Hazard Prevention

Whole-Body Vibration

Health effects, measurement and minimization

By Derek R. Smith and Peter A. Leggat

WHOLE-BODY VIBRATION (WBV) is the vibration transmitted to a person's entire body via his/her contact with a vibration source, usually through sitting or standing on a vibrating surface. WBV is a common occupational problem for workers in high-vibration environments, particularly when the exposure represents a significant part of their working day, not simply an intermittent event.

Exposure to vibration appears to be increasing throughout the working world, with high-vibration environments now representing a significant proportion of all occupations. In Europe, Canada and the U.S. for example, it has been estimated that up to seven percent of all workers are regularly exposed to WBV (Bovenzi and Hulshof). In Great Britain, approximately nine million people are exposed to some form of WBV every week [Palmer, et al(a)]. More than 400,000 cases of low back pain (LBP) in the U.K. may be attributable to occupational WBV [Palmer, et al(b)].

By category, high-vibration workplaces are numerous and may include crane operators [Bongers, et al(a)]; agricultural tractor drivers (Futatsuka, et al; Bovenzi and Betta; Boshuizen, et al; Sjoflot); freight container tractor drivers (Nishiyama, et al); heavy equipment operators [Waters, et al; Teschke, et al; Kittusamy(b); Kittusamy and Miller]; all-terrain vehicle drivers (Rehn, et al); rally car drivers (Mansfield and Marshall); taxi drivers (Chen, et al; Funakoshi, et al) and garbage truck drivers (Maeda and Morioka). Similarly, pilots—particularly helicopter pilots—may be exposed to WBV at significant rates [Lopez-Lopez, et al; de Oliveira, et al; Bongers, et al(b)]. Other studies have shown that WBV exposure can also originate from less-well-defined sources such as high-speed trains (Sumitomo, et al); manual wheelchairs [Maeda, et al(b)]; foundry work (Armstrong, et al); road-traffic noise [Maeda, et al(a)]; and nonspecific low-frequency noise (Takahashi, et al). Table 1 highlights some industries and occupations affected by WBV.

Biomechanics of Whole-Body Vibration

Many biodynamic models have been developed to help understand the biomechanics of WBV (Kitazaki and Griffin; Seidel, et al; Yue and Mester). A key concept is the fact that all objects have a speed at which they naturally vibrate. This phenomenon, which depends greatly on the physical characteristics of the object, is termed its resonant frequency (RF). When objects reach their RF, the maximum amplitude of their vibration increases. For humans, there is no single, definitive RF because various parts of the body with differing physical characteristics (such as density and mass) tend to vibrate at different frequencies.

Nevertheless, a critical range has been proposed, with vibrations between 0.5 Hz (cycles per second) and 80 Hz generally regarded as having significant effects on the human body. For vertical vibration, the most important RF appears to be between 4 and 8 Hz. Although the RF of specific body parts varies, vibration amplitudes between 3 and 5 Hz are known to generate strong resonances in the neck. When seated, it has been suggested that frequencies between 4 and 7 Hz are the most important for the spine (El-Khatib and Guillon). For the lower back, the natural frequency appears to be around 4.5 Hz (Pope, et al). At frequencies between 20 and 30 Hz, RF amplitude may increase up to 350 percent between the head and shoulders (Hedge).

The physical process between vibrating energy transfer and the human body essentially involves two components. First, energy flows from the vibrator and into the human body via a

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Table 1

WBV: Affected Populations, Sources & Preventive Measures

Industry Type	Affected Workers
Agriculture	Tractor drivers and harvester operators.
Construction	Earth moving and heavy machinery equipment operators.
Transportation	Taxi, train, truck, bus and delivery drivers.
Aviation	Helicopter pilots and other commercial aviators.

Most WBV exposure in these industries is transmitted to workers through the seat and floor. Preventive measures include: 1) providing vibration-isolating seating and mechanically isolated flooring; 2) minimizing exposure time; and 3) providing rest breaks where possible.

Heavy equipment operators are an occupational group identified as being at risk of exposure to whole-body vibration.

point(s) of contact and is mainly stored in the muscle-tendon systems. In the second phase, energy flows from the muscle-tendon system back into the vibrator, albeit at a reduced amount due to a certain degree of energy dissipation (Yue and Mester).

