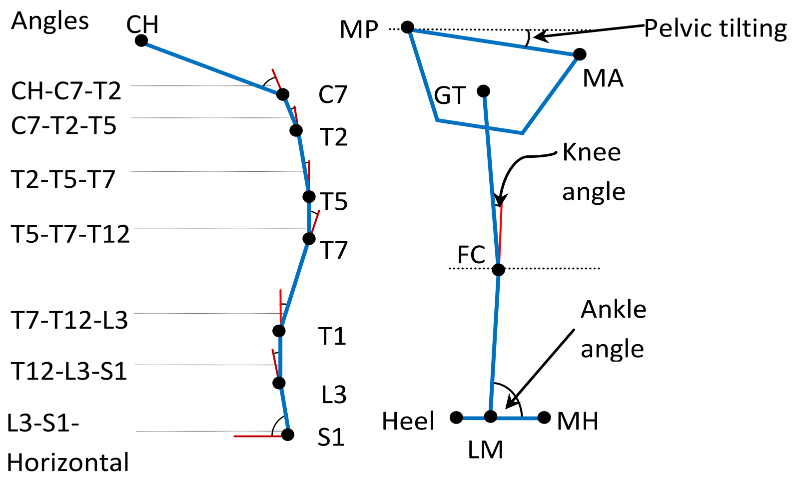

Figure 4 Definitions of various angles of body alignment (Left: Spinal curvature; Right – lower limb angles). CH = chin; MP = mid-point of posterior superior iliac spines; MA = mid-point of anterior superior iliac spine; GT = great trochanter; FC = femoral condyle; LM = lateral malleolus; MH = second metatarsal head

3.3.3.2 Repositioning Test

In the repositioning error test, similar procedure of the O'Sullivan's (2003) study was adopted. Subjects were blindfolded and sat on a rigid stool, with hips and knees kept at 90 degrees, and their shanks had no contact with the stool legs. These set-ups were to prevent any additional sensory input to the subjects (Lam et al. 1999). Moreover, subjects' feet were positioned at shoulder width (Sheeran et al. 2012) and arms were placed on the thighs in a relaxed manner (O'sullivan et al. 2003). Subjects were asked to perform maximum lumbar flexion for three times, and then positioned by the researcher to a criterion position, which was a neutral upright spinal posture. They were given 5 seconds to remember the criterion position and were asked to relax into full lumbar flexion for 5 seconds before reproducing the criterion position five times. During the entire test, each subject was encouraged not to move his thoracic spine and neck during motion (Maffey-Ward et al. 1999) and no feedback was given to the subject about his repositioning accuracy. 3 seconds of data were obtained when the subjects attempted to reproduce the criterion position. Repositioning error was defined as the difference in lumbar flexion angle relative to the pelvis between the 5 trials and the criterion position (Figure 5). Details explaining the calculation of the angles were described in Appendix 7.5.

Repositioning error was expressed in terms of constant error, variable error and absolute error. Constant error is a measurement of the repositioning accuracy. Negative constant error represents that subjects have an undershooting issue towards the criterion position. Variable error is a measurement of the variability based on the standard deviation of constant error of the five attempts, which represents how precisely the subjects reproduced the criterion position. Absolute error is the absolute value of the error between each reproduction attempt and the criterion position and accounted for both bias and variability (Brumagne et al. 2000).

3.3.3.3 Functional Reach Test

The protocols proposed by Silfies et al. (2009) in assessing body balance and characterizing lumbo-pelvic movement using the Dynamical Systems Theory were adopted. In functional reach test, a marker was attached to the ulnar head for defining the onset of each movement cycle. Maximum reach distance of each subject was first acquired by asking the subject to slide the bar on a yardstick at shoulder height as far as possible without taking a step or losing balance (Figure 6).

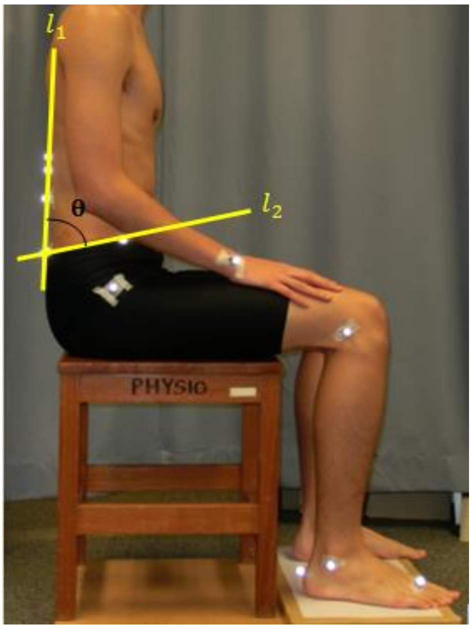

Figure 5 Diagram showing the definition of the formation of the criterion angle and the reproduced angles in each trial

Two practical trials were given before the mean of 3 subsequent trials was measured as the maximum reach distance, and from which the function reach target was determined as the halfway distance of maximum reach distance. Subjects were then asked to reach for the target reaching point using the trunk and pelvis as if reaching over a cupboard without taking a step over a period of 3 seconds, and to restore the upright position in the following 3 seconds with the aid of a metronome (Figure 7). Each movement cycle consisted of 6-second reach and return. Three cycles were performed within each trial and three warm-up trials were given before the data of the fourth trial were used in data analysis. Subjects would be required to perform an additional trial if they failed to touch the target or maintain a steady pace of motion in any cycle. Angular displacements of the lumbar spine and pelvis in each forward and backward motion were time-normalized to 120 points. After obtaining the angular displacement and velocity of the lumbar and pelvis (Figure 8), their phase angles were calculated by arc tangent of velocity of each body segment divided by its own displacement:

$$\vartheta = \tan^{-1}\left(\frac{\text{angular velocity}}{\text{displacement}}\right) \qquad \text{---------} \ (1)$$

The continuous relative phase (CRP) curve between the lumbar spine and the pelvis was calculated as the absolute difference between the pelvis phase angle ($\vartheta_{\text{pelvis}}$) and the lumbar spine phase angle ($\vartheta_{\text{lumbar}}$) at each data point (Hamill et al. 2000):

$$\varphi = \left|\vartheta_{\text{lumbar}} - \vartheta_{\text{pelvis}}\right| \qquad \text{----------} \ (2)$$

These CRP curves were quantified by MARP and DP which were derived by Stergiou et al. (2001) using the ensemble curves method. MARP showed the phasic relationship between the two interested segments and was calculated by adopting the average value of the relative phases over the CRP curve using the equation by Stergiou et al. (2009):

$$\text{MARP} = \sum_{i=1}^{40} \frac{\left|\varphi_{\text{relative phase}}\right|_i}{40} \qquad \text{----------} \ (3)$$

DP quantified the pattern stability throughout the whole reaching process. It was calculated by averaging the standard deviation (SD) of the CRP curves using the equation by Stergiou et al. (2009):

$$\text{DP} = \sum_{i=1}^{40} \frac{\text{SD}_i}{40} \qquad \text{----------} \ (4)$$

Functionally, the smaller the MARP value, the more in-phase would be the pelvis and lumbar region and vice versa. For DP value, the lower the DP, the more stabilized the neuromuscular system was and vice versa.

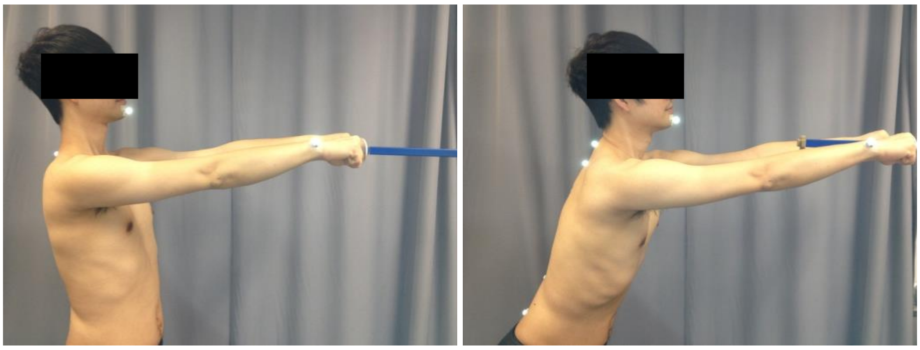

Figure 6 Record maximum reaching distance by asking the Subject to reach as far as possible without taking a step

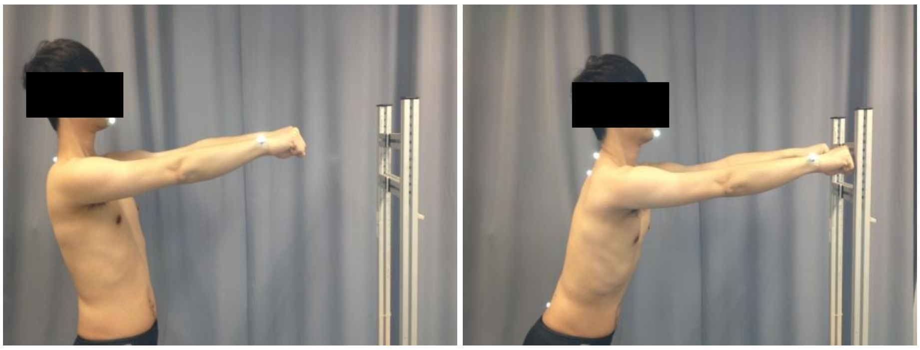

Figure 7 Subject performing functional reach test with 50% of the maximum reaching distance

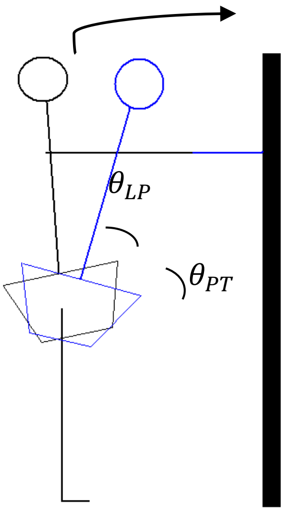

Figure 8 Marker placement (Lateral view) and angle calculation. θ_{LP} *and* θ_{PT} *were calculated to present the posture and movement of the lumbar spine and pelvic relative to the thigh respectively.*

3.3.4 Data Transformation

As symmetric motion was investigated in the study, only angular motion in the sagittal plane was analyzed. All the data were projected onto a sagittal plane of a transformed coordinate system formed by the first set of the coordinates of the bilateral ASISs from the captured data in each trial of each test**.** The construction process of the transformed coordinate system was shown in Figure 9 and details were shown in Appendix 7.4.

3.3.5 Statistical Analysis

In the first stage, variables of the standing group were compared with those of the seated group. In the second stage, the data of the seated group were treated as a control group and were compared with those of the LBP group. The statistical analysis methods used in both stages were the same. Anthropometric data like age, weight and height of the subjects were compared using independent samples T-test. Independent T-test was used to compare the demographic data between the two groups. In both stages of the study, multivariate analysis of variance (MANOVA) was used to study the changes in maximum reaching distance, lumbo-pelvic coordination between participants with and without LBP, and repositioning errors and body alignments (i.e. group factor) before and after WBV (i.e. time factor). Statistical software (IBM SPSS Statistics 20, Inc., Chicago. IL, IBM, USA) was used for data analysis with level of significance set at p=0.05 and LSD criterion was adopted for post-hoc comparisons.

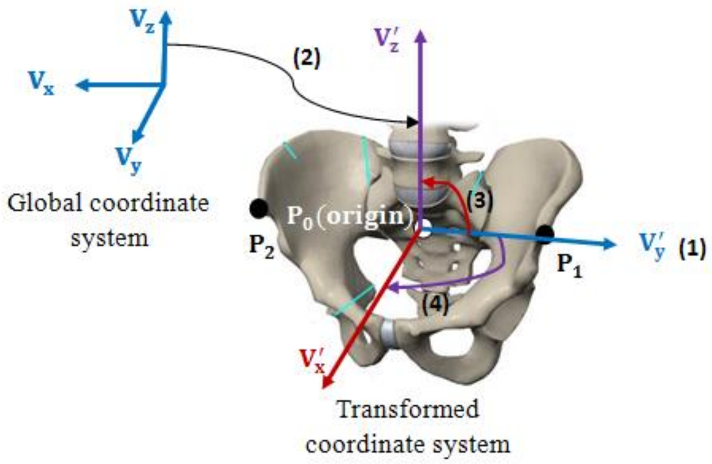

Figure 9 Diagram illustrating the transformed coordinate system using the original coordinates of the bilateral ASISs

Chapter 4. Results

4.1 First stage: Standing group VS Seated group

4.1.1 Anthropometric data

In the first stage, healthy male subjects were recruited and divided into two groups to receive WBV in standing (n = 10) or seated (n = 10) posture. The mean (SD) age, body height and weight of the subjects who received WBV in standing posture were 23.2 (1.2) years, 172.1 (6.3) cm and 63.2 (3.9) kg respectively. For those who received WBV in seated posture, their mean (SD) age, body height and weight were 22.3 (1.1) years, 171.7 (4.3) cm and 59.8 (5.3) kg respectively. There were no significant differences in all anthropometric parameters for two groups (Age: $p = 0.096$; Height: $p = 0.870$; Weight: $p = 0.113$).

4.1.2 Functional Reach Test

For maximum reaching distance, there were no significant interaction between group and time factors ($F(3,16)=0.118$, $p=0.948$, partial $\eta^2=0.022$) and no group difference ($F(3,16)=2.443$, $p=0.135$, partial $\eta^2=0.120$). There was a significant increase in maximum reaching distance after WBV ($F(3,16)=16.905$, $p<0.001$, partial $\eta^2=0.760$) (Figure 10). The difference in maximum reaching distance between participants receiving WBV in standing and seated posture was not significant ($F(3,16)=2.443$, $p=0.135$, partial $\eta^2=0.120$). Post-Hoc comparison showed that maximum reaching distance in both groups was significantly increased immediately after WBV (*p<0.001*), 30 minutes after WBV (*p<0.001*) and 1 hour after WBV (*p=0.001*).

For MARP in flexion, there was no significant interaction between group and time factors ($F(3,16)=0.935$, $p=0.447$, partial $\eta^2=0.149$) and no significant group effect ($F(3,16)=1.004$, $p=0.330$, partial $\eta^2=0.530$).

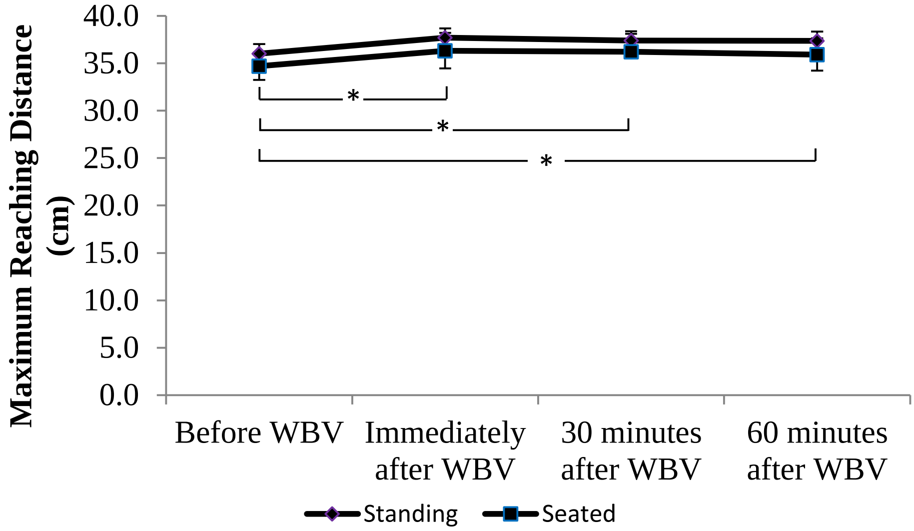

Figure 10 Mean and standard deviation of maximum reaching distance before and periods after whole body vibration of Standing and seated WBV groups (for P < 0.05)*

The main effects of time was statistically significant ($F(3,16)=12.572$, $p<0.001$, partial $\eta^2=0.702$). MARP in flexion of participants in both groups was significantly greater immediately after (*p<0.001*), 30 minutes after (*p<0.001*) and 60 minutes after WBV (*p<0.001*) comparing to that before WBV (Figure 11).

For MARP in extension, there was no significant interaction between group and time factors ($F(3,16)=0.085$,

$p=0.967$, *partial* $\eta^2=0.016$) (Figure 12). No significant difference in MARP in extension between groups ($F(3,16)=0.186$, $p=0.671$, *partial* $\eta^2=0.010$) was observed. MARP in extension for both groups ($F(3,16)=5.069$, $p=0.012$, *partial* $\eta^2=0.487$) decreased significantly after WBV ($p=0.001$) and increased significantly 30 minutes ($p=0.007$) and 60 minutes after WBV ($p=0.027$) (Figure 12).

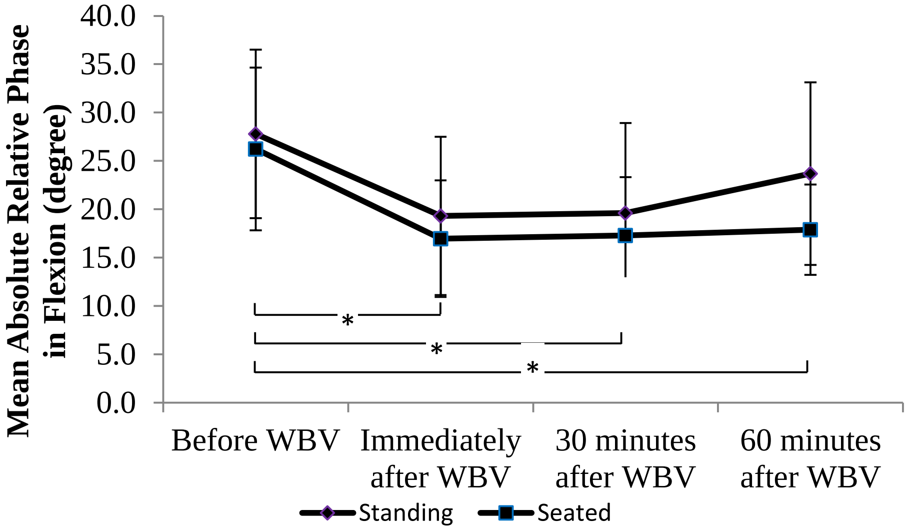

Figure 11 Mean and standard deviation of mean absolute relative phase in forward direction before and periods after whole body vibration of Standing and seated WBV groups (for P < 0.05)*

In addition, MARP in extension 60 minutes after WBV was significantly larger than that immediately after WBV. The corresponding values for MARP in both directions of both groups were shown in Table 2.

