Whole-body vibration and postural stress among operators of construction equipment: A literature review

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Abstract

Introduction: Operators of construction equipment perform various duties at work that expose them to a variety of risk factors that may lead to health problems. A few of the health hazards among operators of construction equipment are: (a) whole-body vibration, (b) awkward postural requirements (including static sitting), (c) dust, (d) noise, (e) temperature extremes, and (f) shift work. It has been suggested that operating engineers (OEs) are exposed to two important risk factors for the development of musculoskeletal disorders: whole-body vibration and non-neutral body postures. *Method:* This review evaluates selected papers that have studied exposure to whole-body vibration and awkward posture among operators of mobile equipment. There have been only few studies that have specifically examined exposure of these risk factors among operators of construction equipment. Thus other studies from related industry and equipment were reviewed as applicable. *Conclusion:* In order to better understand whole-body vibration and postural stress among OEs, it is recommended that future studies are needed in evaluating these risk factors among OEs.

1. Introduction

Work-related injuries and illnesses pose a continuing threat to the health and well being of U.S. workers. The construction industry has been recognized historically as having higher rates of fatality, injury, and illness than other industries (Bureau of Labor Statistics [BLS], 1996; McVittie, 1995). In 1994, there were an estimated 218,800 lost workday injuries in the construction industry (BLS, 1996). Construction also had the second highest incidence rate for sprains and strains.

Operating engineers (OEs), also known as hoisting and portable engineers, operate and maintain heavy construction equipment, such as cranes, bulldozers, front-end loaders, rollers, backhoes, and graders. They may also work as mechanics. The operators use these pieces of equipment to perform four main tasks: (a) the building of roads, bridges, tunnels, and dams; (b) the construction of buildings and power plants; (c) the removal of earth materials and grading earth surfaces and in the replacement of concrete, blacktop, and other paving materials; and (d) the constructing of drainage systems, pipelines, and other related tasks, such as blasting (Stern & Haring-Sweeney, 1997).

A recent estimate shows that there are currently 540,000 operating engineers in the United States (BLS, 2003; this estimate does not include mechanics or oilers) who are exposed to whole-body vibration. A majority of these OEs (90%) perform excavating and paving work (e.g., operating dozers, loaders, excavators), while the remaining are crane operators (10%). Because of the varied duties performed by OEs, they have the potential for exposure to numerous hazards that can be episodic in nature. Some of the health hazards among operators using heavy construction equipment are: whole-body vibration, awkward postural requirements (including static sitting), psychosocial factors, dust, diesel exhaust, asphalt and/or welding fumes, noise, temperature extremes, time pressure, and shift work (Buchholz, Moir, & Virji, 1997; Stern & Haring-Sweeney, 1997; Zimmerman, Cook, & Rosecrance, 1997). Despite the immediate hazards of the trade, there are few reliable data

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that characterize these hazards and their health outcomes. Thus it is imperative that information be gathered to assist in designing better working conditions for these workers, which will enhance their health and well being, productivity, morale, and efficiency in performing their jobs. Pilot research (Buchholz et al., 1997) has shown that the major ergonomic exposures among OEs are whole-body vibration, repetitive arm motions, awkward postures (including static sitting), and poor seat design. There is a current need to do research focusing on ergonomic exposure data that might contribute to the knowledge of the development of musculoskeletal diseases among these operators.

Whole-body vibration (WBV) produces systemic affects on the entire body. Information regarding the chronic effects of WBV is still in infancy. However, there is abundant information regarding subjective responses to vibration. Some limitations of these studies are that they were performed in laboratory settings and that they only evaluated sinusoidal vibration, and thus are not representative of real-life conditions. In general, there are not sufficient data available to characterize the exposures and to better understand the health outcomes among operators of construction equipment.