There is greater transmission of vertical vibration to the lower spine in the standing posture than in the seated posture [Matsumoto and Griffin(a)]. In a seated human being, the dominant movement appears to be bending of the lumbar spine coupled with a rocking motion [Matsumoto and Griffin(b)]. As the human body naturally pivots at a few critical points along the spine, physiological damage tends to concentrate in these regions. Among them, the joint between the seventh cervical vertebra (C7) and the first thoracic vertebra (T1) (C7/T1 intervertebral joint) is known to be an important region. Other areas include the joints between the twelfth thoracic vertebra/first lumbar vertebra (T12/L1) and the fifth lumbar/first sacral vertebras (L5/S1 intervertebral joint).

Physiological Effects of WBV

Vibration is transferred from the source via contact surfaces supporting the body. These contact surfaces usually include the buttocks of seated people, the feet of standing individuals and many points of contact on a recumbent person, such as the back, hips and head. Because contact with the source may not always be direct, the effects of WBV can depend on various external variables such as the type and composition of seating, the type of footwear and the subject's overall body posture. WBV effects depend on many other interrelated variables, such as the distribution of motion within the body and the magnitude of vibration, as well as the vibration direction, frequency and overall duration. Perception thresholds may also vary between individuals with respect to certain aspects of WBV (Matsumoto, et al).

Possible health effects of short- and long-term exposure to WBV are summarized in the sidebar on pg. 37. Short-term exposure is believed to be the least harmful, usually resulting in benign physiological effects such as increases in heart rate, hyperventilation, headache and loss of balance. Cardiovascular system effects may be seen when the frequency is below 20 Hz, while muscles can become unnaturally tense in order to help dampen vibration (Safety Line Institute). The ability to complete assigned workplace tasks may diminish with WBV exposure, and this phenomena can also involve motivation, information collection and information processing. Blurred vision is another common side effect as the retina vibrates, particularly at frequencies between 20 and 90 Hz. Nevertheless, many acute health effects from WBV exposure are reversible and will often resolve when the vibration source is removed (U.S. Army).

On the other hand, chronic WBV is a particular concern, as repeated exposure may result in permanent physiological changes. The most commonly reported adverse effects from WBV are musculoskeletal distoders (MSDs), particularly LBP (Hulshof and van Zanten). It is generally accepted that prolonged WBV exposure is traumatic for the human spine, as intervertebral discs and vertebral structures act as springs and dampers in dissipating WBV energy (Pankoke, et al). Two mechanisms seem to operate simultaneously—stiffening when exposed to shock and softening as the overall WBV magnitude increases (Mansfield, et al). At the lower back's principal RF (4.5 Hz), electromyographic studies have shown that muscle fatigue occurs, which then changes the muscles' response to new and sudden loads (Pope, et al).

WBV at the spinal RF will increase its damaging effects, potentially leading to degenerative physiological changes, such as spinal disc damage and/or disc herniation. At a microlevel within the spine, constant vibrating movement of the intervertebral discs stresses the annular fibers; pressure then increases within the discs and resultant forces may eventually cause the material to fail (Teschke, et al). A failed or herniated spinal disc may protrude from the vertebral structure, placing pressure on spinal nerve and producing LBP. Not all herniated discs are painful, however (Jensen, et al).

Personal discomfort is another negative effect from WBV exposure. Although a somewhat subjective concept, it has been suggested that changes in comfort level may be proportionate to overall vibration levels. As such, doubling the vibration level may cause discomfort to double. Perceived discomfort is generally related to vibration frequency, with 1 to 2 Hz representing a problematic range (SafetyLine Institute). Discomfort usually increases with increasing exposure time, while posture of the exposed subject is also known to affect perception.

Recumbent people seem to have different perception thresholds than seated and standing individuals [Yonekawa, et al; Maeda, et al(c)]. Multi-axis WBV is usually more uncomfortable than single-axis vibration, while other factors such as seat design, body posture, age, gender and exposure to noise may also contribute to a certain extent. Other miscellaneous ailments resulting from chronic WBV exposure have similarly been mentioned in the scientific literature, and may include systemic physiological events such as interference with gastric function (Ishitake, et al). Digestive system effects are believed to be particularly common when the exposed frequency is between 4 and 5 Hz.