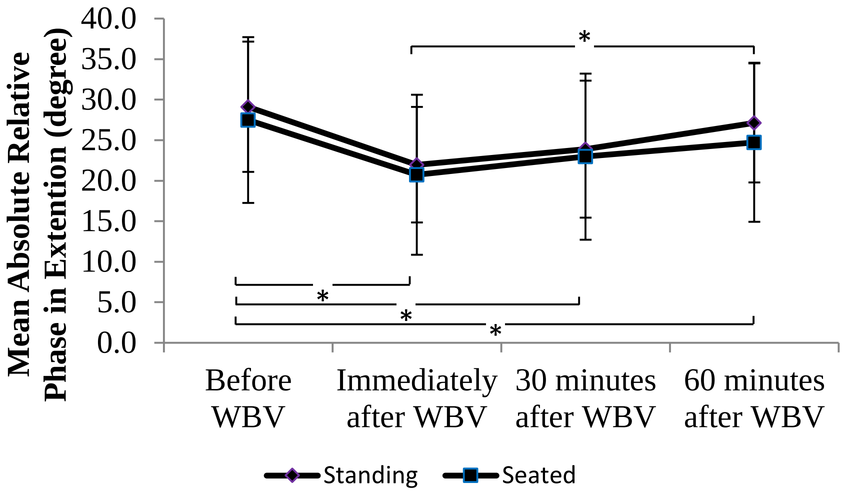

Figure 12 Mean and standard deviation of mean absolute relative phase in backward direction before and periods after whole body vibration of Standing and seated WBV groups (for P < 0.05)*

Assessment period	**Mean Absolute Relative Phase (°) (Mean ± SD)**			
	Forward motion		**Backward motion**	
	Standing group	**Seated group**	**Standing group**	**Seated group**
Before WBV	27.8 ± 8.7	26.3 ± 8.4	29.1 ± 8.0	27.5 ± 10.3
Immediately after WBV	19.3 ± 8.2	17.0 ± 6.0	22.0 ± 7.1	20.7 ± 9.9
30 minutes after WBV	19.6 ± 9.3	17.3 ± 6.0	23.9 ± 8.5	23.0 ± 10.2
60 minutes after WBV	23.7 ± 9.5	17.9 ± 4.7	27.1 ± 7.3	24.7 ± 9.8

Table 2 Mean and standard deviation of mean absolute relative phase before and after whole body vibration for standing and seated groups.

For deviation phase, there was no significant interaction between group and time factors in both flexion (*F(3,16)=0.733, p=0.547, partial* η^2*=0.121*) and extension (*F(3,16)=0.223, p=0.879, partial* η^2*=0.040*). The main effect of time was also not significantly in flexion (*F(3,16)=2.040, p=0.149, partial* η^2*=0.277*) and in extension (*F(3,16)=1.381, p=0.285, partial* η^2*=0.206*). In addition, there was no significant difference in MARP between participants between the two groups in both flexion (*F(3,16)=0.804, p=0.382,* *partial* η^2*=0.043*) and extension (*F(3,16)=1.581, p=0.225, partial* η^2*=0.081*). The corresponding values of deviation phase for both groups were shown in Table 3.

Assessment period	Deviation Phase (Mean ± SD) (°)			
	Forward motion		Backward motion	
	Standing group	Seated group	Standing group	Seated group
Before WBV	17.2 ± 8.1	13.5 ± 3.4	18.7 ± 6.4	15.4 ± 3.8
Immediately after WBV	12.8 ± 5.4	13.4 ± 8.2	14.8 ± 6.4	13.1 ± 4.4
30 minutes after WBV	12.9 ± 5.6	11.2 ± 3.5	16.0 ± 6.3	13.0 ± 6.7
60 minutes after WBV	*13.4 ±4.6*	*12.0 ±2.8*	*15.8 ±5.1*	*14.3 ±4.3*

Table 3 Mean and standard deviation of mean absolute relative phase before and after whole body vibration for standing and seated groups.

4.1.3 Repositioning Test

There was no significant interaction between group and time factors for constant error (*F(3,16)=0.846, p=0.488, partial* η^2*=0.137*), variable error (*F(3,16)=1.204, p=0.340, partial* η^2*=0.184*) and absolute error (*F(3,16)=2.117, p=0.138, partial* η^2*=0.284*). There was also no group difference for constant error (*F(3,16)=0.247, p=0.625, partial* η^2*=0.014*), variable error (*F(3,16)=1.576, p=0.225, partial* η^2*=0.081*) and absolute error (*F(3,16)=0.055, p=0.818, partial* η^2*=0.003*). Although there was no significant time effect on constant error (*F(3,16)=1.874, p=0.175, partial* η^2*=0.260*) and variable error (*F(3,16)=2.917, p=0.066, partial* η^2*=0.354*), there was a significant change in absolute error among different periods (*F(3,16)=4.124, p=0.024,* *partial η^2=0.436*) (Figure 13).

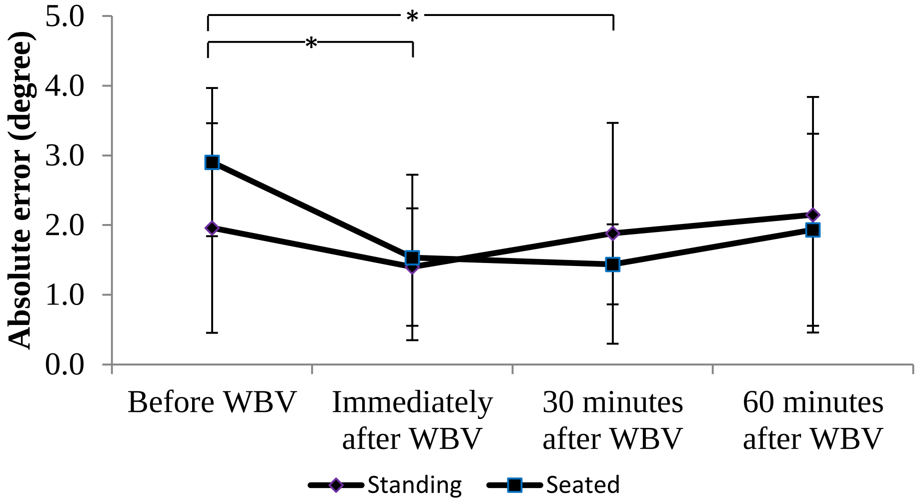

Figure 13 Mean and standard deviation of absolute error before and periods after whole body vibration of Standing and seated WBV groups (for P < 0.05)*

Post-Hoc comparison showed that absolute error in both groups were significantly increased immediately after WBV (*p=0.002*) and 30 minutes after WBV (*p=0.011*) compared to the baseline value. The corresponding values of errors for both groups were shown in Table 4.

	Repositioning Errors (Mean ± SD) (°)					
	Constant Error		**Variable Error**		**Absolute Error**	
	Standing	**Seated**	**Standing**	**Seated**	**Standing**	**Seated**
Before WBV	1.4 ± 2.0	1.4 ± 2.6	1.0 ± 0.4	1.7 ± 1.1	2.0 ± 1.5	2.9 ± 1.1
Immediately after WBV	0.8 ± 1.4	0.9 ± 1.6	0.8 ± 0.4	1.0 ± 0.7	1.4 ± 0.8	1.5 ± 1.2
30 minutes after WBV	0.8 ± 2.3	0.3 ± 1.5	1.1 ± 0.5	1.2 ± 0.5	1.9 ± 1.6	1.4 ± 0.6
60 minutes after WBV	1.1 ± 2.5	-0.1 ± 2.3	1.2 ± 0.7	1.2 ± 0.7	2.1 ± 1.7	1.9 ± 1.4

Table 4 Mean and standard deviation of constant, variable and absolute error before and after whole body vibration for standing and seated groups

4.1.4 Body alignment measurement

There was no interaction between time and group for all parameters except the knee angle (*$F(3,16)=3.642$, $p=0.036$, partial $\eta^2=0.406$*) (Appendix 7.8). However, angular differences among time periods could not be observed for both the standing WBV group (*$F(3,7)=1.168$, $p=0.388$, partial $\eta^2=0.334$*) and the seated WBV group (*$F(3,7)=3.642$, $p=0.036$, partial $\eta^2=0.406$*). Moreover, no significant difference of the knee angle was found between the two groups before (*$p=0.972$*), immediately after (*$p=0.717$*), 30 minutes after (*$p=0.854$*) and 60 minutes after WBV (*$p=0.923$*). There was no significant group effect for all parameters between the groups (Appendix 7.8). L3-S1-Horizontal (*$F(3,16)=3.659$, $p=0.035$, partial $\eta^2=0.407$*) and pelvis tilting (*$F(3,16)=3.416$, $p=0.043$, partial $\eta^2=0.390$*) were significantly different during different periods in both groups. L3-S1-Horizontal immediately after WBV was significantly smaller than that before WBV (*$p=0.01$*), 30 minutes after WBV (*$p=0.03$*) and 60 minutes after WBV (*$p=0.021$*) (Figure 14), while pelvis tilting immediately after WBV was significantly larger than that before WBV (*$p=0.013$*), 30 minutes after WBV (*$p=0.046$*) and 60 minutes after WBV (*$p=0.024$*) (Figure 15). The corresponding values of the angles and statistics of LBP groups were shown in Table 5 and 6 and Appendix 7.8 respectively.

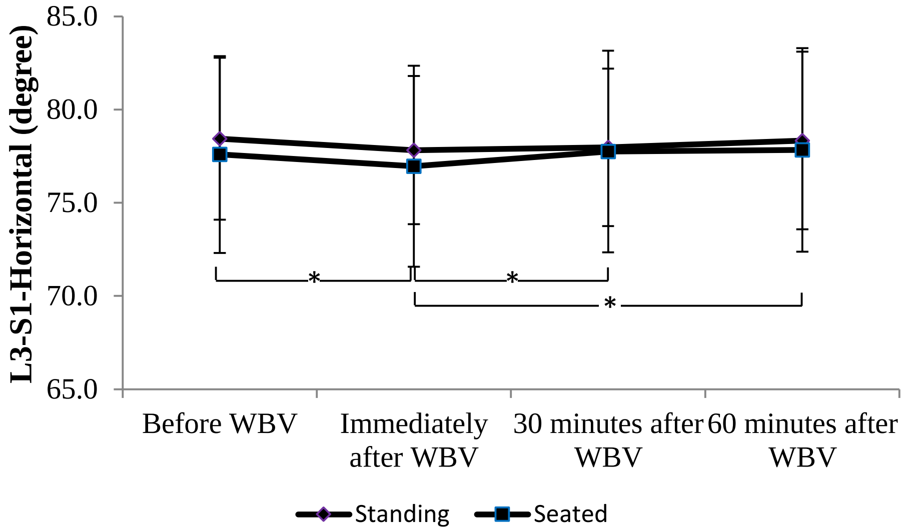

Figure 14 Mean and standard deviation of L3-S1-Horizontal before and after whole body vibration for standing and seated groups (for P < 0.05)*

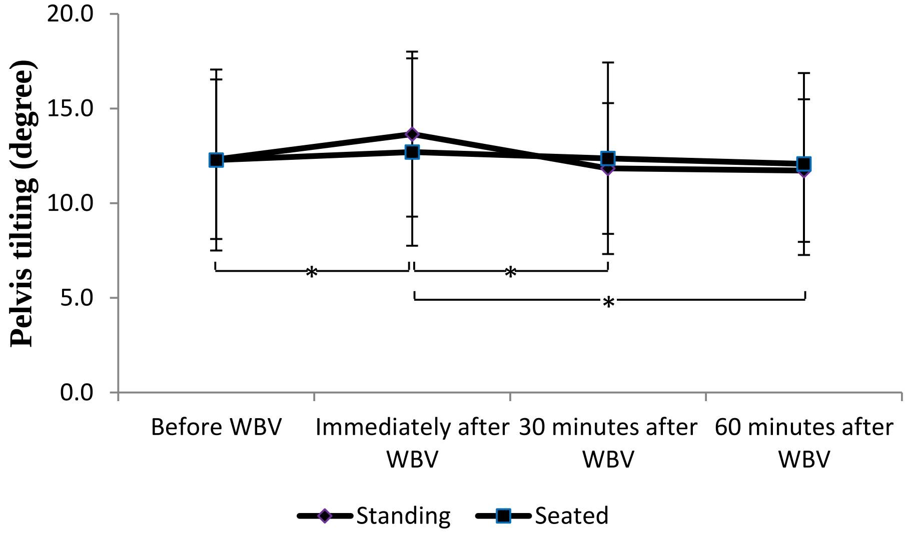

Figure 15 Mean and standard deviation of pelvis tilting before and after whole body vibration for standing and seated groups (for P < 0.05)*

	Angles (Mean ± SD) (°)			
	Before WBV	***Immediately after WBV***	***30 minutes after WBV***	***1 hour after WBV***
CH-C7-T2	53.9 ± 4.8	53.7 ± 5.1	52.7 ± 5.3	52.7 ± 4.8
C7-T2-T5	14.0 ± 7.2	13.9 ± 7.3	13.8 ± 7.5	13.9 ± 7.3
T2-T5-T7	8.0 ± 3.4	7.9 ± 4.1	7.9 ± 4.4	7.9 ± 4.1
T5-T7-T12	11.8 ± 4.1	11.5 ± 3.7	11.0 ± 3.7	11.7 ± 4.1
T7-T12-L3	5.1 ± 2.4	4.4 ± 2.5	3.9 ± 3.0	4.2 ± 3.5
T12-L3-S1	17.6 ± 2.6	17.6 ± 2.5	17.3 ± 3.3	17.5 ± 3.4
L3-S1-Horizontal	78.4 ± 4.3	77.8 ± 4.0	78.0 ± 4.2	78.3 ± 4.8
Pelvis tilting	12.3 ± 4.2	13.7 ± 4.4	11.8 ± 3.4	11.7 ± 3.8
Knee angle	3.6 ± 4.3	4.2 ± 4.4	3.7 ± 4.6	3.5 ± 4.5
Ankle angle	85.4 ± 3.3	86.1 ± 4.3	84.5 ± 2.3	84.3 ± 2.6

Table 5 Mean and standard deviation of body alignment angles before and periods after whole body vibration for standing WBV group.

	Angles (Mean ± SD) (°)			
	Before WBV	***Immediately after WBV***	***30 minutes after WBV***	***1 hour after WBV***
CH-C7-T2	53.5 ± 4.5	53.6 ± 5.2	52.9 ± 5.2	52.7 ± 5.7
C7-T2-T5	12.0 ± 4.2	11.6 ± 4.4	11.9 ± 4.5	11.8 ± 4.4
T2-T5-T7	10.6 ± 3.6	10.2 ± 3.6	10.8 ± 4.0	10.5 ± 3.9
T5-T7-T12	13.5 ± 3.7	13.2 ± 3.5	13.6 ± 3.6	13.4 ± 3.6
T7-T12-L3	4.5 ± 2.5	5.0 ± 2.8	4.3 ± 2.2	5.1 ± 2.4
T12-L3-S1	19.7 ± 5.6	18.7 ± 4.9	19.1 ± 5.1	18.4 ± 4.8
L3-S1-Horizontal	77.6 ± 5.3	77.0 ± 5.4	77.7 ± 5.4	77.8 ± 5.5
Pelvis tilting	12.3 ± 4.8	12.7 ± 4.9	12.4 ± 5.1	12.1 ± 4.8
Knee angle	3.5 ± 4.6	3.4 ± 4.5	3.3 ± 4.7	3.7 ± 4.7
Ankle angle	84.7 ± 1.7	85.0 ± 1.6	84.5 ± 1.7	84.5 ± 1.5

Table 6 Mean and standard deviation of body alignment angles before and periods after whole body vibration for seated WBV group.

4.2 Second stage: Healthy group VS LBP group

4.2.1 Pain Intensity and Anthropometric data

For LBP subjects (n = 8) invited in the second stage, their mean (SD) age, body height and weight were 23.1 (4.3) years, 172.8 (4.7) cm and 62.0 (6.8) kg respectively. All the participants including those in LBP group reported to have no pain before and after the experiment, so pain intensity index was not necessary in the study. There was no significant difference in all anthropometric parameters for two groups (Age: p = 0.563; Height: p = 0.626; Weight: p = 0.450).

4.2.2 Functional Reach Test

For maximum reaching distance, there was no significant interaction between group and time factors ($F(3,14)=0.949$, $p=0.464$, partial $\eta^2=0.169$) and no group difference ($F(3,14)=3.544$, $p=0.079$, partial $\eta^2=0.181$). There was a significant increase in maximum reaching distance after WBV ($F(3,14)=25.328$, $p<0.001$, partial $\eta^2=0.844$) (Figure 16). The difference in maximum reaching distance between participants with and without LBP was marginally insignificant ($F(3,14)=3.554$, $p=0.079$, partial $\eta^2=0.181$). Post-Hoc comparison showed that maximum reaching distance in both groups was significantly increased immediately after WBV ($p<0.001$), 30 minutes after WBV ($p<0.001$) and 1 hour after WBV ($p<0.001$) compared to the baseline value. Maximum reaching distance was also found to be significantly smaller 1 hour after WBV than that immediately after WBV ($p<0.049$) (Figure 16).

For MARP in flexion, there was a significant interaction between group and time factors ($F(3,14)=4.273$, $p=0.024$, *partial* $\eta^2=0.478$). The main effects of time ($F(3,14)=35.215$, $p<0.001$, *partial* $\eta^2=0.883$) and group ($F(3,14)=9.704$, $p=0.007$, *partial* $\eta^2=0.378$) were statistically significant. MARP in flexion of participants with LBP was significantly greater than those of the control (seated group) before ($p=0.007$) and after WBV (30 minutes after: $p=0.025$; 60 minutes after: $p<0.001$) except immediately after WBV (Figure 17). For participants with LBP ($F(3,7)=49.218$, $p<0.001$, *partial* $\eta^2=0.967$), MARP in flexion significantly decreased immediately after WBV ($p<0.001$) and then gradually increased significantly 30 minutes ($p=0.002$) and 60 minutes after WBV ($p<0.001$) (Figure 17). MARP in flexion of participants with LBP after WBV was significantly lower than that before WBV in all periods (immediately after WBV: $p<0.001$; 30 minutes after WBV: $p<0.001$ and 60 minutes after WBV: $p<0.001$) (Figure 17). For the control group ($F(3,7)= 8.796$, $p=0.009$, *partial* $\eta^2=0.844$), MARP in flexion significantly decreased after WBV (immediate after: $p<0.001$; 30 minutes after: $p=0.001$; 60 minutes after: $p=0.001$),which is the exactly the trend in first stage study (Figure 17).