Working posture is believed to be influenced by many factors including workstation layout, location and orientation of work, individual work methods, and the workers' anthropometric characteristics (Hsiao & Keyserling, 1990; Keyserling, Punnett, & Fine, 1988). Awkward posture is one of the important risk factors in the development of musculoskeletal disorders (Chaffin & Andersson, 1984; Keyserling et al., 1988; Putz-Anderson, 1988). Awkward postures refer to joint positions significantly deviated from the neutral body postures and may include static positioning or constrained body postures (twisting or elevated positioning; Putz-Anderson, 1988). Exposure to awkward posture can result in localized fatigue or pain and contribute to the development of musculoskeletal disorders. The relationship between awkward posture and the development of musculoskeletal disorders of the neck, shoulder, and trunk has been reported recently (National Institute for Occupational Safety and Health [NIOSH], 1997).

2. Whole-body vibration

In reviewing the literature, a representative sample of epidemiological papers that studied exposure to whole body vibration among various populations were selected including, operating engineers (or operators of construction equipment), tractor drivers, and drivers of forklifts and freight-container tractors. Most of these studies had a control group for comparison.

A simple descriptive study by Zimmerman et al. (1997) provided insight into the specific population of interest (operating engineers). They investigated work-related musculoskeletal symptoms among operating engineers ($N = 410$). There were no control groups used for comparison. There was a response rate of 38% among the operating engineers. Work-related musculoskeletal symptoms were greatest in the low back (60%), neck (44%), shoulders (37%), and knees (32%). Missed work due to musculoskeletal symptoms was most prevalent in the low back (8%), ankles/feet (3%), wrist/hands (3%), and shoulder (2%). Physician visits due to musculoskeletal symptoms were highest for the low back (25%), neck (20%), upper back (13%), and shoulders (12%). Operators with longer work histories consistently reported greater percentages of symptoms, missed work, and physician visits than the less experienced group. For all body regions the percentage of work-related symptoms, missed work, and physician visits varied greatly among the five different types of equipment (backhoe, crane, pushcat/dozer, pull scraper, and end loader). These results are suggestive of equipment specific demands and stress experienced by the operating engineers. Operators using older equipment reported a higher percentage of missed work and physician visits due to musculoskeletal symptoms than those using newer equipment, and those using a combination of both newer and older equipment.

Dupuis and Zerlett (1987) studied 352 operators of earth-moving equipment with at least three years of work experience based on interviews and medical examinations. From this group, X-rays showing the segments of the spine were available for 251 operators with at least 10 years of work experience. This group was compared with a control group of 315 workers that worked in similar environments with no vibration exposure. From the control group, X-rays of the spine were available for 151 workers. In addition, 149 operators of earth moving equipment were asked to rate their discomfort after exposure to 8 hours of vibration. Among the 352 operators and 315 referents studied, the operators reported significantly higher spinal discomfort during their work shift (75% vs. 49%) and after their shift (59% vs. 45%), as well as more disorders of the spine (70% vs. 54%). Furthermore the operators reported significantly higher discomfort in the lumbar region (69% vs. 42%) than for the control group. The most frequent (and significant) health impairment among the operators was lumbar syndrome (81%) and was significantly higher than found in the control group. The diagnosis of the lumbar syndrome covers all the symptoms that are caused directly or indirectly by degenerative lesions of the lumbar disks. The radiological findings showed morphological changes of the lumbar spine as a function of age. There was statistically higher prevalence of pathological findings among operators compared with the control group. After 8 hours of exposure, backache was reported among 45% of the operators ($N = 149$). The prevalence of backache increased from 35% in the younger group (20–29 years) to 67% in the older group (50–59 years). The authors concluded that long-term exposure to whole-body vibrations causes morphological changes in the lumbar spine.

In a retrospective (10-year) follow-up study, Bongers, Boshuizen, Hulshof, and Koemeester (1988) compared the incidence of permanent work disabilities among crane operators (N = 743) and a control group of “floor workers” (N = 662). It should be noted that 33% of the control group was exposed to vibration 20% of the work time. Both groups consisted of male workers. This study demonstrated that the crane operators were twice as likely to receive disability pension due to intervertebral disc disease as the control group. The crane operators with 5 to 15 years of exposure were at higher risk of disability due to intervertebral disc disorders. When the duration of exposure was included in their model as a time-dependent covariate, a 1.5 time increase in risk of disability due to intervertebral disc disorders was found for each 10 years of additional exposure. Since the control group was exposed to some vibration and there was a potential health-based selection of the index group prior to the start of the study, it is believed that the incidence density ratio (IDR) observed in this study are underestimates of the true IDRs. There may have been some health-based selection during the observation period that could also affect the true estimate of the IDRs.