The most important adverse event regularly reported in scientific studies is an excess of MSDs among workers chronically exposed to WBV. These effects have received increasing attention in recent years, particularly with respect to LBP (Pinto, et al; Bernard). The four main occupational categories where significant WBV exposure appears to correlate with the development of MSDs are agricultural workers (tractor drivers); construction workers (heavy machinery equipment operators); transportation workers (taxi, train, bus and truck drivers); and employees within the aviation industry (particularly helicopter pilots).

Scientific studies of tractor drivers began in the early 1960s and initially showed a reasonable prevalence of MSDs—30 percent with LBP and 70 percent with degenerative changes to the thoracic and lumbar spine. A more-detailed longitudinal investigation of tractor drivers revealed similar degenerative changes and also showed that LBP increased from 20 percent to 58 percent over a 10-year period (Hulshof and van Zanten). Other contemporary research suggests that tractor drivers exposed to WBV suffer approximately 10-percent more LBP than those not exposed to WBV (Boshuizen, et al).

Another study showed that tractor drivers were three times as likely to experience transient LBP and twice as likely to suffer from chronic LBP when compared to nonvibration exposed controls (Bovenzi and Betta). These authors also quantified the peak LBP risks for total vibration dose, equivalent vibration magnitude, duration of exposure and postural load. Although it has been suggested that back-to-chest WBV was the most problematic of all (Nishiyama, et al), introduction of an air-spring suspension system helped to reduce overall LBP among freight-container tractor drivers. Alternatively, Futatsuka, et al showed that although certain Japanese combine harvesters and agricultural tractors exceeded WBV exposure limits, duration of exposure was short and LBP prevalence was not elevated with respect to controls.

Ergonomic problems have been well-studied among construction workers, as has the relationship between WBV exposure and LBP [Kittusamy and Buchholz(b)]. For example, an investigation of Dutch crane operators found the 100 person-years incidence rate for back disorders (0.85) to be almost double that of controls (0.47) who were not exposed to WBV. Between 10 and 14 years of exposure, the risk of back disorders among the exposed group was more than twice that of the control group [Bongers, et al(a)].

Another study [Schwarze, et al] suggested that up to 35 percent of all incidents of lumbar syndrome could be attributed to WBV. LBP was found to affect between 39 percent and 72 percent of workers depending on the intensity of WBV exposure. These researchers also suggested that with increasing WBV dose, the probability of LBP being caused by WBV increased. Teschke, et al summarized the WBV root mean squared (RMS) values of heavy machines and found the risks increased with employment duration and vibration-exposure duration. On a more positive note, Kittusamy and Miller measured shock events among bulldozer operators and reported the vibration of newer dozers to be less than that of older dozers.

Among workers who operate vibrating vehicles, LBP has been reported at various prevalence rates, ranging from 41 percent among forklift drivers to 83 percent among bus drivers. Sciatic pain has been documented in 15 percent of wheel loader operators and 23 percent of subway train drivers (Bovenzi and Hulshof). The relative risk of LBP is also increased in these workers when compared to controls. Bovenzi and Hulshof found that bus drivers were three times more likely and forklift drivers seven times more likely to suffer from LBP than workers not exposed to WBV.

Similarly, subway drivers were around four times more likely to have sciatic pain than nonexposed subjects. A study of WBV among Taiwanese taxi drivers found that nearly half (48 percent) had experienced LBP in the last year (Chen, et al). When driving vehicles, WBV exposure and associated hazards may vary throughout a person's workshift. An investigation of WBV among Japanese garbage truck drivers found that not only were WBV exposures very high, but also that exposure depended on whether the truck was empty or full (Maeda and Morioka).

Nevertheless, it is important to note that continual improvements in vehicle suspension and seat design have to some degree reduced overall WBV exposure among a wide range of vehicle-based workers in recent years. Unfortunately, poorly designed seats still exist, long driving hours remain common and vibration exposure in some vehicles is difficult to avoid entirely.

Helicopters are one such vehicle. Helicopter pilots are exposed to significant WBV at work that may eventually lead to occupational MSD, particularly LBP. Although helicopter seats promote poor posture and constant WBV may cause a cyclic response of the erector spine muscles, not all studies have demonstrated a causal link between helicopter flying and adverse events (de Oliveira, et al).