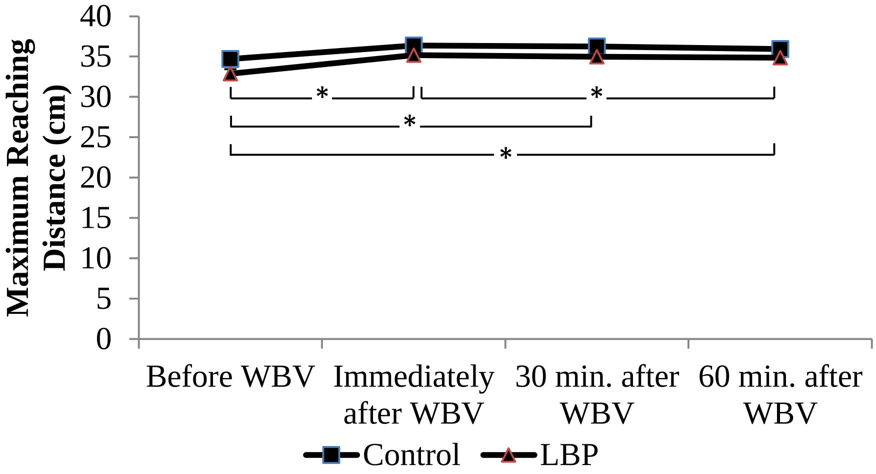

Figure 16 Mean and standard deviation of maximum reaching distance before and periods after whole body vibration of seated control and LBP groups (for P < 0.05).*

For MARP in extension, there was no significant interaction between group and time factors (*F(3,14)=0.431, p=0.734, partial* η^2*=0.085*). There was no significant difference in MARP in extension between participants with and without LBP (*F(3,14)=0.483, p=0.497, partial* η^2*=0.029*). MARP in extension for both groups (*F(3,14)=11.965, p<0.001, partial* η^2*=0.719*) decreased significantly immediately after WBV (*p<0.001*) and increased significantly 30 minutes (*p=0.013*) and 60 minutes after WBV (*p=0.047*) (Figure 18). MARP in extension was significantly lower than that before WBV in all periods (immediately after WBV: *p=0.013;* 30 minutes after WBV: *p=0.002* and 60 minutes after WBV: *p=0.047*) (Figure 18). All the corresponding parameters were shown in Table 7.

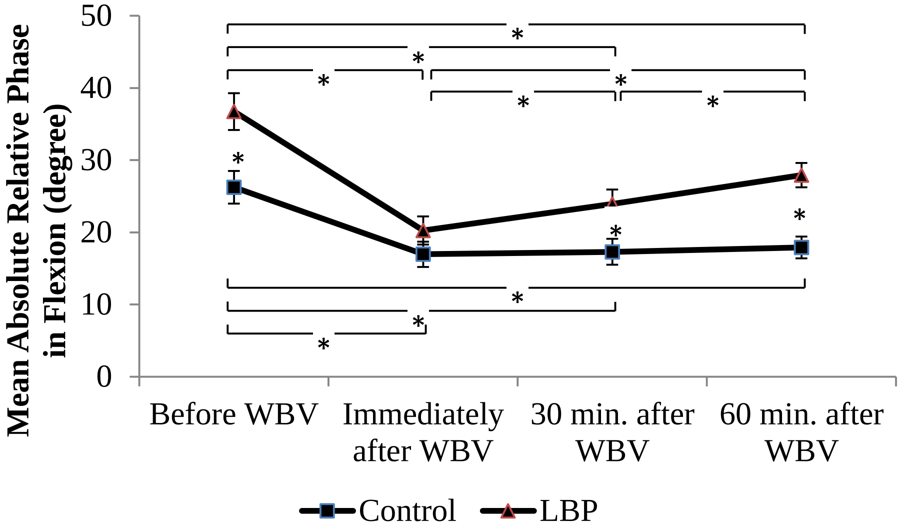

Figure 17 Mean and standard deviation of mean absolute relative phase in forward direction before and periods after whole body vibration of seated control and LBP groups (for P < 0.05).*

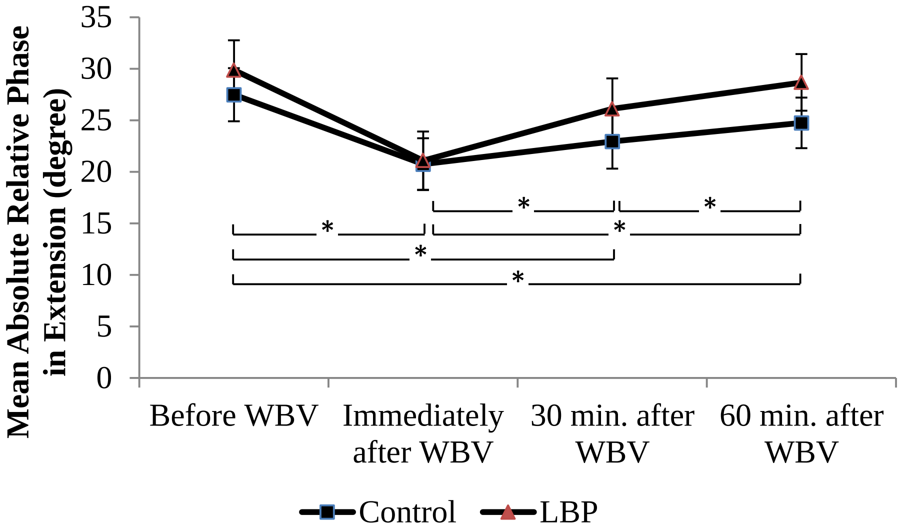

Figure 18 Mean and standard deviation of mean absolute relative phase in backward direction before and periods after whole body vibration of seated control and LBP groups (for P < 0.05).*

For deviation phase, there was no significant interaction between group and time factors in both flexion (*F(3,14)=0.385, p=0.765, partial* η^2*=0.076*) and extension (*F(3,14)=0.204, p=0.892, partial* η^2*=0.042*). The main effect of time was not significantly in flexion (*F(3,14)=2.411, p=0.110, partial* η^2*=0.341*) and in extension (*F(3,14)=2.977, p=0.068, partial* η^2*=0.389*). There was a significant difference in MARP between participants with and without LBP in both flexion (*F(3,14)=29.847, p<0.001, partial* η^2*=0.651*) and extension (*F(3,14)=14.341, p=0.002, partial* η^2*=0.473*) (Figure 19, 20). The corresponding values for both groups were shown in Table 8.

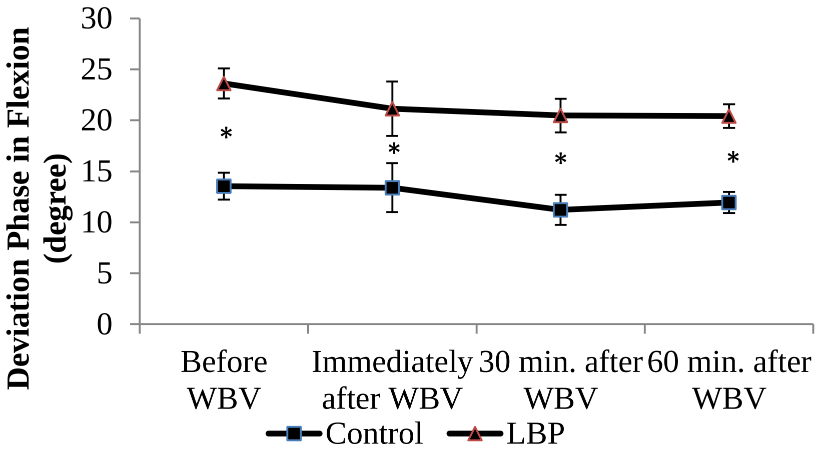

Figure 19 Mean and standard deviation of deviation phase in flexion before and periods after whole body vibration of seated control and LBP groups (for P < 0.05).*

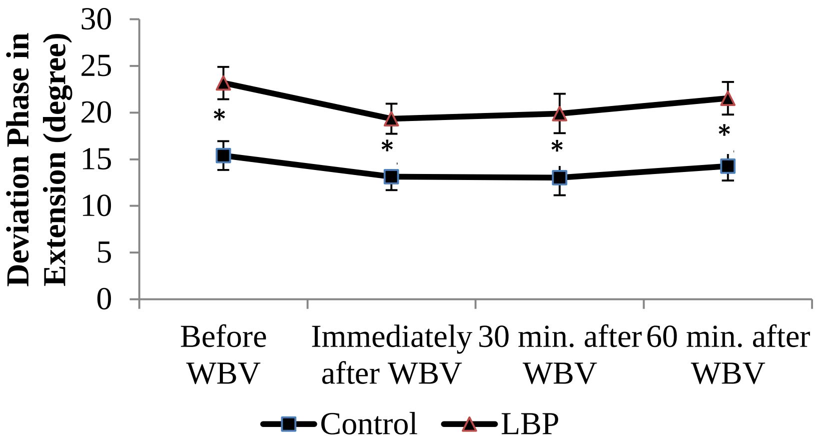

Figure 20 Mean and standard deviation of deviation phase in extension before and periods after whole body vibration of seated control and LBP groups (for P < 0.05).*

Assessment period	Mean Absolute Relative Phase (°) (Mean ± SD)			
	Forward motion		Backward motion	
	Seated group	LBP group	Seated group	LBP group
Before WBV	26.3 ± 8.4	36.7 ± 5.2	27.5 ± 10.3	29.9 ± 4.1
Immediately after WBV	17.0 ± 6.0	20.3 ± 4.7	20.7 ± 9.9	21.1 ± 4.4
30 minutes after WBV	17.3 ± 6.0	24.0 ± 5.1	23.0 ± 10.2	26.1 ± 4.9
1 hour after WBV	17.9 ± 4.7	27.9 ± 4.9	24.7 ± 9.8	28.7 ± 3.7

Table 7 Mean and standard deviation of mean absolute relative phase before and after whole body vibration of seated and LBP groups.

Assessment period	Deviation Phase (Mean ± SD) (°)			
	Forward motion		Backward motion	
	Seated group	LBP group	Seated group	LBP group
Before WBV	13.5 ± 3.4	23.6 ± 5.1	15.4 ± 3.8	23.2 ± 6.0
Immediately after WBV	13.4 ± 8.2	21.2 ± 6.5	13.1 ± 4.4	19.3 ± 4.7
30 minutes after WBV	11.2 ± 3.5	20.5 ± 5.8	13.0 ± 6.7	19.9 ± 4.8
1 hour after WBV	*12.0 ± 2.8*	20.4 ± 3.8	*14.3 ± 4.3*	21.5 ± 5.7

Table 8 Mean and standard deviation of deviation phase before and after whole body vibration for seated and LBP groups.

4.2.3 Repositioning Test

There was no significant interaction between group and time factors for constant error ($F(3,14)=2.034$, $p=0.155$, partial $\eta^2=0.304$), variable error ($F(3,14)=0.813$, $p=0.508$, partial $\eta^2=0.148$) and absolute error ($F(3,14)=1.884$, $p=0.179$, partial $\eta^2=0.288$). There was also no group difference for constant error ($F(3,14)=0.336$, $p=0.570$, partial $\eta^2=0.021$), variable error ($F(3,14)=0.712$, $p=0.411$, partial $\eta^2=0.043$) and absolute error ($F(3,14)=2.432$, $p=0.138$, partial $\eta^2=0.132$). Although there was no significant time effect on constant ($F(3,14)=2.594$, $p=0.094$, partial $\eta^2=0.357$) and variable ($F(3,14)=1.456$, $p=0.269$, partial $\eta^2=0.238$) error, there was a significant change in absolute error among different periods ($F(3,14)=27.336$, $p<0.001$, partial $\eta^2=0.854$) (Figure 19). Post-Hoc comparison showed that absolute error in both groups was significantly increased immediately after WBV ($p<0.001$), 30 minutes after WBV ($p<0.001$) and 1 hour after WBV ($p<0.001$) compared to the baseline value. The corresponding values of errors for both groups were shown in Table 9.

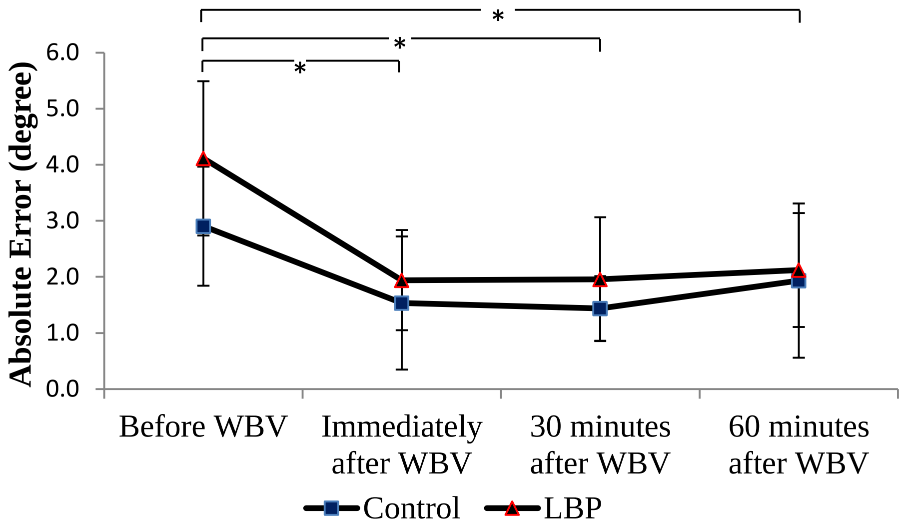

Figure 21 Mean and standard deviation of absolute error before and after whole body vibration for seated control and LBP groups (for P < 0.05)*

	Repositioning Errors (Mean ± SD) (°)					
	Constant Error		**Variable Error**		**Absolute Error**	
	Seated	**LBP**	**Seated**	**LBP**	**Seated**	**LBP**
Before WBV	1.4 ± 2.6	2.4 ± 3.7	1.7 ± 1.1	1.2 ± 0.5	2.9 ± 1.1	4.1 ± 1.4
Immediately after WBV	0.9 ± 1.6	0.4 ± 2.2	1.0 ± 0.7	1.0 ± 0.7	1.5 ± 1.2	1.9 ± 0.9
30 minutes after WBV	0.3 ± 1.5	0.6 ± 2.2	1.2 ± 0.5	0.9 ± 0.6	1.4 ± 0.6	2.0 ± 1.1
60 minutes after WBV	-0.1 ± 2.3	1.3 ± 1.9	1.2 ± 0.7	1.2 ± 0.5	1.9 ± 1.4	2.1 ± 1.0

Table 9 Mean and standard deviation of constant, variable and absolute error before and after whole body vibration for seated control and LBP groups

4.2.4 Body alignment measurement

For CH-C7-T2**,** T5-T7-T12, T7-T12-L3 and knee angle, there were no interaction between time and group; and time and group effect (Appendix 7.7). Interaction between time and group could only be observed in T12-L3-S1 ($F(3,14)=4.297$, $p=0.024$, partial $\eta^2=0.479$), however, angular differences among time periods could not be observed for both the control group ($F(3,5)=3.834$, $p=0.065$, partial $\eta^2=0.622$) and the LBP group ($F(3,5)=1.146$, $p=0.416$, partial $\eta^2=0.408$). Moreover, no significant difference of the knee angle was found between the two groups before ($p=0.934$), immediately after ($p=0.495$), 30 minutes after ($p=0.824$) and 60 minutes after WBV ($p=0.589$). Pelvis tilt was found to be larger in LBP group than control group ($F(3,14)=5.203$, $p=0.037$, partial $\eta^2=0.479$) (Figure 20). C7-T2-T5 ($F(3,14)=3.345$, $p=0.043$, partial $\eta^2=0.432$) (Figure 21), T2-T5-T7 ($F(3,14)=4.363$, $p=0.023$, partial $\eta^2=0.483$) (Figure 22), L3-S1-Horizontal ($F(3,14)=5.342$, $p=0.012$, partial $\eta^2=0.534$) (Figure 23), ankle angle ($F(3,14)=7.76$, $p=0.003$, partial $\eta^2=0.624$) (Figure 20) were significantly different during different periods in both groups. C7-T2-T5 was significantly smaller immediately after WBV ($p=0.008$), while T2-T5-T7 immediately after WBV was significantly smaller than that 30 minutes after WBV ($p=0.004$). L3-S1-horizontal was significantly smaller immediately after WBV ($p=0.017$) and became significantly larger 30 minutes after WBV ($p=0.005$), while ankle angle was significantly larger immediately after WBV ($p=0.004$) and became significantly smaller 30 minutes after WBV (*p=0.002*). The corresponding values of the angles and statistics of LBP groups were shown in Table 10 and Appendix 7.8 respectively.

	Angles (Mean ± SD) (°)			
	Before WBV	***Immediately after WBV***	***30 minutes after WBV***	***1 hour after WBV***
CH-C7-T2	53.1 ± 4.0	54.1 ± 3.0	53.2 ± 4.6	54.0 ± 4.0
C7-T2-T5	15.3 ± 1.9	14.7 ± 2.1	15.1 ± 2.0	15.3 ± 1.5
T2-T5-T7	10.2 ± 4.0	10.0 ± 3.8	10.3 ± 4.0	10.2 ± 4.1
T5-T7-T12	13.1 ± 4.9	12.3 ± 4.6	12.5 ± 5.0	12.3 ± 5.1
T7-T12-L3	4.4 ± 3.6	4.4 ± 3.2	4.5 ± 3.3	4.9 ± 4.4
T12-L3-S1	13.9 ± 3.4	14.2 ± 3.8	13.6 ± 3.8	13.6 ± 3.7
L3-S1-Horizontal	82.0 ± 3.5	80.9 ± 4.7	81.4 ± 4.6	81.2 ± 4.3
Pelvis tilting	16.5 ± 3.3	17.1 ± 3.1	16.8 ± 3.0	16.9 ± 2.7
Knee angle	3.9 ± 2.5	3.3 ± 2.1	3.6 ± 2.5	3.2 ± 2.1
Ankle angle	83.3 ± 3.0	83.9 ± 2.8	83.3 ± 3.2	83.7 ± 3.6

Table 10 Mean and standard deviation of body alignment angles before and periods after whole body vibration for LBP group (for P < 0.05).*

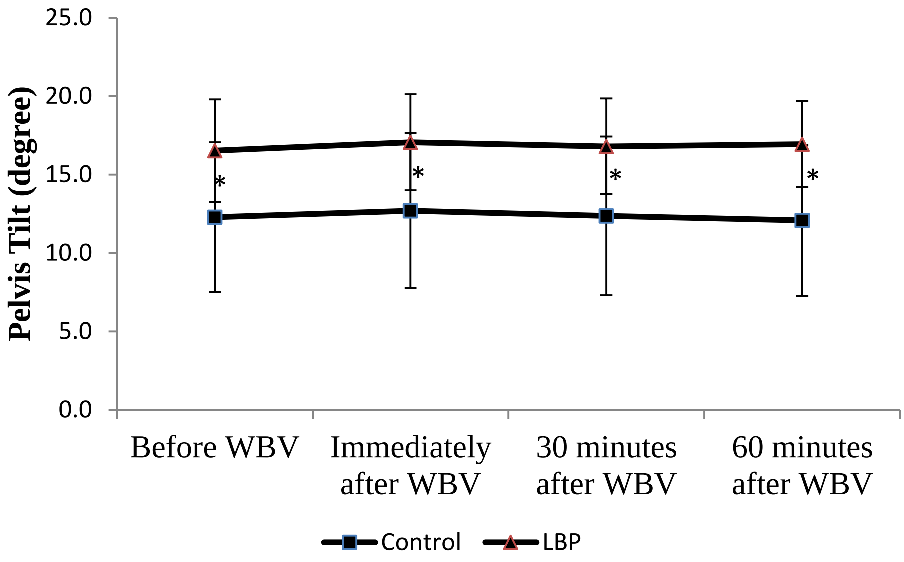

Figure 22 Mean and standard deviation of pelvis tilting before and after whole body vibration for seated control and LBP groups (for P < 0.05)*