Boshuizen, Bongers, and Hulshof (1992) examined self-reported back pain among drivers of forklift and freight-container tractors (N = 196) and a reference group of non-drivers (N = 107) from six harbor companies (5 trans-shipment companies and a container repair company). The response rates in the index and control groups were 78% and 83%, respectively. The younger drivers (<35 years) reported a higher prevalence of back pain (58%) than the controls in the same age group (25%). The older drivers had less prevalence than the younger group. The lack of effect found among older workers could be attributed to health-based selection.

Boshuizen, Bongers, and Hulshof (1990a) examined self-reported back pain in tractor drivers exposed to vibration (N = 450) and a reference group of non-exposed workers (N = 110). There was a 79% response rate in this study. The workers were classified as being in the index or reference group according to their vehicle driving history. In general, the prevalence of back pain was higher among the tractor drivers and was also higher with an increasing vibration dose. Total vibration dose was calculated as being equal to $\Sigma_i \; a_i^2 \; t_i$. Where a_i is the estimated vector sum of the frequency weighted root mean square (rms) acceleration in X, Y, and Z directions (axes) for vehicle i (in units of m/s^2) and t_i is the time duration of driving a vehicle (in units of full time years). The highest prevalence odds ratio were found for severe types of back pain, but these prevalence odds ratio did not increase with vibration dose, which might have been due to health-based selection.

In an 11-year follow-up study, Boshuizen, Hulshof, and Bongers (1990b), investigated disability pensioning and the incidence of the first sick leave of 4 weeks or longer due to back disorders in a group of drivers exposed to WBV (N = 689) and a reference group of workers exposed to slight or no vibration (N = 109). The workers were classified as being in the index or reference group according to their vehicle driving history. Most of the employees assigned to the reference group were mechanics and maintenance workers. The drivers used tractors or other highly vibrating vehicles used in farming. The incidence of long-term sick leave due to a back disorder was about 50% higher in the drivers. This incidence seemed to increase with duration of exposure and vibration dose (dose calculated as described in Boshuizen et al., 1990a). The tractor drivers were at a higher risk of being disabled at a younger age than the reference group. This study provides evidence of an association between driving tractors and other vibrating vehicles and long-term sick leave due to back disorders.

Bovenzi and Betta (1994) investigated the occurrence of low back pain among agricultural tractor drivers (N = 1155) and a control group of office workers (N = 220). All of the workers in both groups were males. The response rates among the tractor drivers and controls were 91% and 92%, respectively. Age, occupation, vibration exposure, perceived postural load, and back trauma were found to be the most important predictors for the occurrence of lifetime, transient, and chronic LBP for the complete sample. A significant trend of higher prevalence of lifetime LBP, acute LBP, and sciatic pain was associated with an increase in total tractor driving hours. The crude prevalence for back pain and low-back symptoms was consistently greater among the tractor drivers than the controls. With an increase in total vibration dose (dose calculated as described in Boshuizen et al., 1990a) there was a consistent increase in odds ratios for back pain and low back symptoms in drivers. This study also demonstrated that the duration of exposure was associated more with LBP compared with vibration exposure magnitude alone. This is in agreement with Boshuizen et al. (1990a).

Several authors have performed extensive reviews on the health effects of long-term exposure to whole body vibration (Hulshof & Veldhuijzen van Zanten, 1987; Seidel & Heide, 1986; Wikstrom, Kjellberg, & Landstrom, 1994). A summary of these reviews will further help understand the adverse health effects of WBV, albeit in concert with other risk factors.