A study of this occupational group in the Netherlands found 68 percent to be suffering from any back pain and 55 percent from LBP. When compared to a control group, the pilots were up to nine times more likely to have LBP. Overall, these authors found that transient back pain was related to the

Acute & Chronic Health Effects of WBV

Acute Effects (short-term exposures)

- Benign physiological effects such as:
  - increase in heart rate
  - hyperventilation
  - headache
  - loss of balance
  - motion sickness
- Muscle fatigue
- Discomfort
- Effects on motor performance
- Effects on cognitive functions involving demanding tasks
- Effects on speech
- Effects on vision, producing difficulties reading instruments and performing visual searches

Chronic Effects (long-term exposures)

- Degenerative disorders of the spine, especially the lumbar and thoracic spine
- Spinal disc disease and failure
- Low back pain
- Disorders of the gastrointestinal system (e.g., suppression of gastric function)

average number of flying hours per day, while chronic LBP correlated with either: 1) more than 2,000 hours total flying time or 2) a vibration dose of 400 $m^2/h/s^4$ [Bongers, et al(b)].

Further investigation of lumbar muscle activity among helicopter pilots found that they did not maintain a symmetrical posture; rather, their backs contracted one side more than the other. This result suggests the strain on pilots' backs is not evenly distributed and the risk of injury may be concentrated on a particular side, depending on the pilot. Although 35 flights were measured, a threshold for vibration dose and lumbar muscle activity was not established (Lopez-Lopez, et al).

One of the biggest problems in WBV/MSD research is the lack of a clear dose-response relationship (Magnusson, et al). How much WBV is too much and how much WBV is needed to cause MSDs? Another important issue is potential confounders—factors other than WBV that also contribute to MSDs. Numerous ergonomic studies have already been conducted among many kinds of workers (both WBV-exposed and unexposed), many of which identified MSD risk factors. These risks can be divided into intrinsic (personal) factors and extrinsic (workplace or environmental) factors. Confounding intrinsic factors include age, sex, fitness levels, weight, height, physical condition, body type, tobacco smoking and previous LBP. Confounding extrinsic factors include working postures, repeated lifting, heavy labor, falls, injury-causing events, work stress and lack of job satisfaction.

Measurement of WBV

Measuring WBV exposure is not a straightforward process. A comprehensive assessment must incorporate numerous parameters, including the acceleration of each vibration frequency; direction of WBV transmission to the body; frequency spectrum; and overall timed duration of WBV exposure. Fortunately, WBV measurement has become increasingly sophisticated as understanding of the discipline has advanced. Technological progress has enabled more accurate and complex measurements of the forces at work on human bodies.

In its infancy some 40 years ago, ergonomics studies measured WBV as a simple function of up-and-down movement or single-axis (Z-axis) vertical vibration. Over time, measurement techniques began to incorporate the effects of forward/backward motion (X-axis) and left/right motion (Y-axis). More recently, roll, pitch and yaw variables have been incorporated into each of these three motions, leading to the current measurement standard of 12-axis vibration.

Modern WBV measurement systems usually consist of a transducer to sense vibrations, a pre-amplifying device, a frequency-weighting filter, a data-recording device and a signal analyzer to obtain the appropriate parameters such as acceleration RMS and peak values (SafetyLine Institute). Another important facet of WBV investigation is laboratory research in which field conditions are accurately recreated and observed in a controlled environment. Although numerous devices are available to facilitate such measurements, one of the most important simulators is the multi-axis vibrator. This apparatus allows precise and controlled vibration to be experimentally transmitted in a laboratory environment. However, such equipment is large, cumbersome, expensive and fairly rare worldwide.

International Vibration Standards

The evolution of international standards for WBV exposure and measurement has reflected an increased understanding and sophistication of human biomechanics over time. As such, WBV standards have undergone various revisions, from single axis, progressing to 3-axis, 6-axis and, finally, the current standard 12-axis vibration. Although development of an international whole-body vibration standard began around 1966, it was not published until 1974. The standard was then republished in 1978 and 1985 (Griffin). The International Organization for Standardization (ISO) WBV standard is now known as ISO 2631-1:1997, Mechanical Vibration and Shock: Evaluation of Human Exposure to Whole-Body Vibration (General Requirements).