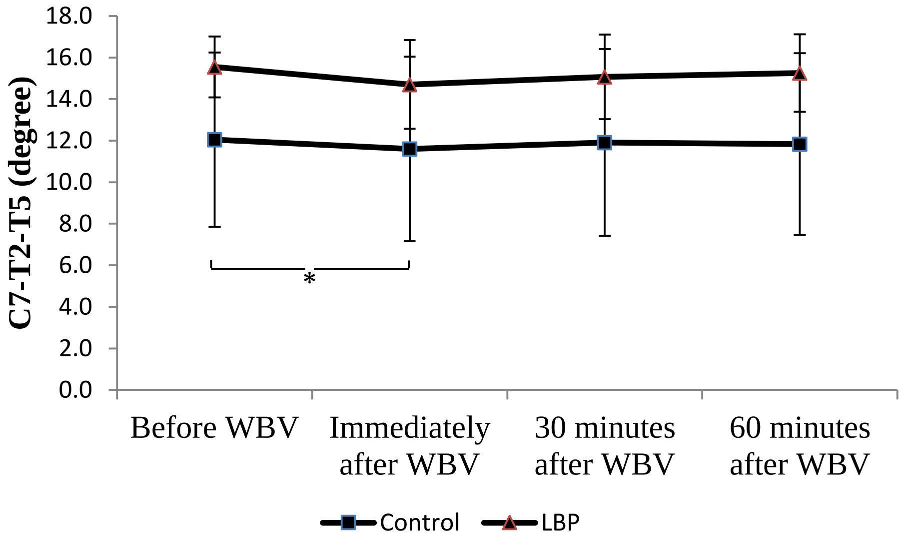

Figure 23 Mean and standard deviation of C7-T2-T5 before and after whole body vibration for seated control and LBP groups (for P < 0.05)*

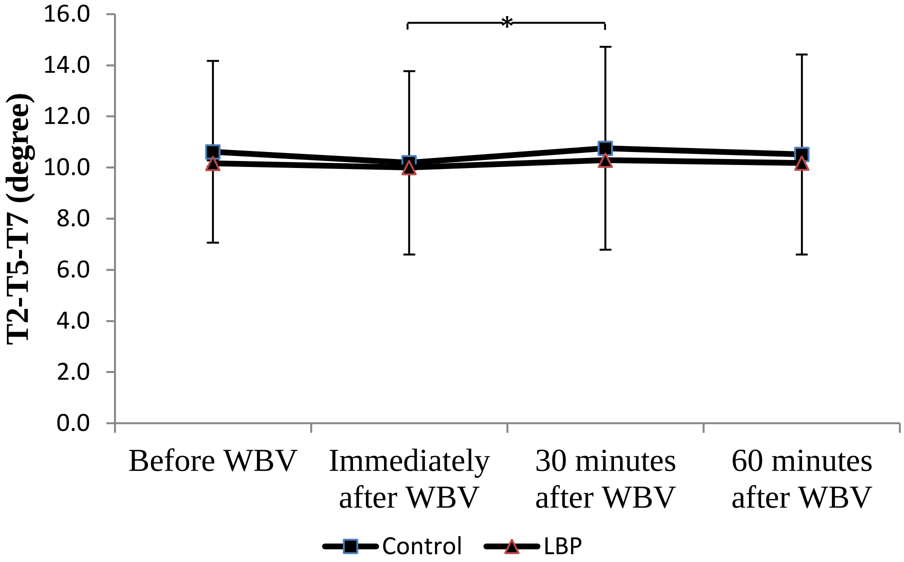

Figure 24 Mean and standard deviation of T2-T5-T7 before and after whole body vibration for seated control and LBP groups (for P < 0.05)*

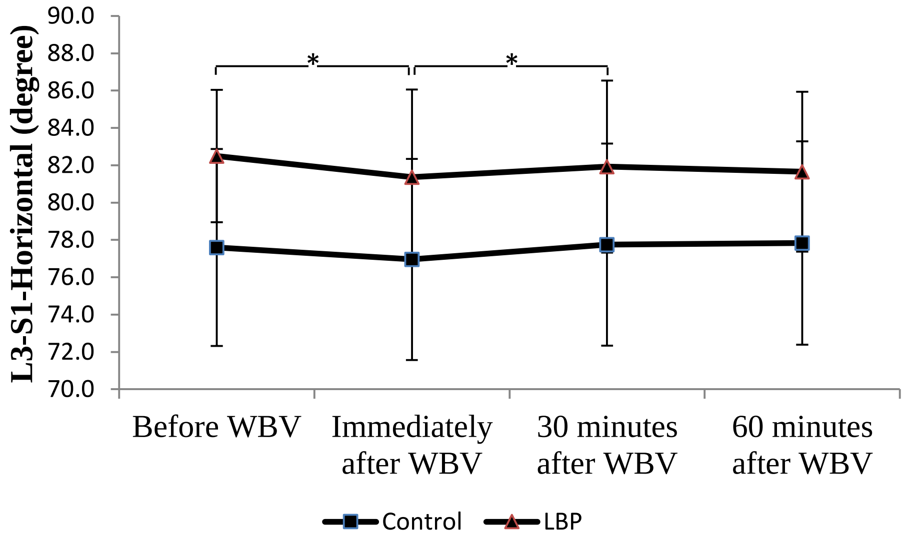

Figure 25 Mean and standard deviation of L3-S1-Horizontal before and after whole body vibration for seated control and LBP groups (for P < 0.05)*

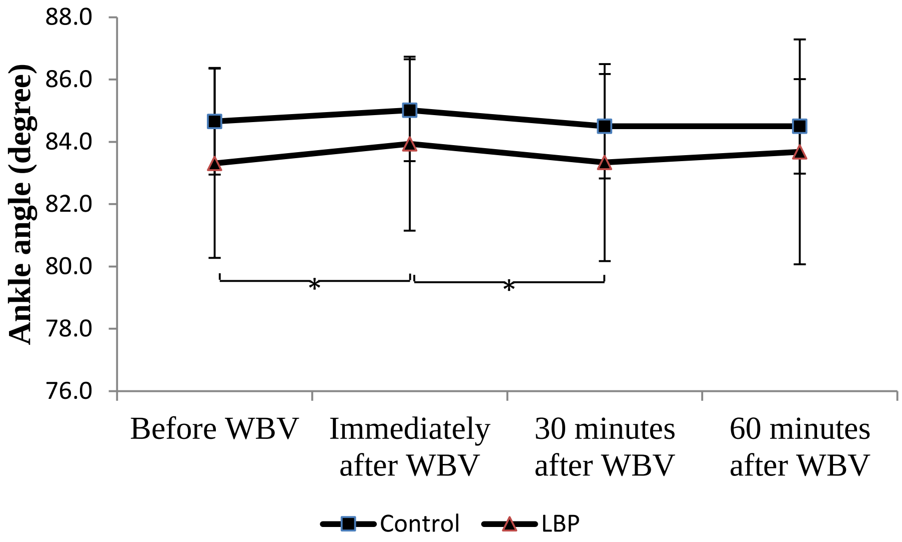

Figure 26 Mean and standard deviation of ankle angle before and after whole body vibration for seated control and LBP groups (for P < 0.05)*

Chapter 5. Discussion

5.1 Different measurements used in this study

Three subsystems, namely, the active musculoskeletal, the passive musculoskeletal and the neural feedback, are required for maintaining spinal stability (Duncan et al. 1990). Within the neural feedback subsystem, mechanical receptors located in the muscles and tendons co-operate with the visual and vestibular systems to provide dynamic updates of self-orientation relating to the surroundings during locomotion and navigation (Panjabi 1992), thereby providing proprioception for spinal motor control and spinal stability. To assess spinal proprioception of an individual, different approaches have been used, e.g. measuring repositioning error, motion perception and the variation of the centre of pressure (Feipel et al. 2003) in performing different tasks. Hence, different tests were performed in this study to thoroughly investigate the effects of WBV on spinal proprioception.

5.2 Body alignment variation

Spinal curvature and lower limb angulations constitute spinal proprioception. The joint mechanoreceptors on the spine and the muscle spindles of the back muscles provide the sense of joint positioning and affect spinal proprioception. By studying the changes of these parameters, it could be verified if they were affected by WBV and if they had any correlation with other measured parameters after WBV treatment.

Upon comparing the standing and the seated WBV groups in the first stage of the study, there was no significant change in body posture before and after WBV, apart from a significant increase in the lower lumbar extension angle and pelvis tilting immediately after WBV. However, in the second stage of the study, several significant alterations of body alignments were detected: the upper thoracic angle, the middle thoracic angle and the lower extension angle were smaller immediately after WBV. This showed that there was a decreased kyphosis in the thoracic region and an increased lordosis in the lordotic region. Such changes could be hypothesized as a compensative mechanism. Furthermore, since all subjects received WBV in seated posture in the second stage of the study, significant increase of the knee angle immediately after WBV was more likely the result of increased lordosis in compensation for the lower extension angle decrement rather than WBV.

Changes in the spinal curvature could probably be explained by increased flexibility of the muscle and the virtual muscle lengthening effect of WBV (Roll et al. 1989), which in turn was likely attributable to the vibratory stimulation of the primary ending of the muscle spindles (Issurin et al. 1999).

As both the pelvis tilting angle and the lower lumbar extension angle of the LBP group were significantly larger than those of the normal seated group, this stated that patients with LBP had a comparatively less lordotic lumbar region and a more tilted pelvis. This finding was similar to the finding of Jackson's whose study revealed a loss of lumbar lordosis and an increase of pelvis tilt in patients with chronic LBP (Jackson et al. 1994). It seemed that seated WBV could induce a larger lordosis to the subjects immediately afterwards, which could not be demonstrated in the first stage of the study.

However, since correlation of changes in spinal curvature, lower limb alignment and proprioception could not be clearly demonstrated in this study, it could only implicate that WBV had some effects on body alignments but the changes might not account for the improvement of proprioception. In addition, it should be noted that the standard deviations of the variables among different assessment periods were relatively high. The results were therefore errors-prone and hence some alterations of the parameters could not be well explained and further study would be required to thoroughly investigate the relationship between the effect of WBV and the body alignment parameters.

5.3 Changes in repositioning ability

In both stages of the study, significant reduction in lumbar repositioning error was observed immediately after WBV for all groups. This finding suggested that WBV could improve repositioning ability and thus enhance proprioception. As such significant improvement still existed 30 minutes afterwards, it indicated 5 minutes of WBV had a positive carryover effect for at least half an hour, irrespective of the subject's group nature and posture. Further, as significant decrease of the repositioning error was only demonstrated between the seated (control) group and the LBP group in the second stage of the study 60 minutes after WBV, it might suggest that WBV would be more beneficial and long lasting to users in seated posture since the subjects in the second stage received it in seated posture.

Trunk muscle dysfunction was probably one of the reasons which caused changes in normal afferent input from the affected muscles and hence proprioceptive deficit in patients with LBP (Newcomer et al. 2001). Although there was no significant group difference between the control and LBP groups in the second stage of the study, it was observed that the baseline value of the absolute error of the LBP group tended to be larger than that of the control group. In addition, the fact that the difference of repositioning error between healthy and LBP subjects decreased after WBV demonstrated that the improvement of the repositioning performance of the LBP patients after WBV was somewhat comparable to the healthy individuals.

Since the criterion position used in this study was a neutral position, it could be hypothesized that muscle afferents were the primary contributors for proprioceptive sense since the ligaments and other connective tissues should be under least tension (Heikkila et al. 1998). It could be further hypothesized that the vibration of WBV stimulated the muscle spindles on the trunk muscles, which probably refreshed the altered afferent input of the LBP subjects, thereby resulting in improved repositioning ability. But it seemed that not all types of vibration could improve proprioception. Brumagne et al. (2000c) proved that hand-held vibration (70 Hz, 0.5 mm amplitude) to the lumbar multifidus in the neutral sitting posture actually weakened repositioning ability. This study also showed that the lumbar multifidus muscle might play an important role in proprioceptive sense during neutral position (Brumagne et al. 2000c). In light of the aforesaid, the improvement in repositioning ability after WBV in both the healthy and LBP groups might be due to the advantageous vibratory stimulation to this muscle group.

To investigate static repositioning performance of the participants, spinal repositioning error was measured. Although both standing and four-point kneeling demonstrated significant differences in repositioning ability between normal individuals and LBP patients in previous studies (Gills et al. 1998), the subjects in the current study were only asked to adopt a seated posture in performing the repositioning task, to avoid input from the vestibular system and the afferents of the lower limbs when standing (Newcomer et al. 2000a). Preuss et al. (2003) found that repositioning error in standing was comparatively smaller than that of sitting and suggested that this might be attributable to the changes in spinal sensory input from mechanoreceptors on load-bearing structures such as intervertebral discs (Preuss et al. 2003).

5.4 Alteration in reaching distance

Significant increase in maximum reaching distances after WBV in all three groups suggested that balance and postural control improved after WBV. Interestingly, this effect persisted for 1 hour after WBV for all groups too. This showed that 5 minutes of 18 Hz WBV in either standing or seated posture could improve proprioception for both normal and LBP individuals and induce at least 60 minutes carryover improvement.

Although group difference was marginally insignificant and hence not demonstrative in the second stage of the study, it was nevertheless observed that the maximum reaching distance of the LBP group was shorter than that of the seated control group. This was because lumbar flexibility and static balancing ability of patients with chronic LBP were weaker than normal individuals (Alexander et al. 1998, Brumagne et al. 2000).

Upon analyzing the maximum reaching distance of the seated control group against the LBP group, it was noted that the carryover effect for the LBP group seemed to be less persistent in intensity as the maximum reaching distance at 60 minutes after WBV was significantly shorter than that immediately after WBV. Such phenomenon did not exist when comparing the healthy groups in the first stage of the study. This evidence demonstrated that the improvement tended to persist shorter in patients with LBP.

Reaching tasks are necessary for daily activities (Row et al. 2007; Huang et al. 2013). These tasks generally involve reaching forward and grasping objects in different heights, and returning to an upright position (Huang et al. 2013). As the performance of functional reaching is related to the ability of dynamic balance and postural control of an individual, functional reaching distance is a popular indicator of balance ability (Liao et al. 2013). The advantage of adopting a functional reaching test is that it is an inexpensive and easy way to assess an individual's limits of stability in the forward direction (Duncan et al. 1990). Moreover, functional reaching test has a good correlation with the resultant center of pressure excursion (r = 0.71). Furthermore, it has been demonstrated to be a marker of physical frailty (Weiner et al. 1992). It is therefore sensible to measure dynamic balance with reference to an individual's reaching ability within stability limits (Duncan et al. 1990), as was the case in this study.

5.5 Improvement in lumbo-pelvic coordination

The dynamic reaching test was used to assess postural stability and activity of the lower limb and trunk muscles (Rothmuller et al. 1995). No significant difference on the effect of WBV was observed between standing and seated WBV on healthy subjects in both movement directions. When the standing and seated healthy groups performed the forward and backward reaching motions in the first stage of the study, there was no significant difference of the baseline value of MARP as expected. The baseline MARP value of the LBP group in the second stage was significantly larger than that of the seated group, which demonstrated that patients with LBP had worse inter-segment coordination, as was consistent with previous findings from other studies about altered trunk and pelvis coordination in patients with LBP during other functional tasks (Shum et al. 2007, Vogt et al. 2001).

In the first stage of the study, MARP was found to be significantly reduced for all periods after WBV for both groups in both directions, which showed that the lumbar and pelvic regions were moving in a more coordinated way after WBV and such advantageous effect persisted for at least an hour long. The results also suggested that receiving WBV in seated posture was equally beneficial as receiving WBV in standing. However, it could be observed that MARP in the backward motion had a tendency to restore to the baseline level. This indicated that WBV probably had better training effect on the trunk muscle and thus better improvement in the forward motion. Similar improvement of the movement coordination could also be observed in the LBP group upon comparison. In both forward and backward reaching motions, the lasting effect of WBV on lumbo-pelvic coordination was shorter in the LBP group, since MARP values in both directions increased significantly. However, as the lumbo-pelvic coordination of the LPB group was still significantly better after WBV, it established that long-lasting carryover effect existed for both LBP and healthy subjects, which further proved the beneficial effect of WBV on spinal proprioception.

Improvement of the inter-segment coordination may be caused by repetitive WBV mechanical stimulation, leading to a rearrangement of postural control strategies (Schuhfried et al. 2005). As improvement of the inter-segment coordination was more apparent in the forward motion than in the backward direction, this suggested that WBV might have a stronger effect on back muscles as compared to other trunk muscles. Patients with LBP have been observed to have altered trunk muscle activation pattern (Shirado et al. 1995), which is related to abnormal lumbo-pelvic interaction, especially during flexion motion (Shirado et al. 1995). This probably explained the resultant larger MARP value in the LBP group during the forward motion.

Similar carryover effect appeared in both the LBP and the healthy seated groups in the second stage of our study. Despite both groups received WBV in seated posture, the effect of WBV on lumbo-pelvis coordination of the LBP subjects, however, was not as long-lasting as that of the normal individuals. This stated that the coordination and stability of the movement patterns of patients with LBP tended to deteriorate faster than normal individuals (Stergiou et al.

2006), which in turn suggested that longer period of WBV treatment would be needed for patients with LBP.

The altered motion pattern after WBV could be attributable to the change of the motor plan caused by vibration to the neuromuscular system (Shum et al. 2007), but further investigation on the motion pattern would be necessary to prove it. Nevertheless, improvement of the inter-segmental dynamics showed that WBV enhanced the ability of the subjects to monitor and incorporate dynamic reaching motion. This stated that WBV did have an immediate effect on improving proprioception, which might explain the improvement of motor function and pain relief in LBP patients after receiving 12-week WBV treatment (Rittweger et al., 2002).

5.6 Deviation phase variability

Deviation phase is used as an indicator for reflecting the stability and the variability of the motion pattern. For normal healthy participants, it is not surprising that this parameter was not significantly affected after WBV, since WBV might not be sufficient to induce adaptive changes in young, healthy individuals' neuromuscular system (Dolny et al., 2008). Interestingly, this was also the case for patients with LBP, which showed that WBV might not have any effect on the variability of the motion pattern.

As the deviation phase of the LBP group was always significantly larger than that of the seated control group, it indicated a lack of ability to maintain a consistently coordinate pattern, thereby proving that the neuromuscular system of the LBP group was less stable as compared to normal individuals. Furthermore, the significant constant value of the deviation phase suggested that the improvement of coordination after WBV could not be reflected in terms of neuromuscular variability.