Development of this standard is an ongoing process, with revisions being constantly debated and occasionally incorporated. At this time, no consensus has been reached regarding the exact direction in which revisions should proceed. Some contend the current standard underestimates WBV exposure risks [Paddan and Griffin(b)]. Others suggest it may cause unnecessary confusion (Griffin). According to Griffin, it is difficult to use ISO 2631-1 to establish whether a particular WBV exposure is acceptable.

In addition, fundamental disagreements have arisen between those who favor the British WBV standard (BS 6841:1987, which takes shock loading into account) and those who prefer the ISO standard (which does not consider shock loading). As a result, it is difficult to predict what direction future revisions of ISO 2631-1 will take. Certainly, an increasing number of high-quality studies have been published, which suggests a continuing refinement of current knowledge. In the meantime, the ISO standard is gradually being incorporated into legislation and guidelines around the world.

Predicting Risks of WBV

Although many studies have suggested that MSDs (particularly LBP) are more common among workers exposed to WBV, a distinct dose-response relationship between these variables has not been clearly established. This situation has primarily arisen because many pioneering studies focused on the assessment of acute effects such as discomfort or decreased performance (Hulshof and van Zanten). Furthermore, the scientific quality of WBV studies has been limited until recently, with many lacking control groups and few reporting any meaningful dose-response relationships between WBV and adverse symptoms (Lings and Leboeuf-Yde).

Establishing the definitive risks of WBV is important from both a hazard assessment and workers' compensation perspective. An increasing number of detailed WBV evaluation studies are suggesting that LBP is common among most types of vehicle drivers (Bovenzi and Betta; Funakoshi, et al; Mansfield and Marshall; Rehn, et al; Schwarze, et al). Less-definitively shown, yet mentioned nevertheless, is that these workers may also be at increased risk of damage to the lower back—with some X-ray evaluations providing evidence of degenerative changes to the lumbar spine (Dupuis and Zerlett). In addition, several models are being developed to help simulate and evaluate biomechanical responses to WBV (Kitazaki and Griffin; Seidel, et al; Yue and Mester).

Minimizing Risks of WBV

As noted, the effects of WBV on the human body vary according to several parameters, most importantly the seating arrangement, seating position, posture and various physiological characteristics of exposed individuals. For example, among taxi drivers, WBV increases have been shown to relate to driving speed, engine size, body weight, age and the use of seat cushions (Chen, et al). Internal stress seems to vary proportionally to body mass (Seidel, et al). The design and use of seats appears to be particularly critical in WBV exposure [Paddan and Griffin(a)]. Posture, seating and seat inclination can affect frequency response, while overall improper seating dynamics and bent-forward posture may also contribute [Seidel, et al; Pope, et al; Paddan and Griffin(a)]. As such, all of these factors should be considered when evaluating the ergonomic concerns of workers exposed to WBV.

For heavy vehicle operators, Kittusamy has suggested the following measures:

1) Seat design should consider vibration transmissibility rather than just comfort.

2) Seats need to specifically dampen frequencies between 1 and 8 Hz.

3) Equipment should be properly maintained to reduce wear that may increase overall vibration.

4) Speeds should be limited (especially when traversing uneven ground).

5) Workers should be encouraged to not jump out of vehicles when exiting as this applies unnecessary shock to a body that has just been subjected to WBV for a few hours [Kittusamy(b); Kittusamy and Buchholz(a)]. As noted, the current lack of consensus regarding safe WBV exposure limits makes it difficult to definitively suggest a safe WBV exposure dose.

That said, sufficient evidence is available to warrant a reduction of WBV to the lowest possible level (Lings and Leboeuf-Yde). Various measures to reduce WBV are suggested in the sidebar on this page. These include introducing measures to reduce equipment vibration, such as updating or replacing equipment that produces excessive levels of vibration wherever possible. Hazard reduction strategies for WBV include controlling the source of vibration via engineering controls such as balancing or vibration dampening; providing seated workers with vibration-isolated seating; and providing standing workers with mechanically isolated flooring. Other complementary strategies include isolating the source and the use of personal protective measures to minimize vibration. Overall, one of the most practical hazard reduction strategies is to limit the duration of exposure. Such initiatives will become critical as more powerful machines are developed.

Conclusion

Whole-body vibration is an important risk factor for occupational illness and injury. Technological advances have created more powerful and faster machines that in turn produce more vibration, meaning more workers are potentially affected by WBV. Fortunately, WBV research has also evolved in recent years thanks to an increased understanding of biomechanics and the increasing sophistication of WBV measurement devices. Although many preventive methodologies have been proposed, by far the most useful strategy focuses on the reduction of WBV exposure to the lowest possible level and limiting the overall duration of WBV exposure wherever possible. ■

Controlling WBV

Reducing Equipment Vibration

- Replace equipment that produces excessive levels of vibration.
- Implement a means to reduce vibration.

Reducing WBV

- Control the source of vibration by engineered means such as balancing or vibration dampening.
- Provide seated workers with vibration-isolated seating.
- Provide standing workers with mechanically isolated flooring.
- Isolate the source of vibration by other measures.
- Use personal protective measures for vibration dampening.
- Limit the duration of exposure.

References

Armstrong, T.J., et al. "Exposure to Forceful Exertions and Vibration in a Foundry." *International Journal of Industrial Ergonomics.* 30(2002): 163-179.

Bernard, B.P., ed. "Musculoskeletal Disorders and Workplace Factors. A Critical Review of Epidemiologic Evidence for Work-Related Musculoskeletal Disorders of the Neck, Upper Extremity and Low Back." DHHS/NIOSH Publication No. 97-141. Washington, DC: U.S. Dept. of Health and Human Services, CDC, NIOSH, 1997.

Bongers, P.M., et al(a). "Back Disorders in Crane Operators Exposed to Whole-Body Vibration." *International Archives of Occupational and Environmental Health.* 60(1988): 129-137.

Bongers, P.M., et al(b). "Back Pain and Exposure to Whole Body Vibration in Helicopter Pilots." *Ergonomics.* 33(1990): 1007-1026.

Boshuizen, H.C., et al. "Self-Reported Back Pain in Tractor Drivers Exposed to Whole-Body Vibration." *International Archives of Occupational and Environmental Health.* 62(1990): 109-115.

Bovenzi, M. and A. Betta. "Low-Back Disorders in Agricultural Tractor Drivers Exposed to Whole-Body Vibration and Postural Stress." *Applied Ergonomics.* 25(1994): 231-241.

Bovenzi, M. and C.T.J. Hulshof. "An Updated Review of Epidemiologic Studies on the Relationship Between Exposure to Whole-Body Vibration and Low Back Pain." *Journal of Sound and Vibration.* 215(1998): 595-611.

Chen, J.C., et al. "Predictors of Whole-Body Vibration Levels among Urban Taxi Drivers." *Ergonomics.* 46(2003): 1075-1090.

de Oliveira, C.G., et al. "Lumbar Back Muscle Activity in Helicopter Pilots and Whole-Body Vibration." *Journal of Biomechanics.* 34(2001): 1309-1315.

Dupuis, H. and G. Zerlett. "Whole-Body Vibration and Disorders of the Spine." *International Archives of Occupational and Environmental Health.* 59(1987): 323-336.

El-Khatib, A. and F. Guillon. "Lumbar Intradiscal Pressure and Whole-Body Vibration: First Results." *Clinical Biomechanics.* Supplement 16(2001): S127-S134.

By far, the most useful WBV control strategy focuses on the reduction of WBV exposure to the lowest possible level and limiting the overall duration of WBV exposure wherever possible.

Funakoshi, M., et al. "Measurement of Whole-Body Vibration in Taxi Drivers." *Journal of Occupational Health.* 46(2004): 119-124.

Futatsuka, M., et al. "Whole-Body Vibration and Health Effects in the Agricultural Machinery Drivers." *Industrial Health.* 36(1998): 127-132.

Griffin, M.J. "A Comparison of Standardized Methods for Predicting the Hazards of Whole-Body Vibration and Repeated Shocks." *Journal of Sound and Vibration.* 215(1998): 883-914.

Hedge, A. "Whole-Body Vibration." Document DEA350. Ithaca, NY: Cornell University, Ergonomics Web. <http://ergo.human.cornell.edu>.

Hulshof, C. and B.V. van Zanten. "Whole-Body Vibration and Low Back Pain. A Review of Epidemiologic Studies." *International Archives of Occupational and Environmental Health.* 59(1987): 205-220.

International Organization for Standardization (ISO). "ISO Standard 2631-1: Mechanical Vibration and Shock—Evaluation of Human Exposure to Whole-Body Vibration, Part 1: General Requirements." Geneva: ISO, 1997.