5.7 Further discussion for the alterations in the parameters

As mentioned in the introduction, several neurophysiological response wouild be initiated by vibration stimulus, such as the change of muscles' lengths which in turn triggers the primary and the secondary ending of receptors by detecting the alternation (Berthoz 2001). When mechanoreceptors such as the muscle spindles are activated by WBV, the α-motor neurons are also activated, leading to muscle contractions similar to the tonic vibration reflex (Bosco et al. 1999). Similar to the afferent of the muscle spindles, the Ib-afferents of the Golgi tendon would also respond to the vibration (Burke et al. 1976). When the muscle contracts due to WBV, the afferent Golgi organs become more sensitive to the vibration and send corresponding signals to the motor system throughout central nervous system for motor control (Lundberg et al. 1975). Hence, ultimately the improved performance from the groups after WBV is very probably caused by the extensive sensory stimulation and the increased efficiency of the proprioceptive feedback loop due to WBV (Bogaerts et al. 2007).

Similar to the findings of other studies, it was observed in this research that WBV could improve neuromuscular function (Abercromby et al. 2007) and increase muscle flexibility (Van der Tilaar R 2006, Jacobs et al. 2009, Karatrantou et al. 2012) and hence improving the maximum reaching distance and lumbo-pelvic coordination. Such improvements were likely induced by the activation of the Ia-afferent fibers and α-motor neurons by repetitive stimulation of the back muscles during WBV (Seidel 1988), which led to enhanced flexibility. It has also been hypothesized that increased muscle flexibility and improvement of proprioception could be caused by a larger number of type II muscle fibre recruitment, without inducing muscle fatigue or overexertion (Avelar et al. 2012). The improved movement coordination and postural stability in LBP patients might also be due to increased muscle strength, improved synchronization of the firing of motor units and improved co-contraction of synergist muscles after WBV training (Jordan et al., 2005). While WBV was delivered to the subjects in this study, redness of the skin could be observed on some of them, which was a sign of increased blood flow in muscles, which in turn led to increased muscle temperature and thereby increase muscle extensibility (Issurin et al. 1994). This might be another possible explanation for increased muscle flexibility after WBV in this study reflected by the longer maximum reaching distance (Kerschan-Schindl K et al. 2001). Duclos et al. found that activation of sensory motor cortical networks by the signals from the proprioceptive receptors, as induced by mechanical stimulation, sustained after WBV application (Duclos et al. 2007). This might account for the carryover effect.

Improvements in neuromuscular performance and muscle flexibility have also been observed after static stretching (Flopp et al. 2006, Magnusson et al. 1997). However, such increased flexibility might likely be contributed by stretch tolerance rather than the modification of the muscle viscoelastic properties. While passive warm-up or voluntary exercise could not recruit type II muscle fibres in the working muscles, WBV could. Through stimulation, WBV facilitates neuromuscular coordination (Kelly et al. 2010) by providing a greater activation of the mechanoreceptors and the tonic vibration reflex, which acts predominantly on α-motor neurons (Roll et al. 1980). Moreover, it has been demonstrated that the effect of WBV together with stretching on knee flexibility persisted longer than stretching alone (Cardinale et al. 2003), demonstrating that such beneficial effect of WBV on limb muscles could also happen in the spinal musculature (Feland et al. 2010).

Last but not least, hip–knee intra-limb coordination was found to have been improved in a study investigating about the effects of WBV on walking function, which suggested that WBV might provide some sorts of locomotor training to the lower limb (Ness et al. 2009). Accordingly, it could be hypothesized that WBV could also provide similar training effect to the lumbar and pelvis regions and thus improved coordination of the lumbar-pelvis segment as observed in this study.

5.8 Limitations and future studies

There were several limitations of this study. 1. The vibration used in this study consists of high intensity and special precautions might be necessary during the application of WBV to the users. Once the vibration intensity exceeds the exposure or the fatigue limit, possible hazardous effect might be induced if such vibration is applied in long term (Appendix 7.6). 2. Learning effect might exist with repetition of the task performance by the subjects. A control group might be necessary in future study to justify the absence of learning effect. However in this study, since different trends had been observed in each group in this study, it could be assumed that such effect was negligible. Moreover, sufficient practices were provided to the subjects for the functional reach test, including the static and dynamic reach task, and the repositioning test. For instance, at least three trials were given to the subjects for the static reaching task prior to the experiment assessment. They will only be allowed to start the experiment once they could well perform the standard of the defined tasks in this study. . 3. As analysis was limited to the sagittal plane and trunk movement in the tests should be 3-dimentional, the findings only provided a partial picture of the subjects' motion analysis. 4. Since the experiment lasted for more than two and a half hours for each subject who had to spend at least another hour on assessment (Appendix 7.8), it was possible that they might be fatigued, even though the assessment tasks had been sequenced to minimize such effect. 5. EMGs of the spinal and leg muscles were not investigated in this study, so no conclusive effect of WBV on any alternation of muscle strength could be reported. One of the difficulties encountered in this study for not measuring EMG of the muscles was that surface electrode of the EMG might easily fall off during WBV and it would not be feasible for re-attachment of electrodes. Moreover, there were markers attached on the back and limbs, which may cause extra difficulty when attaching the patches. 6. As (i) WBV delivered to the spinal region could differ within groups due to the subjects' BMI differences and (ii) the magnitude difference of WBV delivered to the spine in standing and seated postures had not been taken into account, further researches would be required to thoroughly investigate the transmissibility of WBV delivered in both postures and to control, if possible, its intensity for better comparison of effects.

The absence of a control group was one of the major limitations of this study, and it would be necessary in future study to justify the absence of learning effect. Nevertheless, sufficient practices were provided to the subjects for the functional reach test, including the static and dynamic reach tasks, and the repositioning test. For instance, at least three trials were given to the subjects for the static reaching task prior to the experiment assessment. They will only be allowed to start the experiment once they could well perform the standard of the defined tasks in this study.

Above all, WBV protocol should be selected very carefully so as to balance its risk and benefit. In future studies, effects of WBV using the same parameters in this study on EMG of the lower limb and trunk muscles should be studied, in order to investigate whether there is any correlation between the muscle strength and the improvement of proprioception. In addition, the effect of standing WBV group for LBP patients would also be suggested in order to find out whether similar outcomes would be obtained comparing with LBP receiving WBV in seated posture. Moreover, WBV with different amplitudes and durations in 18 Hz should be investigation to figure out the best combination for LBP treatment. Since the possible learning effect is one of the major limitations in this study, it would also be necessary to investigate the possibility of the existence of learning effect of repeated assessments used in this study.

Chapter 6. Conclusion

By measuring proprioception in terms of the coordination pattern with the dynamical systems approach, the repositioning ability and the body alignment, it provided a better understanding on the effect of WBV on the neuromuscular system of both normal and LBP individuals. Though vibration intensities of WBV received in standing and seated posture may be different, the beneficial effects on proprioception on normal individuals seemed to have no difference. In short, the results in the study demonstrated that 5 minutes of 18 Hz low frequency WBV could significantly improve proprioception in terms of lumbo-pelvic coordination and reaching function without any apparent adverse effect for both normal and LBP individuals, suggesting that WBV had the potential of reducing the recurrent rate for patients with LBP, although more experiments would be necessary for further confirmation. It should be noted that the frequency and amplitude of WBV could be critical, because vibration could produce very different impact, either beneficial or detrimental (Cardinale et al. 2003). Further study on patients with LBP who have undergone similar WBV protocol is recommended to confirm its clinical application on improving proprioception.

Chapter 7. Appendices

7.1 Residual Analysis

When a motion study was being performed, signal might vary with time during data capture. For instance, the coordinate of the marker on the ulnar head used in the functional reach test during the forward direction would have certain higher frequencies than those of other locations such as the ASISs and the great trochanter. Winter et al. (1974) had shown that the highest harmonics for normal walking was around the toe and heel trajectories, and most of the signal power existed below 6 Hz, which represented the lower seven harmonic. Noise was above the seven harmonic and could possibly add a random component to the actual signal (Winter et al. 1974). This phenomenon would thus appear in the dynamical functional reach test and hence data filtering would be required for the removal of the noise. One of the methods was to perform a residual analysis, which showed the differences between a non-filtered and a filtered signal over a range of cutoff frequencies (f_c) (Figure 27).

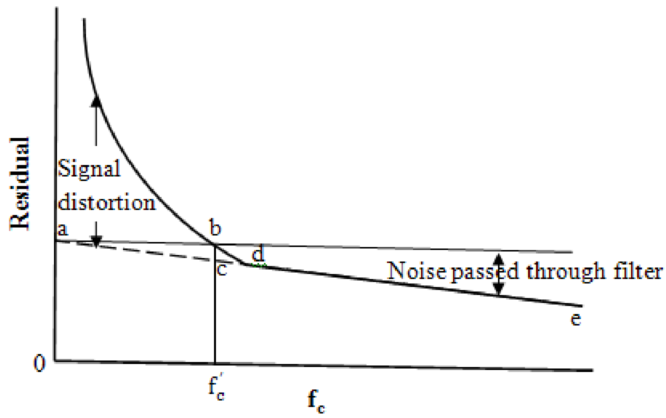

Figure 27 Theoretical plot of the residual between a non-filtered and a filtered signal as a function of the filter cutoff frequency

The residual at any cutoff frequency ($R(f_c)$) for a signal of N data frames in time was calculated as below:

$$R(f_c) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \hat{x}_i)^2} \qquad \text{---------- (5)}$$

where x_i represented the raw data of *i*th sample and $\hat{x}_i$ represented the filtered data of *i*th sample.

If the data was composed of mere random noise, the residual plot would be purely a straight line with a negative slope, starting from the vertical intercept at 0 Hz frequency to the horizontal intercept at the Nyquist frequency (f_s) (Winter et al. 1974). The line *de* was the best estimate of the noise residual. In Figure 27, point *a* represented the root mean square (RMS) of the noise at 0 Hz frequency. The residual value would rise above the dotted line when the data consisted of true and noise signals as f_c decreased. The rise would further increase when f_c reduced.

In order to determine the optimal value of f_c, a line was projected horizontally from *a* to *b*. Line *bc* represented the signal distortion when $f_c = f_c'$, which also represented the estimate of the noise signal passing through the filter. The plot of four markers from a functional reach task trial in the x, y and z coordinates were shown as an example in Figure 28. The straight line near the bottom part of the graph was the regression line. It could be seen that the regression line was essential for all markers and for informing how much noise was being introduced to the system. Based on the graph, the cutoff frequency was decided as $f_c = 3$ Hz.

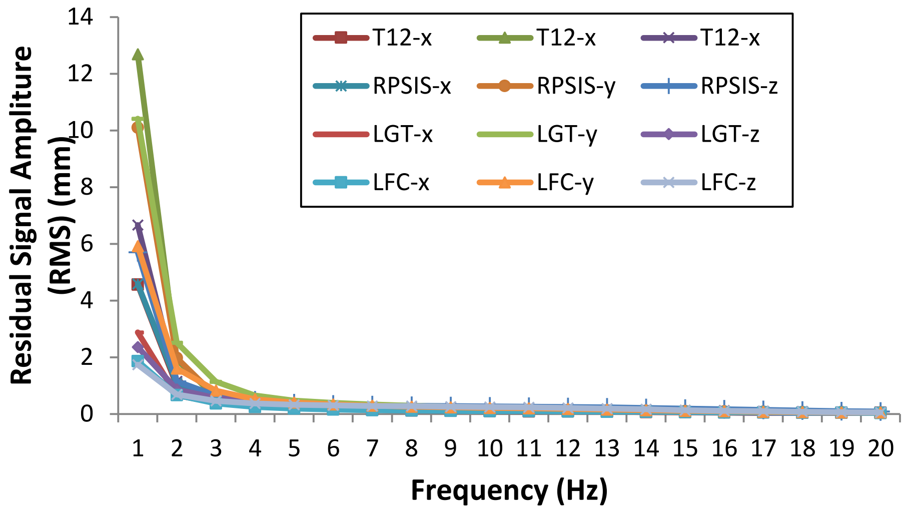

Figure 28 Plot of the residual of four markers from a functional reach task trial; the x, y and z displacement data. All the data were digitized using the motion analysis system.

7.2 Phase Angle

The phase angle quantifies the behaviour of interested body segments and iss used to calculate relative phase. To calculate the phase angle, Cartesian coordinate was transformed into polar coordinate, with a radius r and phase angle θ (Figure 29) (Kelso et al. 1986). The angle formed by the radius and the horizontal axis is the phase angle of the trajectory which equals to tanarc (y/x), where y was the angular velocity and x is the angular displacement at the ith point of the trajectory (i.e. equation 1 in page 39). Relative phase provides a measure of the interaction or coordination of two segments during the gait cycle (Haken et al. 1985). To calculate relative phase, the phase angle of the proximal segment is subtracted from that of the distal segment for each ith data point of the time-normalized gait cycle as follows:

$$\theta_{\text{relative phase}} = \phi_{\text{distal segment}} - \phi_{\text{proximal segment}} \qquad \text{----------} \ (6)$$

The distal and proximal segments were the lumbar and pelvis regions respectively in this study and formed equation 2 in page 39.

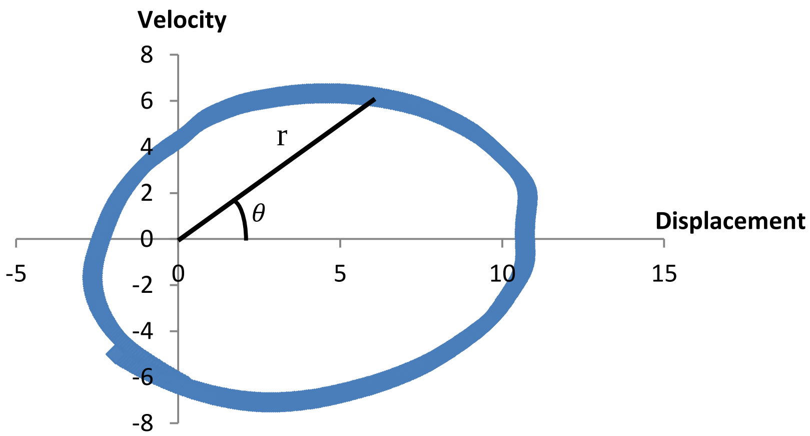

Figure 29 A phase angle plot with r as radius and θ as phase angle

The advantage of the relative phase measure was that it compressed proximal and segments' displacement and velocity into one measure. Relative phase values that are zero degrees suggested that the two oscillating segments were in phase, while relative phase values that approached 180 degrees were considered out of phase (Diedrich and Warren, 1995). Using equations 3 and 4 in page 39, MARP and DP could be derived.

The purpose of using phase plot normalization was to produce a scalar multiple of the original trajectory so that it could be centralized to the origin to ensure that the amplitude differences between interested segments would not affect the measurements (Li et al. 1999). However, there was a possibility that normalization would modify the dynamic qualities of the oscillating segments, namely, the lumbar and pelvis regions in this study, because this technique would normalize the phase plot coordinates with different scaling factors (Kurz et al. 2002). Hence, the aspect ratio of the dynamics of the oscillating segments would be lost and this would lead to an alteration of the non-linear characteristics of the segments. In fact, amplitude differences might not be problematic since the phase angle calculation used the arc tangent function, i.e. $\vartheta = \tan^{-1}\left(\frac{\text{angular velocity}}{\text{displacement}}\right)$, which would remove the differences in amplitude. Hence, the amplitude normalization of the phase plot was not necessary.

7.3 Markers Attachment

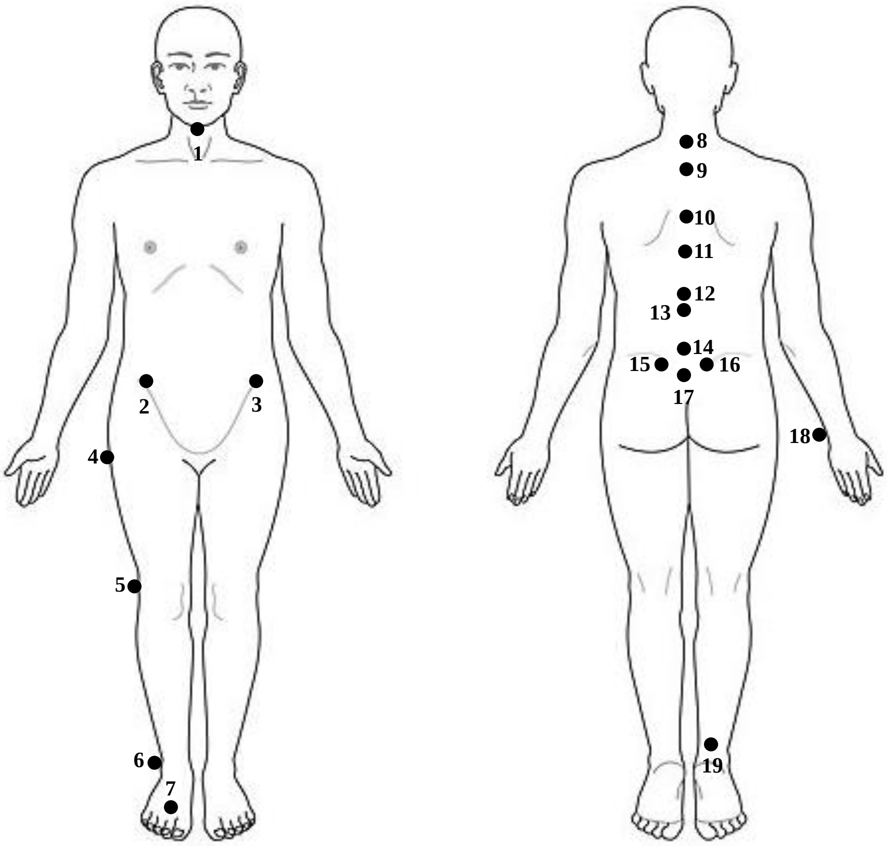

Figure 30 Markers placement illustration (Left: Front view; Right: Back view)

1. Chin	6. Right lateral malleolus	11. T7	16. Left Posterior Superior Iliac Spine
2. Right Anterior Superior Iliac Spine	7. Right second metatarsal head	12. T12	17. S1
3. Left Anterior Superior Iliac Spine	8. C7	13. L1	18. Right hand ulnar styled process
4. Right Great Trochanter	9. T2	14. L3	19. Right heel
5. Right lateral condyle	10. T5	15. Left Posterior Superior Iliac Spine	

Table 11 Location of the markers attached corresponded to Figure 30

7.4 Transformation details

The process of the formation of the transformed coordinate system was illustrated in Figure 9. The y axis (V_y') of the transformed coordinate system ($V_x' - V_y' - V_z'$) was firstly formed by using the first frame of the global coordinates of the left ASIS (P_1) and right ASIS (P_2) from each data set trial (Step 1), with the origin set at the mid-point of P_1 and P_2 (P_0). The x axis (V_x') of the transformed coordinate system was formed by partially treating the original global z axis (V_z) to be the z axis of the transformed coordinate system (Step 2), and then crossed by V_y' (Step 3). The real z axis (V_z') of the transformed coordinate system was formed by crossing V_y' and V_x' at the last stage (step 4). After setting up the transformed coordinate system, all the coordinates of the markers captured by the Vicon would be firstly transformed with respect to the new coordinate system before further angular calculation to obtain the interested variables.