Ishitake, T., et al. "Suppressive Mechanism of Gastric Motility by Whole-Body Vibration." *International Archives of Occupational and Environmental Health.* 72(1999): 469-474.

Jensen, M.C., et al. "Magnetic Resonance Imaging of the Lumbar Spine in People without Back Pain." *New England Journal of Medicine.* 331(1994): 69-73.

Kitazaki, S. and M.J. Griffin. "A Modal Analysis of Whole-Body Vertical Vibration, Using a Finite Element Model of the Human Body." *Journal of Sound and Vibration.* 200(1997): 83-103.

Kittusamy, N.K.(a). "A Checklist for Evaluating Cab Design of Construction Equipment." *Applied Occupational and Environmental Hygiene.* 18(2003): 721-723.

Kittusamy, N.K.(b). "Ergonomic Risk Factors: A Study of Heavy Earthmoving Machinery Operators." *Professional Safety.* Oct. 2002: 38-45.

Kittusamy, N.K. and B. Buchholz(a). "An Ergonomic Evaluation of Excavating Operations: A Pilot Study." *Applied Occupational and Environmental Hygiene.* 16(2001): 723-726.

Kittusamy, N.K. and B. Buchholz(b). "Whole-Body Vibration and Postural Stress Among Operators of Construction Equipment: A Literature Review." *Journal of Safety Research.* 35(2004): 255-261.

Kittusamy, N.K. and R.E. Miller. "Comparison of Jolting and Jarring in a Newer and Older Bulldozer at a Highway Construction Site." Presented at the 15th Triennial Congress of the International Ergonomics Assn., Seoul, Korea, August 2003.

Lings, S. and C. Leboeuf-Yde. "Whole-Body Vibration and Low Back Pain: A Systematic, Critical Review of the Epidemiologic Literature 1992-1999." *International Archives of Occupational and Environmental Health.* 73(2000): 290-297.

Lopez-Lopez, J.A., et al. "Determination of Lumbar Muscular Activity in Helicopter Pilots: A New Approach." *Aviation Space and Environmental Medicine.* 72(2001): 38-43.

Maeda, S., et al(a). "Experimental Studies of Subjective Response to Road Traffic-Induced Building Vibration." *Industrial Health.* 36(1998): 112-119.

Maeda, S., et al(b). "Relationship Between Questionnaire Survey Results of Vibration Complaints of Wheelchair Users and Vibration Transmissibility of Manual Wheelchair." *Environmental Health and Preventive Medicine.* 8(2003): 82-89.

Maeda, S., et al(c). "Whole-Body Vibration Perception Thresholds of Recumbent Subjects. Part 2: Effect of Vibration Direction." *Industrial Health.* 37(1999): 404-414.

Maeda, S. and M. Morioka. "Measurement of Whole-Body Vibration Exposure from Garbage Trucks." *Journal of Sound and Vibration.* 215(1998): 959-964.

Magnusson, M.L., et al. "Development of a Protocol for Epidemiological Studies of Whole-Body Vibration and Musculoskeletal Disorders of the Lower Back." *Journal of Sound and Vibration.* 215(1998): 643-651.

Mansfield, N.J. and M.J. Griffin. "Non-Linearities in Apparent Mass and Transmissibility During Exposure to Whole-Body Vertical Vibration." *Journal of Biomechanics.* 33(2000): 933-941.

Mansfield, N.J. and J.M. Marshall. "Symptoms of Musculoskeletal Disorders in Stage Rally Drivers and Co-Drivers." *British Journal of Sports Medicine.* 35(2001): 314-320.

Mansfield, N.J., et al. "Apparent Mass and Absorbed Power During Exposure to Whole-Body Vibration and Repeated Shocks." *Journal of Sound and Vibration.* 248(2001): 427-440.

Matsumoto, Y. and M.J. Griffin(a). "Comparison of Biodynamic Responses in Standing and Seated Human Bodies." *Journal of Sound and Vibration.* 238(2000): 691-704.

Matsumoto, Y. and M.J. Griffin(b). "Movement of the Upper-Body of Seated Subjects Exposed to Vertical Whole-Body Vibration at the Principal Resonance Frequency." *Journal of Sound and Vibration.* 215(1998): 743-762.

Matsumoto, Y., et al. "Influence of Frequency on Difference Thresholds for Magnitude of Vertical Sinusoidal Whole-Body Vibration." *Industrial Health.* 40(2002): 313-319.