Let $[M_G]$ be the global coordinate system, i.e. an identity matrix,

$$[M_G] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = [I] \qquad \text{---------- (7)}$$

By assuming the coordinates of left and right ASISs to be $P_1(x_{1,} y_1, z_1)$ and $P_2(x_{2,} y_2, z_2)$, V_y' could be formed:

$$\overrightarrow{V_y'} = \frac{\overrightarrow{P_2P_1}}{|\overrightarrow{P_2P_1}|} = \frac{\overrightarrow{OP_1} - \overrightarrow{OP_2}}{|\overrightarrow{OP_1} - \overrightarrow{OP_2}|} = \begin{pmatrix} y_x' \\ y_y' \\ y_z' \end{pmatrix} \qquad \text{----------(8)}$$

By partially treating V_z to be the z axis of the transformed coordinate system, V_x' could be formed:

$$\overrightarrow{V'_x} = \frac{\overrightarrow{V'_y} \times \overrightarrow{V_z}}{\left|\overrightarrow{V'_y} \times \overrightarrow{V_z}\right|} = \begin{pmatrix} x'_x \\ x'_y \\ x'_z \end{pmatrix} \qquad \text{----------(9)}$$

$$\overrightarrow{V'_z} = \frac{\overrightarrow{V'_x} \times \overrightarrow{V'_y}}{\left|\overrightarrow{V'_x} \times \overrightarrow{V'_y}\right|} = \begin{pmatrix} z'_x \\ z'_y \\ z'_z \end{pmatrix} \qquad \text{----------(10)}$$

Hence, the transformed coordinate system at any time t denoted by $[M_T]_t$ would be:

$$[M_T]_t = \begin{bmatrix} \overrightarrow{V'_x} \\ \overrightarrow{V'_y} \\ \overrightarrow{V'_z} \end{bmatrix}_t = \begin{bmatrix} x'_x & x'_y & x'_z \\ y'_x & y'_y & y'_z \\ z'_x & z'_y & z'_z \end{bmatrix}_t \qquad \text{----------(11)}$$

7.5 Calculation of the angles in different assessments

To calculate different angles, the vectors forming the angles should be obtained first. For body alignment test, line of vectors forming the spinal curvature angles and lower limb angulations were formed using the markers illustrated in Figure 4. For instance, angle representing T2-T5-T7 was formed from the lines joining T2/T5 and T5/T7 (Figure 31). For repositioning test, according to Figure 5, l_1 was formed by the coordinates of the markers on L1 and L3 and l_2 was formed by joining the mid-point of the ASISs and PSISs. Then, the criterion and the reproduced angles could be found.

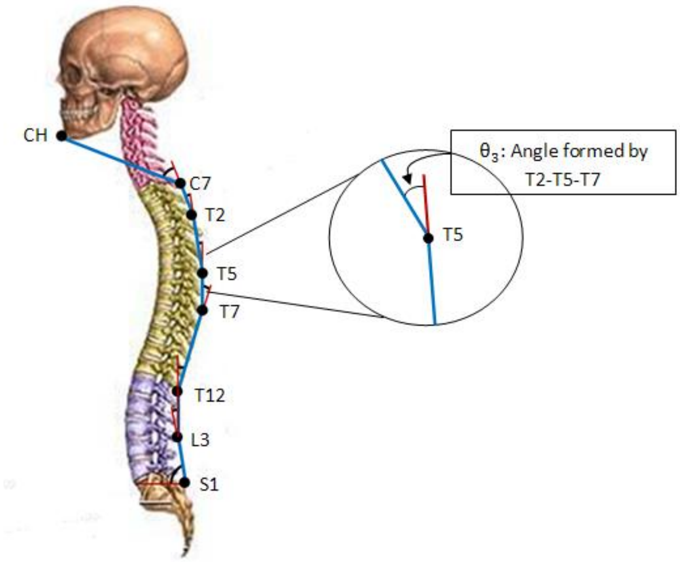

Figure 31 Diagram illustrated the formation of the angles in the body alignment test

P_1	T12
P_2	L1
P_3	Mid-point of ASISs
P_4	Mid-point of PSISs
P_5	Right femoral condyle
P_6	Right great trochanter

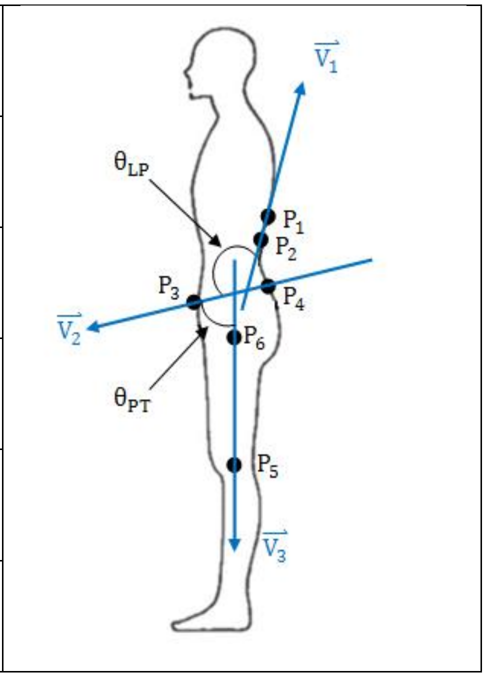

Figure 32 Diagram illustrating the formation of the vectors and lumbo-pelvis angles used in the functional reach test.

For functional reach test, T12/L1, mid-point of ASISs / PSISs and right great trochanter / lateral condyle were used to form the vector line representing the lumbar $\overrightarrow{V_1}$, pelvis $\overrightarrow{V_2}$ and thigh $\overrightarrow{V_3}$ regions respectively (Figure 30). After obtaining the lumbar angle θ_{LP} and the pelvis angle θ_{PT}. MARP and DP could be calculated using Equations 1-4. To demonstrate the calculation of the angles, we used angle of Chin-C7-T2 in the body alignment test as an example. We assumed that the coordinates of the markers of the chin (CH) and the spinous processes of C7 and T2 relative to the global coordinate system were $\mathrm{P_a(x_a, y_a, z_a)}$, $\mathrm{P_b(x_b, y_b, z_b)}$, $\mathrm{P_c(x_c, y_c, z_c)}$. Using equation 9, the data from the global coordinate system were transformed to the transformed coordinate system by:

$$\overrightarrow{P_0P_i}\Big|_T = [M_T]_t \cdot \overrightarrow{P_0P_i}\Big|_G = \begin{pmatrix} x_i' \\ y_i' \\ z_i' \end{pmatrix} \qquad \text{---------- (12)}$$

where *i* equals to a, b and c and $\overrightarrow{P_0P_i}\Big|_T$ and $\overrightarrow{P_0P_i}\Big|_G$ were the vectors of P_a, P_b and P_c with respect to the transformed origin (P_0) relative to the transformed coordinate system and global coordinate system respectively. Hence, the transformed coordinates of the markers of the chin (CH) and the spinous processes of C7 and T2 were $P_a'(x_a', y_a', z_a')$, $P_b'(x_b', y_b', z_b')$ and $P_c'(x_c', y_c', z_c')$ respectively.

In order to calculate the angle formed by these three markers, vectors were created by joining two adjacent markers to form the angle in interest and the angle formed by the two vectors could be found by:

$$\theta = \cos^{-1}\frac{\overrightarrow{P_c'P_b'} \cdot \overrightarrow{P_b'P_a'}}{\left|\overrightarrow{P_c'P_b'}\right|\left|\overrightarrow{P_b'P_a'}\right|} \qquad \text{---------- (13)}$$

However, since only 2-dimention measurement was interested, only the x and z coordinates of the transformed markers were used in the calculation. Hence,

$$\overrightarrow{P_c'P_b'} = \overrightarrow{P_0P_b'} - \overrightarrow{P_0P_c'} = \begin{pmatrix} x_b' - x_c' \\ z_b' - z_c' \end{pmatrix} \text{ and } \overrightarrow{P_b'P_a'} = \overrightarrow{P_0P_a'} - \overrightarrow{P_0P_b'} = \begin{pmatrix} x_a' - x_b' \\ z_a' - z_b' \end{pmatrix}$$

By equation (11),

$$\theta = \cos^{-1}\frac{(x_b'-x_c')*(x_a'-x_b')+(z_b'-z_c')*(z_a'-z_b')}{\sqrt{(x_b'-x_c')^2+(z_b'-z_c')^2}*\sqrt{(x_a'-x_b')^2+(z_a'-z_b')^2}} \qquad \text{---------- (14)}$$

Hence, the angle Chin-C7-T2 could be calculated. Other angles in interest such as the repositioning angles and lumbo-pelvic angles in the functional reach test could also be calculated in a similar way.

7.6 Vibration intensity issue

There are four major physical factors which determine human response to vibration, which are the intensity, frequency, direction of the vibration propagates and the duration of the vibration applied. Generally, there are four physical descriptions in evaluating vibration of any kind, which are 1) Fatigue-decreased proficiency boundary; 2) Exposure limit; 3) Reduced comfort boundary and 4) Motion toleration (ISO 2631). In this study, the fourth description could be ignored since only vibration less than 0.5 Hz would induce a problem related to motion sickness (BS 6841). For fatigue-decreaed proficiency boundary, it specifies a limit beyond which exposure to vibration can be regarded as carrying a potential risk of working impairment, for instance, during driving (ISO 2631). It also indicates the possibility of vibration of certain frequency and duration that may lead to impairment in hand control and vision (BS 6841). For exposure limits, it is regarded to an individual's safety and health issue and is mostly applied to the effects of vertical vibration to the subjects (BS 6841). Lastly for the reduced comfort boundary, it estimates the likely effect on the comfort of healthy individuals who experienced WBV and repeated shocks during work and travel and describes the measurement procedures for estimating WBV perception threshold.

The manner in which vibration affects the above physical properties depends on the frequency of the vibration source. Different frequency weightings would be necessary for different axes of vibration and for the different effects of vibration on the body (BS 6841). In this study, standing and seated vibrations were applied to the subjects, which represent vibration applied in the z-direction in standing and seated posture according to ISO 2631. Since the vibration applied in the study was 18 Hz, the corresponding weighting factor in the longitudinal direction and transverse direction would be around 0.45 and 0.12 respectively (ISO 2631).

A simple investigation was performed to estimate the vibration to the lumbo-pelvis region from the Galileo sport platform in standing posture. A marker was attached onto the platform at position 3, which was equivalent to the position of the foot placement of the subjects during standing WBV session. Four additional markers were attached onto the bilateral ASISs and acromion processes and paper surgical tape was used to further secure the markers. The amplitude of the vibration obtained, as expected, was 6 mm p-p. By using the equations used in Pollock et al. 2010, the acceleration obtained was around 2.3g. The averaged accelerations obtained for ASISs and acromion processes were about 0.6g and 0.2g respectively. The accelerations obtained at the ASISs and the acromion processes was acceptable and comparable to those in Pollock et al's study, provided that larger knee flexion was maintained by the subject in this investigation study since greater WBV attenuation would result for greater degree of knee flexion (Pollock et al. 2010). The acceleration was calculated and presented as root-mean-square (RMS) since the crest factor was less than 2, which does not exceed 6.0 (BS 6841). The crest factor is obtained by dividing the weighted peak acceleration with the weighted r.m.s. acceleration.

According to ISO 2631, induced acceleration of 5 minutes of

18Hz WBV should not exceed more than 5 m/s^2 in order not to reach the decreased proficiency boundary. This stated that the vibration applied to the lower spine in this study exceeded the limit. In figure 33, it showed that the maximum approximate time for experiencing WBV for about 18Hz with acceleration about 0.6g without inducing fatigue effect should not be more than 1 minute. Since the acceleration is required to be raised by a factor by 2 for the exposure limit, hence the vibration applied would also exceed the limit boundary. For the comfort boundary, it is assumed to lie at approximately 1/3 of the corresponding fatigue level, so the applied vibration would not exceed this limit. According to BS 6841, the estimated vibration dose value of the vibration in z-direction used in standing WBV was 2 times larger than 15 m/s^2, which is a limit that would cause severe discomfort and increase the rist of injury if exceeded. For the vibration induced in the transverse direction, the acceleration threshold will be large enough to avoid any possible harmful physical properties being induced by the transverse acceleration recorded in this investigation, so it would not be discussed.

It should be noted that vibration with different amplitudes would cause discomfort and pain would be raised due to possible injuries during vibration, although the sensation of pain may not be correlated with pathological damage. In this study, unweighted maximum acceleration applied to the subject exceeded 1g, this showed that the subject might lift off from the platform during WBV and impact with it, which may possibly cause injury in long period.

For the above limit mentioned, it intends to apply on those who receive the corresponding vibration continuously and daily, but not for temporarily short period vibration (ISO 2631, BS 6841). It might be possible that for less frequently experienced vibration, the tolerable combination of acceleration and time would very likely be higher (ISO 2631, BS 6841). In conclusion, different parameters of WBV should be carefully choosen before application, since hazardous effect would be results if long term WBV is applied. In future study, it is necessary to investigate the long term effect of the WBV using the protocols in this study.

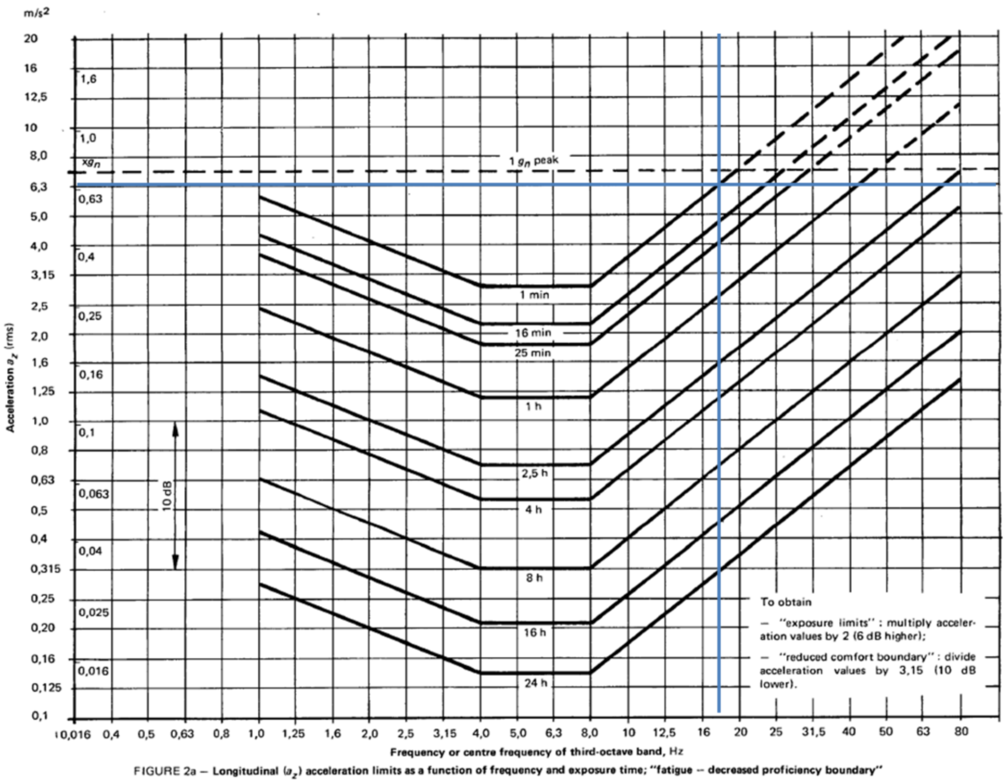

Figure 33 Longitudinal acceleration limits as a function of frequency and exposure time for 'fatigue - decreased proficiency boundary'

7.7 Ethical Approval

THE HONG KONG
POLYTECHNIC UNIVERSITY
香港理工大學

To	CHOW Hung Kay (Interdisciplinary Division of Biomedical Engineering)		
From	ZHANG Ming, Chair, Departmental Research Committee		
Email	htmzhang@	Date	15-Jun-2012

Application for Ethical Review for Teaching/Research Involving Human Subjects

I write to inform you that approval has been given to your application for human subjects ethics review of the following project for a period from 18-Jun-2012 to 18-Jun-2014:

Project Title:	Effects of whole body vibration on spinal motor control in patients with low back pain
Department:	Interdisciplinary Division of Biomedical Engineering
Principal Investigator:	CHOW Hung Kay

Please note that you will be held responsible for the ethical approval granted for the project and the ethical conduct of the personnel involved in the project. In the case of the Co-PI, if any, has also obtained ethical approval for the project, the Co-PI will also assume the responsibility in respect of the ethical approval (in relation to the areas of expertise of respective Co-PI in accordance with the stipulations given by the approving authority).

You are responsible for informing the Departmental Research Committee in advance of any changes in the proposal or procedures which may affect the validity of this ethical approval.

You will receive separate email notification should you be required to obtain fresh approval.

ZHANG Ming

Chair

Departmental Research Committee

Figure 34 Ethical Approval obtained for the WBV study

7.8 Total sample sizes required

For the sample sizes needed for both stages were calculated using the software G*Power 3.1.2 (Erdfelder, Faul, & Buchner, 1996). The test family and the statistical test used for both stages were ‘F tests’ and ‘MANOVA: Repeated measures, within-between interaction’ respectively. α error probability was set to 0.05 and power was set to 0.95. From the table, it could be observed that the sample size should be increased to about 30 so that significant findings would be observed for the dynamic reaching and repositioning variables. For the body alignment documentation, significant changes would also be expected in the lumbar region and lower limbs if the sample sizes could be increased to about 60.

	Stage 1: Standing WBV VS Seated WBV		Stage 2: Healthy VS LBP (Seated WBV)	
Parameters	**Effect Size**	**Total sample size**	**Effect Size**	**Total sample size**
MRD	0.18	554	0.49	75
MARPF	2.59	8	4.57	7
MARPB	0.87	28	2.1	10
DPF	0.7	40	1.31	15
DPB	0.26	254	0.91	26
CE	0.82	31	0.59	54
VE	0.43	99	0.34	157
AE	0.82	30	1.12	20
CH-C7-T2	0.34	151	0.96	24
C7-T2-T5	0.23	318	0.28	220
T2-T5-T7	0.34	157	0.18	554
T5-T7-T12	0.62	50	0.45	88
T7-T12-L3	0.89	26	0.45	88
T12-L3-S1	0.78	33	0.83	30
L3-S1-Horizontal	0.34	157	0.58	56
Pelvis tilting	0.97	23	0.34	149
Knee angle	0.58	55	0.56	59
Ankle angle	0.83	30	0.34	151

Table 12 Sample size required for future study

7.9 Individual data from the results

7.9.1 Standing WBV group

MRD (cm)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	32.0	33.7	33.3	32.7
Subject 2	36.7	37.3	37.0	37.7
Subject 3	36.0	38.3	38.7	40.3
Subject 4	37.5	40.7	39.7	40.0
Subject 5	33.0	35.3	35.3	37.0
Subject 6	35.0	37.3	39.3	36.0
Subject 7	36.7	37.7	37.0	37.3
Subject 8	39.0	41.3	40.0	38.7
Subject 9	36.3	36.0	35.3	35.3
Subject 10	38.0	39.3	38.3	38.7

Table 13 Maximum reaching distance of individual subject in different periods of the standing WBV group

MARPF (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	25.3	16.9	28.8	21.1
Subject 2	18.6	11.5	16.5	12.5
Subject 3	35.3	17.6	29.0	38.5
Subject 4	25.6	13.1	8.5	25.5
Subject 5	24.5	13.2	12.5	12.7
Subject 6	23.6	30.5	26.4	29.2
Subject 7	26.4	14.1	6.5	23.5
Subject 8	37.8	22.9	18.5	22.3
Subject 9	44.4	36.2	33.4	37.8
Subject 10	16.6	17.1	15.9	13.8

Table 14 Mean absolute relative phase in forward motion of individual subject in different periods of the standing WBV group

MARPB (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	32.6	28.4	28.7	26.2
Subject 2	21.1	10.5	18.1	17.4
Subject 3	34.4	19.4	29.0	29.3
Subject 4	29.8	10.6	9.4	26.2
Subject 5	40.5	23.5	29.7	31.0
Subject 6	29.0	28.2	37.9	29.0
Subject 7	38.2	25.8	20.6	37.2
Subject 8	23.7	23.6	19.0	27.4
Subject 9	27.9	30.9	29.8	34.8
Subject 10	13.9	18.7	16.7	12.9

Table 15 Mean absolute relative phase in backward motion of individual subject in different periods of the standing WBV group

DPF (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	13.5	9.7	20.3	13.9
Subject 2	8.5	5.9	10.0	10.0
Subject 3	31.3	16.7	22.6	20.8
Subject 4	22.2	8.8	15.5	21.4
Subject 5	18.8	13.1	12.9	13.3
Subject 6	11.4	23.7	10.7	13.8
Subject 7	14.1	10.4	5.4	8.4
Subject 8	29.9	18.8	9.9	13.1
Subject 9	9.7	10.6	6.4	8.3
Subject 10	12.6	9.9	15.6	10.6

Table 16 Deviation phase in forward motion of individual subject in different periods of the standing WBV group

DPB (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	24.5	9.7	24.7	14.7
Subject 2	10.0	7.4	14.4	9.9
Subject 3	23.4	17.6	20.6	16.9
Subject 4	26.0	6.0	4.9	14.7
Subject 5	21.4	21.8	21.4	25.7
Subject 6	24.0	18.3	16.4	20.1
Subject 7	16.5	23.9	22.2	19.8
Subject 8	20.1	20.1	11.2	15.9
Subject 9	10.1	10.0	9.2	11.3
Subject 10	10.7	13.1	15.4	9.1

Table 17 Deviation phase in backward motion of individual subject in different periods of the standing WBV group

CE (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	2.0	3.2	-0.3	1.4
Subject 2	-0.1	1.4	0.2	0.6
Subject 3	1.2	1.3	-2.3	-2.5
Subject 4	-1.1	0.6	1.1	-1.6
Subject 5	-0.2	-0.5	-0.6	0.0
Subject 6	-0.2	-0.7	-1.0	-0.1
Subject 7	0.8	1.3	2.8	2.2
Subject 8	4.2	2.4	5.8	6.4
Subject 9	4.3	-1.0	2.3	1.9
Subject 10	3.5	-0.5	-0.4	2.2

Table 18 Constant error of individual subject in different periods of the standing WBV group

VE (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	0.9	0.4	1.6	2.7
Subject 2	0.5	0.6	0.7	0.4
Subject 3	2.1	1.9	1.2	1.3
Subject 4	1.2	1.1	1.3	1.6
Subject 5	1.1	0.3	0.5	1.2
Subject 6	0.9	0.6	0.7	0.6
Subject 7	0.9	0.7	2.2	1.2
Subject 8	0.8	0.8	0.7	1.7
Subject 9	0.7	0.5	0.8	0.5
Subject 10	1.3	0.9	1.1	1.1

Table 19 Variable error of individual subject in different periods of the standing WBV group

AE (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	2.0	3.2	1.3	2.6
Subject 2	0.3	1.4	0.5	0.6
Subject 3	1.8	1.8	2.3	2.5
Subject 4	1.1	1.1	1.5	1.8
Subject 5	0.9	0.5	0.6	0.9
Subject 6	0.7	0.7	1.0	0.4
Subject 7	0.9	1.3	2.8	2.2
Subject 8	4.2	2.4	5.8	6.4
Subject 9	4.3	1.0	2.3	1.9
Subject 10	3.5	0.7	0.6	2.2

Table 20 Absolute error of individual subject in different periods of the standing WBV group

CH-C7-T2 (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	57.1	57.6	59.6	59.1
Subject 2	52.5	52.6	52.1	52.4
Subject 3	46.2	44.6	43.2	43.5
Subject 4	50.9	49.0	48.2	48.5
Subject 5	53.3	53.0	53.4	53.9
Subject 6	48.7	48.1	49.5	49.5
Subject 7	52.5	58.7	52.8	51.4
Subject 8	57.9	57.0	51.2	53.8
Subject 9	61.7	58.8	61.1	59.0
Subject 10	58.6	58.1	56.2	56.1

Table 21 Neck flexion angle of individual subject in different periods of the standing WBV group

C7-T2-T5 (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	4.1	2.4	2.6	2.7
Subject 2	17.3	17.2	17.2	17.4
Subject 3	20.3	21.1	21.7	21.7
Subject 4	22.5	22.7	22.9	22.8
Subject 5	15.2	14.5	15.3	15.5
Subject 6	10.6	10.3	10.4	11.1
Subject 7	20.1	19.8	19.9	20.3
Subject 8	19.5	19.3	17.2	16.0
Subject 9	2.4	4.5	2.9	3.8
Subject 10	8.2	7.5	7.5	7.9

Table 22 Upper thoracic flexion angle of individual subject in different periods of the standing WBV group

T2-T5-T7 (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	3.9	2.1	1.5	1.6
Subject 2	5.1	5.6	5.9	5.6
Subject 3	11.3	11.6	10.8	11.0
Subject 4	7.7	7.8	7.7	7.7
Subject 5	6.9	6.8	7.0	7.2
Subject 6	8.0	8.0	7.6	7.4
Subject 7	8.9	10.5	9.0	9.9
Subject 8	14.4	14.4	16.2	14.5
Subject 9	10.4	10.8	11.8	12.0
Subject 10	3.4	1.4	1.9	2.3

Table 23 Middle thoracic flexion angle of individual subject in different periods of the standing WBV group

T5-T7-T12 (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	14.0	14.0	11.9	13.4
Subject 2	3.9	4.5	3.9	4.3
Subject 3	11.7	12.1	11.7	11.1
Subject 4	8.9	9.2	8.9	9.8
Subject 5	17.5	16.9	16.8	17.0
Subject 6	9.0	8.2	7.6	6.4
Subject 7	13.7	11.5	12.5	14.7
Subject 8	10.6	9.7	9.5	11.8
Subject 9	11.5	13.3	11.8	12.5
Subject 10	17.4	15.6	15.4	16.5

Table 24 Lower thoracic flexion angle of individual subject in different periods of the standing WBV group

T7-T12-L3 (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	4.2	2.9	0.9	2.3
Subject 2	4.2	6.4	4.3	4.1
Subject 3	3.1	3.1	3.0	2.9
Subject 4	3.3	2.3	4.5	2.0
Subject 5	3.6	2.5	2.4	2.2
Subject 6	3.7	3.0	2.0	0.7
Subject 7	10.3	10.2	11.3	12.1
Subject 8	7.1	4.0	1.7	4.5
Subject 9	4.0	3.4	2.9	2.7
Subject 10	7.7	6.3	5.7	8.3

Table 25 Upper lumbar extension angle of individual subject in different periods of the standing WBV group

T12-L3-S1 (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	14.9	16.1	15.1	14.7
Subject 2	17.5	18.9	17.2	17.4
Subject 3	17.3	17.0	15.9	15.0
Subject 4	18.6	18.5	17.0	18.4
Subject 5	19.8	20.5	22.1	22.5
Subject 6	13.2	13.1	12.6	12.3
Subject 7	19.4	17.3	17.9	18.3
Subject 8	20.6	21.7	23.3	22.6
Subject 9	14.6	15.5	14.4	14.5
Subject 10	20.5	17.8	17.6	19.1

Table 26 Middle lumbar extension angle of individual subject in different periods of the standing WBV group

L3-S1-Horizontal (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	82.7	79.7	79.4	81.0
Subject 2	80.8	78.8	80.4	80.7
Subject 3	78.7	79.2	79.6	80.1
Subject 4	77.9	77.3	77.8	78.2
Subject 5	71.1	70.5	69.3	69.1
Subject 6	83.8	82.8	82.6	82.6
Subject 7	72.6	73.4	72.9	72.3
Subject 8	75.6	75.3	76.0	75.5
Subject 9	78.3	77.9	79.2	79.3
Subject 10	82.9	83.3	82.7	84.6

Table 27 Lower lumbar extension angle of individual subject in different periods of the standing WBV group

Pelvis tilt (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	7.7	9.7	8.1	7.2
Subject 2	5.5	8.0	6.4	6.2
Subject 3	13.0	13.0	12.8	12.4
Subject 4	11.8	12.1	11.7	11.4
Subject 5	14.3	14.6	16.1	16.1
Subject 6	9.0	8.3	8.6	8.9
Subject 7	11.7	17.7	12.4	12.9
Subject 8	18.5	20.0	11.2	10.7
Subject 9	18.3	19.5	17.2	18.5
Subject 10	13.5	13.5	13.9	12.9

Table 28 Pelvis tilting of individual subject in different periods of the standing WBV group

Knee angle (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	-2.6	-3.7	-2.7	-2.6
Subject 2	-0.3	1.6	2.0	1.5
Subject 3	4.6	5.6	5.8	6.0
Subject 4	-0.5	-0.6	-1.4	-1.7
Subject 5	3.4	4.3	1.0	1.1
Subject 6	8.8	9.9	9.8	9.6
Subject 7	3.4	5.0	2.5	1.5
Subject 8	6.1	5.7	5.9	6.0
Subject 9	11.2	11.1	11.5	11.0
Subject 10	2.2	2.9	2.6	2.2

Table 29 Knee angle of individual subject in different periods of the standing WBV group

Ankle angle (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	85.4	86.4	87.5	87.6
Subject 2	86.2	85.5	85.5	85.6
Subject 3	84.7	83.5	83.0	83.1
Subject 4	87.6	87.6	87.8	88.0
Subject 5	83.4	83.8	84.4	84.0
Subject 6	80.1	80.1	82.1	80.4
Subject 7	84.1	93.3	83.7	83.7
Subject 8	92.7	92.9	83.0	82.6
Subject 9	83.6	81.8	81.3	81.2
Subject 10	85.9	86.3	86.7	86.4

Table 30 Ankle angle of individual subject in different periods of the standing WBV group

7.9.2 Seated WBV group

MRD (cm)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 11	32.7	34.0	34.7	34.0
Subject 12	34.7	36.7	37.0	37.0
Subject 13	33.0	34.7	34.0	34.0
Subject 14	33.7	36.3	34.7	35.3
Subject 15	35.7	37.0	37.0	37.3
Subject 16	37.0	39.7	40.0	38.7
Subject 17	36.0	36.7	36.0	35.0
Subject 18	35.3	35.7	36.7	36.3
Subject 19	35.7	38.7	38.0	37.7
Subject 20	33.3	34.0	34.3	34.0

Table 31 Maximum reaching distance of individual subject in different periods of the seated WBV group

MARPF (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 11	32.9	23.9	23.4	23.0
Subject 12	22.6	6.8	11.5	15.8
Subject 13	25.9	13.0	12.4	16.5
Subject 14	16.8	12.4	21.3	15.7
Subject 15	22.1	15.5	14.1	16.3
Subject 16	35.4	23.6	20.6	15.2
Subject 17	36.7	23.5	24.4	23.6
Subject 18	20.4	19.8	10.9	15.0
Subject 19	13.9	11.1	10.0	11.7
Subject 20	35.8	20.0	24.4	26.3

Table 32 Mean absolute relative phase in forward motion of individual subject in different periods of the seated WBV group

MARPB (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 11	29.4	30.3	31.0	27.2
Subject 12	24.6	12.2	15.0	18.0
Subject 13	28.1	25.2	18.7	20.2
Subject 14	23.0	18.4	23.4	20.3
Subject 15	20.7	16.1	16.0	18.7
Subject 16	42.8	30.7	36.5	33.8
Subject 17	44.0	38.6	41.1	43.0
Subject 18	18.3	15.1	11.4	20.6
Subject 19	11.6	9.2	12.9	10.6
Subject 20	32.3	11.6	23.5	34.9

Table 33 Mean absolute relative phase in backward motion of individual subject in different periods of the seated WBV group

DPF (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 11	11.3	21.4	19.7	7.2
Subject 12	14.7	4.3	10.7	16.5
Subject 13	14.4	7.3	8.5	13.3
Subject 14	13.8	8.1	8.4	9.9
Subject 15	10.8	8.5	9.7	9.0
Subject 16	9.9	17.3	12.6	13.6
Subject 17	14.0	13.8	10.7	10.4
Subject 18	12.8	12.8	7.8	12.6
Subject 19	11.8	8.7	10.5	14.5
Subject 20	21.9	31.8	13.5	12.5

Table 34 Deviation phase in forward motion of individual subject in different periods of the seated WBV group

DPB (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 11	17.1	17.6	19.0	11.8
Subject 12	16.7	8.5	9.6	15.2
Subject 13	20.0	14.4	12.8	13.9
Subject 14	16.9	11.6	8.5	13.4
Subject 15	9.1	9.9	10.1	12.8
Subject 16	14.9	17.5	22.8	25.2
Subject 17	16.2	19.9	16.0	15.3
Subject 18	14.5	10.1	4.6	14.4
Subject 19	9.0	6.5	4.7	9.2
Subject 20	19.7	15.2	22.3	11.5

Table 35 Deviation phase in backward motion of individual subject in different periods of the seated WBV group

CE (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 11	1.5	1.1	0.6	-0.7
Subject 12	-2.5	0.5	0.8	-1.3
Subject 13	2.1	0.6	1.4	1.9
Subject 14	2.0	0.4	-2.1	1.3
Subject 15	-2.2	-0.8	0.1	-5.4
Subject 16	3.2	1.1	-2.0	1.1
Subject 17	2.2	1.1	1.3	-0.5
Subject 18	5.2	4.6	2.2	3.0
Subject 19	3.7	1.9	1.8	0.8
Subject 20	-1.5	-1.2	-0.7	-1.0

Table 36 Constant error of individual subject in different periods of the seated WBV group

VE (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 11	3.6	2.5	1.0	0.8
Subject 12	2.3	0.2	0.9	1.8
Subject 13	0.2	0.4	0.9	0.6
Subject 14	1.6	1.7	2.2	1.1
Subject 15	3.6	0.9	1.2	2.3
Subject 16	1.7	0.9	1.6	1.5
Subject 17	1.2	1.5	1.1	1.1
Subject 18	1.4	0.8	1.1	0.5
Subject 19	1.1	1.4	1.0	1.9
Subject 20	0.8	0.2	0.6	0.3

Table 37 Variable error of individual subject in different periods of the seated WBV group

AE (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 11	2.8	1.9	0.8	0.8
Subject 12	2.5	0.5	1.0	2.0
Subject 13	2.1	0.6	1.4	1.9
Subject 14	2.3	1.4	2.1	1.3
Subject 15	3.5	0.8	0.9	5.4
Subject 16	3.2	1.2	2.1	1.4
Subject 17	2.2	1.2	1.4	1.0
Subject 18	5.2	4.6	2.2	3.0
Subject 19	3.7	2.1	1.8	1.5
Subject 20	1.5	1.2	0.7	1.0

Table 38 Absolute error of individual subject in different periods of the seated WBV group

CH-C7-T2 (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 11	48.5	47.6	48.5	49.1
Subject 12	53.5	54.6	51.5	53.5
Subject 13	54.5	56.1	57.1	56.2
Subject 14	48.8	48.0	44.6	45.2
Subject 15	54.0	53.3	53.6	53.7
Subject 16	62.7	63.2	61.7	62.1
Subject 17	56.9	59.1	58.7	61.1
Subject 18	52.4	49.9	50.4	48.4
Subject 19	55.8	56.0	54.0	51.2
Subject 20	47.6	48.5	48.4	46.9

Table 39 Neck flexion angle of individual subject in different periods of the seated WBV group

C7-T2-T5 (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 11	13.2	12.9	13.5	12.5
Subject 12	15.3	14.6	15.6	15.1
Subject 13	12.8	13.1	12.6	12.4
Subject 14	17.2	16.7	17.3	16.5
Subject 15	13.9	13.5	13.4	13.8
Subject 16	1.8	0.8	1.0	0.5
Subject 17	12.9	11.9	12.0	11.5
Subject 18	13.2	13.6	13.7	12.7
Subject 19	9.0	7.8	8.5	9.8
Subject 20	11.2	11.1	11.5	13.4

Table 40 Upper thoracic flexion angle of individual subject in different periods of the seated WBV group

T2-T5-T7 (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 11	7.6	7.6	7.5	7.7
Subject 12	11.3	9.0	9.0	10.0
Subject 13	10.6	10.1	10.0	10.4
Subject 14	14.3	13.6	15.2	14.7
Subject 15	9.7	9.5	9.6	9.6
Subject 16	18.9	19.1	20.4	19.9
Subject 17	8.9	8.5	8.9	8.7
Subject 18	7.3	8.2	9.0	7.4
Subject 19	8.6	8.5	9.6	9.0
Subject 20	8.9	7.8	8.3	7.7

Table 41 Middle thoracic flexion angle of individual subject in different periods of the seated WBV group

T5-T7-T12 (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 11	10.5	9.5	9.9	10.0
Subject 12	11.2	12.9	12.6	12.4
Subject 13	9.6	9.2	9.7	9.3
Subject 14	13.8	13.6	15.5	15.0
Subject 15	15.3	15.2	15.6	15.1
Subject 16	13.4	13.4	12.5	13.3
Subject 17	11.0	10.0	10.9	8.3
Subject 18	13.0	13.0	12.1	14.1
Subject 19	14.9	14.4	15.7	16.6
Subject 20	22.5	21.3	21.5	20.2

Table 42 Lower thoracic flexion angle of individual subject in different periods of the seated WBV group

T7-T12-L3 (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 11	0.2	0.4	0.5	0.6
Subject 12	7.6	6.6	5.9	6.5
Subject 13	5.8	8.7	7.4	7.4
Subject 14	8.2	8.5	6.1	5.9
Subject 15	5.7	7.0	5.6	7.7
Subject 16	4.9	3.8	3.1	3.0
Subject 17	4.6	2.5	1.4	3.3
Subject 18	3.4	4.8	4.5	4.4
Subject 19	2.9	2.2	4.1	3.9
Subject 20	1.6	5.0	4.8	7.8

Table 43 Upper lumbar extension angle of individual subject in different periods of the seated WBV group