Nishiyama, K., et al. "A Decade of Improvement in Whole-Body Vibration and Low Back Pain for Freight Container Tractor Drivers." *Journal of Sound and Vibration.* 215(1998): 635-642.

Paddan, G.S. and M.J. Griffin(a). "Effect of Seating on Exposures to Whole-Body Vibration in Vehicles." *Journal of Sound and Vibration.* 253(2002): 215-241.

Paddan, G.S. and M.J. Griffin(b). "Evaluation of Whole-Body Vibration in Vehicles." *Journal of Sound and Vibration.* 253(2002): 195-213.

Palmer, K.T., et al(a). "Prevalence and Pattern of Occupational Exposure to Whole Body Vibration in Great Britain: Findings from a National Survey." *Occupational and Environmental Medicine.* 57(2000): 229-236.

Palmer, K.T., et al(b). "The Relative Importance of Whole Body Vibration and Occupational Lifting as Risk Factors for Low-Back Pain." *Occupational and Environmental Medicine.* 60(2003): 715-721.

Pankoke, S., et al. "Dynamic FE Model of Sitting Man Adjustable to Body Height, Body Mass and Posture Used for Calculating Internal Forces in the Lumbar Vertebral Disks." *Journal of Sound and Vibration.* 215(1998): 827-839.

Pinto, I., et al. "Abstracts from the Second International Conference on Whole-Body Vibration Injuries, Held in Sienna, Italy, Nov. 7-9, 2000." *Journal of Sound and Vibration.* 253(2002): 1-2.

Pope, M.H., et al. "Possible Mechanisms of Low Back Pain Due to Whole-Body Vibration." *Journal of Sound and Vibration.* 215(1998): 687-697.

Rehn, B., et al. "Musculoskeletal Symptoms among Drivers of All-Terrain Vehicles." *Journal of Sound and Vibration.* 253(2002): 21-29.

SafetyLine Institute. "Human Vibration: Whole Body Vibration." West Perth, Western Australia: Worksafe Western Australia. <http://www.safetyline.wa.gov.au>.

Schwarze, S., et al. "Dose-Response Relationships Between Whole-Body Vibration and Lumbar Disk Disease: A Field Study on 388 Drivers of Different Vehicles." *Journal of Sound and Vibration.* 215(1998): 613-628.

Seidel, H., et al. "Application of Finite-Element Models to Predict Forces Acting on the Lumbar Spine During Whole-Body Vibration." *Clinical Biomechanics.* Supplement 16(2001): S57-S63.

Sjoflot, L. "The Tractor as a Workplace. A Preliminary Report on a Survey among Norwegian Farmers and Tractor Drivers." *Ergonomics.* 25(1982): 11-18.

Sumitomo, S., et al. "The Influence of the Great Hanshin Earthquake on Human Response to Environmental Vibration Due to the Shinkansen." *Industrial Health.* 36(1998): 290-296.

Takahashi, Y., et al. "A Pilot Study on the Human Body Vibration Induced by Low Frequency Noise." *Industrial Health.* 37(1999): 28-35.

Teschke, K., et al. "Whole Body Vibration and Back Disorders among Motor Vehicle Drivers and Heavy Equipment Operators. A Review of the Scientific Evidence." Report to the Workers' Compensation Board. Vancouver, British Columbia: Workers' Compensation Board, 1999.

U.S. Army. "Whole-Body Vibration." Washington, DC: U.S. Dept. of Defense, U.S. Army, Center for Health Promotion and Preventive Medicine. <http://chppm-www.apgea.army.mil/doem>.

Waters, T.R., et al. "Biomechanical Modeling of Spinal Loading Due to Jarring and Jolting for Heavy Equipment Operators." Presented at the 15th Triennial Congress of the International Ergonomics Assn. in Seoul, Korea, Aug. 2003.

Yonekawa, Y., et al. "Whole-Body Vibration Perception Thresholds of Recumbent Subjects. Part 1: Supine Posture." *Industrial Health.* 37(1999): 398-403.

Yue, Z. and J. Mester. "A Model Analysis of Internal Loads, Energetics and Effects of Wobbling Mass During the Whole-Body Vibration." *Journal of Biomechanics.* 35(2002): 639-647.