T12-L3-S1 (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 11	15.0	12.9	13.7	14.0
Subject 12	15.8	16.4	17.0	16.7
Subject 13	20.4	19.3	20.8	20.2
Subject 14	28.5	26.3	26.3	26.5
Subject 15	17.6	17.1	17.5	15.6
Subject 16	15.1	14.9	14.1	14.4
Subject 17	25.3	24.5	25.5	21.4
Subject 18	16.6	15.1	16.4	15.8
Subject 19	14.6	14.7	14.2	13.9
Subject 20	28.1	25.3	25.6	25.7

Table 44 Middle lumbar extension angle of individual subject in different periods of the seated WBV group

L3-S1-Horizontal (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 11	86.2	86.1	87.0	87.5
Subject 12	78.8	79.3	79.6	79.7
Subject 13	73.5	71.9	73.0	72.8
Subject 14	68.2	67.4	69.4	70.3
Subject 15	81.7	80.2	81.0	81.6
Subject 16	79.3	79.2	80.4	80.3
Subject 17	72.8	73.1	73.3	74.2
Subject 18	79.2	78.6	78.2	77.5
Subject 19	81.5	80.3	82.5	82.5
Subject 20	74.7	73.6	73.1	72.1

Table 45 Lower lumbar extension angle of individual subject in different periods of the seated WBV group

Pelvis tilt (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 11	8.7	8.3	8.3	7.6
Subject 12	17.3	16.9	17.2	16.7
Subject 13	16.0	17.0	16.3	16.3
Subject 14	18.2	19.5	18.3	17.1
Subject 15	10.2	10.3	10.2	9.6
Subject 16	11.9	12.5	11.1	11.5
Subject 17	17.2	17.4	17.7	16.4
Subject 18	10.6	11.4	11.6	12.1
Subject 19	3.3	3.6	2.3	2.2
Subject 20	9.4	10.0	10.6	11.2

Table 46 Pelvis tilting of individual subject in different periods of the seated WBV group

Knee angle (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 11	5.9	6.5	6.7	7.2
Subject 12	-3.6	-2.1	-3.3	-3.2
Subject 13	13.1	12.9	13.0	13.2
Subject 14	-0.1	-0.3	-0.6	0.0
Subject 15	3.0	3.9	3.6	4.6
Subject 16	5.2	4.8	4.0	4.5
Subject 17	6.9	7.2	6.8	7.0
Subject 18	2.1	0.7	1.2	2.0
Subject 19	2.5	0.8	2.0	1.9
Subject 20	0.6	0.2	-0.5	-0.6

Table 47 Knee angle of individual subject in different periods of the seated WBV group

Ankle angle (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 11	83.9	84.5	83.4	83.4
Subject 12	86.3	85.5	84.1	84.5
Subject 13	80.9	81.3	80.7	81.1
Subject 14	87.0	87.1	86.3	85.7
Subject 15	84.4	85.4	85.0	84.8
Subject 16	83.8	83.8	84.4	84.3
Subject 17	84.0	85.2	84.8	85.4
Subject 18	84.9	85.2	85.0	84.9
Subject 19	85.5	85.1	84.5	83.9
Subject 20	86.0	87.0	86.9	86.8

Table 48 Ankle angle of individual subject in different periods of the seated WBV group

7.9.3 LBP group

MRD (cm)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	33.0	34.0	33.3	33.0
Subject 2	29.7	32.3	33.7	33.3
Subject 3	33.7	36.7	35.7	36.0
Subject 4	33.0	36.7	36.7	36.0
Subject 5	32.0	34.7	34.3	34.3
Subject 6	34.7	36.0	35.3	35.3
Subject 7	34.0	36.0	35.7	36.0
Subject 8	33.0	35.0	35.0	35.0

Table 49 Maximum reaching distance of individual subject in different periods of the LBP WBV group

MARPF (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	42.2	19.9	22.5	29.7
Subject 2	29.7	11.1	14.2	18.4
Subject 3	42.2	19.9	22.5	29.7
Subject 4	36.5	22.0	30.6	30.1
Subject 5	41.8	26.0	28.2	32.0
Subject 6	29.6	17.5	22.8	22.2
Subject 7	35.0	20.0	22.4	30.4
Subject 8	36.9	25.7	28.4	31.0

Table 50 Mean absolute relative phase in forward motion of individual subject in different periods of the LBP WBV group

MARPB (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	23.9	16.0	19.9	21.0
Subject 2	31.6	23.1	20.9	26.2
Subject 3	29.9	22.0	21.9	27.0
Subject 4	35.1	19.6	33.9	31.7
Subject 5	29.9	28.4	28.2	30.2
Subject 6	32.5	23.7	28.4	30.9
Subject 7	23.5	14.4	26.1	30.8
Subject 8	32.5	21.5	29.5	31.5

Table 51 Mean absolute relative phase in backward motion of individual subject in different periods of the LBP WBV group

DPF (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	29.7	30.3	30.5	13.6
Subject 2	24.7	20.5	25.1	22.2
Subject 3	29.7	30.3	20.5	23.6
Subject 4	15.8	12.3	10.9	18.5
Subject 5	20.5	21.9	21.2	19.6
Subject 6	26.0	16.7	19.7	24.9
Subject 7	24.2	15.5	15.7	17.5
Subject 8	18.3	21.7	20.2	23.5

Table 52 Deviation phase in forward motion of individual subject in different periods of the LBP WBV group

DPB (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	22.8	20.9	24.4	11.9
Subject 2	27.2	24.0	12.0	23.1
Subject 3	22.8	20.9	24.4	21.9
Subject 4	17.8	11.7	19.0	18.0
Subject 5	14.7	17.2	15.1	20.5
Subject 6	34.1	22.6	23.3	31.6
Subject 7	20.1	13.7	17.0	20.1
Subject 8	25.9	23.7	24.0	25.2

Table 53 Deviation phase in backward motion of individual subject in different periods of the LBP WBV group

CE (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	6.1	-0.9	2.3	0.6
Subject 2	3.5	-2.1	2.2	1.0
Subject 3	-4.2	-2.1	-2.0	-2.4
Subject 4	6.1	4.0	3.8	2.8
Subject 5	-2.1	-0.1	-1.7	0.5
Subject 6	4.3	2.6	0.4	3.7
Subject 7	3.3	0.6	-1.9	2.5
Subject 8	2.0	1.3	1.4	1.5

Table 54 Constant error of individual subject in different periods of the LBP WBV group

VE (degree)	**Before WBV**	**Immediately after WBV**	**30 minutes after WBV**	**60 minutes after WBV**
Subject 1	1.8	0.2	2.2	1.6
Subject 2	0.9	2.0	0.4	1.6
Subject 3	1.4	0.8	0.7	0.5
Subject 4	0.6	0.6	0.7	0.8
Subject 5	0.4	0.3	0.8	0.7
Subject 6	1.3	1.8	1.0	1.8
Subject 7	1.8	1.6	1.0	1.4
Subject 8	1.5	0.9	0.7	1.4

Table 55 Variable error of individual subject in different periods of the LBP WBV group

AE (degree)	**Before WBV**	**Immediately after WBV**	**30 minutes after WBV**	**60 minutes after WBV**
Subject 1	6.1	2.4	0.9	1.1
Subject 2	3.5	2.2	2.2	1.4
Subject 3	4.2	2.0	2.1	2.4
Subject 4	6.1	3.8	4.0	2.8
Subject 5	2.1	1.7	0.2	0.6
Subject 6	4.3	0.9	2.6	3.7
Subject 7	3.3	1.4	1.9	2.5
Subject 8	3.5	1.3	1.8	2.5

Table 56 Absolute error of individual subject in different periods of the LBP WBV group

CH-C7-T2 (degree)	**Before WBV**	**Immediately after WBV**	**30 minutes after WBV**	**60 minutes after WBV**
Subject 1	53.3	54.8	52.8	54.3
Subject 2	52.6	54.5	54.2	54.5
Subject 3	46.9	49.5	46.6	52.0
Subject 4	50.6	50.6	47.9	48.2
Subject 5	56.0	56.2	58.1	58.2
Subject 6	60.3	59.1	59.8	60.1
Subject 7	50.6	54.4	50.9	49.7
Subject 8	54.8	53.9	55.2	55.0

Table 57 Neck flexion angle of individual subject in different periods of the LBP WBV group

C7-T2-T5 (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	15.3	16.0	16.6	17.2
Subject 2	15.4	12.8	11.7	12.7
Subject 3	13.0	10.4	12.3	13.2
Subject 4	17.8	16.6	17.4	17.7
Subject 5	16.8	16.2	16.1	16.2
Subject 6	14.8	14.9	14.8	14.9
Subject 7	14.8	14.5	15.3	13.8
Subject 8	16.5	16.3	16.3	16.3

Table 58 Upper thoracic flexion angle of individual subject in different periods of the LBP WBV group

T2-T5-T7 (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	10.6	10.5	11.0	10.6
Subject 2	4.2	4.3	4.8	4.2
Subject 3	9.9	9.1	9.1	8.8
Subject 4	7.4	7.9	7.4	7.8
Subject 5	16.6	16.1	16.5	16.3
Subject 6	13.6	13.9	14.3	14.5
Subject 7	12.4	11.2	12.3	12.4
Subject 8	6.8	7.0	7.0	6.8

Table 59 Middle thoracic flexion angle of individual subject in different periods of the LBP WBV group

T5-T7-T12 (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	12.0	12.1	12.8	13.3
Subject 2	15.9	12.8	13.6	12.0
Subject 3	21.7	20.9	21.5	21.3
Subject 4	9.1	8.8	8.5	8.1
Subject 5	6.5	6.2	5.5	5.3
Subject 6	8.9	9.3	9.0	8.9
Subject 7	14.4	11.8	12.7	13.4
Subject 8	16.3	16.4	16.5	16.5

Table 60 Lower thoracic flexion angle of individual subject in different periods of the LBP WBV group

T7-T12-L3 (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	4.4	4.6	3.4	3.3
Subject 2	10.7	8.8	9.7	13.0
Subject 3	0.8	0.5	1.1	0.6
Subject 4	0.8	0.3	0.4	0.4
Subject 5	7.1	8.0	8.7	9.2
Subject 6	5.9	5.7	5.4	6.2
Subject 7	0.5	2.5	2.7	2.5
Subject 8	4.5	4.6	4.6	4.4

Table 61 Upper lumbar extension angle of individual subject in different periods of the LBP WBV group

T12-L3-S1 (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	23.8	23.3	22.2	22.8
Subject 2	21.3	22.7	22.3	18.4
Subject 3	20.9	19.9	18.6	19.9
Subject 4	13.9	14.1	12.5	12.8
Subject 5	16.1	16.3	16.7	17.3
Subject 6	19.3	18.9	19.3	19.6
Subject 7	23.6	25.7	24.9	25.4
Subject 8	20.2	20.3	20.3	20.3

Table 62 Middle lumbar extension angle of individual subject in different periods of the LBP WBV group

L3-S1-Horizontal (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	79.7	81.4	81.0	80.8
Subject 2	75.9	71.2	72.3	72.9
Subject 3	86.4	86.4	87.5	86.8
Subject 4	86.8	85.4	86.1	85.8
Subject 5	81.5	80.6	80.5	79.5
Subject 6	84.0	83.3	83.8	83.6
Subject 7	82.7	79.7	81.7	81.8
Subject 8	82.9	82.8	82.5	82.2

Table 63 Lower lumbar extension angle of individual subject in different periods of the LBP WBV group

Pelvis tilt (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	21.2	20.9	20.9	20.7
Subject 2	13.7	17.6	16.5	14.8
Subject 3	13.0	12.4	12.6	13.2
Subject 4	18.0	18.6	18.4	18.6
Subject 5	12.9	13.1	13.4	15.2
Subject 6	20.5	20.4	20.5	20.4
Subject 7	15.5	16.9	15.2	15.6
Subject 8	17.5	16.6	17.0	17.0

Table 64 Pelvis tilting of individual subject in different periods of the LBP WBV group

Knee angle (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	6.7	6.5	5.7	5.9
Subject 2	3.9	2.8	3.8	3.7
Subject 3	1.8	1.9	3.4	2.4
Subject 4	4.3	1.8	1.3	1.2
Subject 5	-0.3	0.9	0.4	0.3
Subject 6	3.0	2.1	1.8	2.0
Subject 7	7.4	6.2	8.0	6.2
Subject 8	4.0	4.2	4.3	4.2

Table 65 Knee angle of individual subject in different periods of the LBP WBV group

Ankle angle (degree)	Before WBV	Immediately after WBV	30 minutes after WBV	60 minutes after WBV
Subject 1	84.8	86.1	85.3	86.1
Subject 2	84.7	85.9	85.3	86.3
Subject 3	79.7	80.2	78.8	79.3
Subject 4	82.0	83.3	83.3	84.0
Subject 5	89.0	88.4	88.2	88.9
Subject 6	84.2	84.5	83.7	84.1
Subject 7	80.0	80.9	79.1	78.1
Subject 8	82.0	82.4	83.0	82.6

Table 66 Ankle angle of individual subject in different periods of the LBP WBV group

7.10 Statistical values for the results

7.10.1 First stage study

Parameters	Time			Time*Group			Group		
	F	p	η^2	F	p	η^2	F	p	η^2
MRD	16.905	<0.001	0.760	0.118	0.948	0.022	2.443	0.135	0.120
MARP (Forward)	12.572	<0.001	0.702	0.935	0.447	0.149	1.004	0.330	0.530
MARP (Backward)	5.069	0.012	0.487	0.085	0.967	0.016	0.186	0.671	0.010
DP (Forward)	2.040	0.149	0.277	0.733	0.547	0.121	0.804	0.382	0.043
DP (Backward)	1.381	0.285	0.206	0.223	0.879	0.040	1.581	0.225	0.081
CE	1.874	0.175	0.260	0.846	0.488	0.137	0.247	0.625	0.014
VE	2.917	0.066	0.354	1.204	0.340	0.184	1.576	0.225	0.081
AE	4.124	0.024	0.436	2.117	0.138	0.284	0.055	0.818	0.003
CH-C7-T12	1.327	0.300	0.199	0.110	0.953	0.020	0.003	0.960	0.000
C7-T2-T5	0.693	0.570	0.115	0.915	0.456	0.146	0.593	0.451	0.032
T2-T5-T7	1.271	0.318	0.193	0.819	0.502	0.133	2.230	0.153	0.110
T5-T7-T12	1.273	0.317	0.193	2.400	0.104	0.312	1.357	0.259	0.070
T7-T12-L3	1.443	0.267	0.213	1.014	0.412	0.160	0.076	0.786	0.004
T12-L3-S1	2.022	0.151	0.275	3.015	0.061	0.361	0.632	0.437	0.034
L3-S1-Horizontal	3.659	0.035	0.407	1.065	0.391	0.166	0.080	0.780	0.004
Pelvis Tilt	3.416	0.043	0.390	0.851	0.486	0.138	0.000	0.998	0.000
Knee Angle	1.143	0.362	0.176	3.642	0.036	0.406	0.015	0.903	0.001
Ankle Angle	1.318	0.303	0.198	0.663	0.587	0.111	0.187	0.67	0.01

Table 67 Data analysis by comparing the results of all the variables between standing WBV and seated WBV in the first stage study

Parameters	Post-hoc (Time)					
	T1 Vs T2	T1 Vs T3	T1 Vs T4	T2 Vs T3	T2 Vs T4	T3 Vs T4
MRD	<0.001	<0.001	0.001	0.322	0.156	0.513
MARP (Forward)	<0.001	<0.001	<0.001	0.807	0.082	0.122
MARP (Backward)	0.001	0.007	0.027	0.106	0.01	0.129
AE	0.002	0.011	0.189	0.495	0.121	0.17
L3-S1-Horizontal	0.01	0.569	0.826	0.03	0.021	0.192
Pelvis Tilt	0.013	0.643	0.389	0.046	0.024	0.196

Table 68 Post-hoc comparison of parameters in the first stage study with significant time effect only

7.10.2 Second stage study

Parameters	Time			Time*Group			Group		
	F	*p*	η^2	*F*	*p*	η^2	*F*	*p*	η^2
MRD	25.328	<0.001	0.844	0.949	0.464	0.169	3.544	0.079	0.181
MARP (Forward)	35.215	<0.001	0.883	4.273	0.024	0.478	9.704	0.007	0.378
MARP (Backward)	11.965	<0.001	0.719	0.431	0.734	0.085	0.483	0.497	0.029
DP (Forward)	2.411	0.110	0.341	0.385	0.765	0.076	29.847	<0.001	0.651
DP (Backward)	2.977	0.068	0.389	0.204	0.892	0.042	14.341	0.002	0.473
CE	2.594	0.094	0.357	2.034	0.155	0.304	0.336	0.570	0.021
VE	1.456	0.269	0.238	0.813	0.508	0.148	0.712	0.411	0.043
AE	27.336	<0.001	0.854	1.884	0.179	0.288	2.432	0.138	0.132
CH-C7-T12	1.276	0.321	0.215	0.593	0.630	0.113	0.042	0.840	0.003
C7-T2-T5	3.345	0.043	0.432	0.276	0.842	0.056	4.023	0.062	0.201
T2-T5-T7	4.363	0.023	0.483	0.497	0.690	0.096	0.037	0.849	0.002
T5-T7-T12	1.540	0.248	0.248	0.538	0.664	0.103	0.198	0.662	0.012
T7-T12-L3	1.766	0.200	0.275	0.930	0.452	0.166	0.014	0.908	0.001
T12-L3-S1	1.877	0.180	0.287	4.297	0.024	0.479	0.151	0.702	0.009
L3-S1-Horizontal	5.342	0.012	0.534	0.818	0.505	0.149	3.482	0.080	0.179
Pelvis Tilt	1.117	0.375	0.193	0.518	0.677	0.100	5.203	0.037	0.245
Knee Angle	0.512	0.680	0.099	2.727	0.084	0.369	0.000	0.998	0.000
Ankle Angle	7.76	0.003	0.624	0.781	0.524	0.143	0.95	0.344	0.056

Table 69 Data analysis by comparing the results of all the variables between seated WBV (control) and LBP group in the second stage study

Parameters	Post-hoc (Time)					
	T1 Vs T2	T1 Vs T3	T1 Vs T4	T2 Vs T3	T2 Vs T4	T3 Vs T4
MRD	<0.001	<0.001	<0.001	0.408	0.049	0.11
MARP (Backward)	<0.001	0.001	0.05	0.013	0.002	0.047
DP (Forward)	<0.001	<0.001	<0.001	0.845	0.482	0.284
DP (Backward)	0.008	0.23	0.365	0.052	0.165	0.817
CE	0.104	0.581	0.707	0.004	0.065	0.18
VE	0.017	0.503	0.409	0.005	0.061	0.562
AE	0.004	0.795	0.699	0.002	0.078	0.216

Table 70 Post-hoc comparison of parameters in the first stage study with significant time effect only

7.11 Experiment schedule

Time Consumed (in minutes)	15	5	5	15	15	15	15	15
Assessment Period	Before WBV	Rest	WBV	Immediately after WBV	Rest	30 minutes after WBV	Rest	1 hour after WBV

Table 71 Schedule of the experiment showing the approximate time consumption; WBV: whole body vibrati

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