Wikstrom et al. (1994) reviewed 45 health studies in which index groups exposed to WBV were compared to a reference group not exposed to WBV. There were also studies that have made comparison between groups with different exposure levels. In all, the review covered about 18,000 workers exposed to WBV and around 29,000 control subjects. In 27 of the studies the combined affect of WBV and other risk factors was discussed, but only 50% of them actually studied these factors. Work postures were mostly considered in the studies, but noise and other stressors have also been discussed. The following conclusions were advanced from their review:

- Cumulative exposure (in years) to WBV may contribute to injuries and disorders of the lower back.

- WBV in combination with awkward posture (including static sitting) may result in excessive risk of injury and disorder to the lower back.
- An exposure-response relationship cannot be established at this time.
- Disorders of the gastrointestinal system and urogenital system, especially in women, have been observed in those exposed to WBV. As such these health effects warrant further study.

Hulshof and Veldhuijzen van Zanten (1987) performed an evaluation of 19 epidemiologic studies on the effect of WBV. In all, this review covered about 17,000 exposed and 11,000 reference workers. This review was restricted to the relationship between WBV and symptoms and/or signs of thoracic and lumbar disorders. A scoring procedure was used to assess the relative quality of the contribution of each epidemiologic study. The evaluative criteria were: the quality of exposure data, effect (health) data, study design, and methodology. The most frequently reported adverse health effects were low back pain, early degeneration of the spinal system, and herniated lumbar disc. The results of the scoring procedure indicated that most of the studies scored relatively low in the assessment. None of the studies reached a score of more than 50% in all criteria of evaluation. In spite of the weakness in the studies, almost all findings in the different studies, particularly the studies with better methodology, demonstrated a strong tendency in a similar direction, the authors concluded that long-term exposure to WBV can be harmful to the spinal system. An exposure-response relationship cannot be established at this time. The main shortcomings of the epidemiological studies to date were that their description of vibration exposure, the exposure-time history, and the contributing occupational environment was not sufficient, and that the challenge of finding groups that were not exposed to vibration was not met. The authors suggested that more epidemiologic research, especially with better study design and methodology, are needed to understand the relationship between long-term WBV exposure and adverse health effects.

Seidel and Heide (1986) performed a critical survey of the literature (185 articles) to study the long-term health effects of exposure to whole-body vibration. The review contains health data on 43,000 workers exposed to whole-body vibration and 24,000 workers in the reference group. Only a third of the papers contained a measured value for WBV, while more than 30% did not contain any exposure data. The authors conclude that workers exposed to seated vibration equal to or greater than the ISO Exposure Limit manifested an increased health risk of the musculoskeletal and peripheral nervous system. With a lower probability, the digestive system, the peripheral veins, the female reproductive organs, and the vestibular system were also affected. On average, the health risk increased with higher intensity or duration of WBV exposure. However, a quantitative exposure-response relationship could not be determined. This review favors changing the ISO limit to a lower level.

In summary, more musculoskeletal symptoms (specifically relating to the low back) were observed among the index group(s) than the reference group(s). WBV exposure equal to or greater than the ISO limit can adversely affect the health and well being of the worker. Also various studies have shown that many different occupational groups are affected by whole-body vibration. Most of the studies reviewed indicate that adverse health effects were also attributed to the combined affect of awkward posture (including static sitting) in concert with WBV. As such it is important to measure the postural requirements of the work, in addition to WBV, when epidemiological studies are performed and when exposure characterization is established. Other risk factors should be evaluated to present a holistic view of the exposure to the operator.

3. Awkward posture

Awkward posture is another important risk factor observed among operating engineers. The significance of assessing the postural requirements of operators exposed to whole-body vibration has been echoed in the recent literature (e.g., Bongers et al., 1988; Bongers, Hulshof, Dijkstra, & Boshuizen, 1990; Bovenzi & Zadini, 1992; Johanning, 1991). But in reviewing the literature it was found that there are very limited, if any, studies quantifying awkward postures among operators of heavy construction equipment. Thus other studies from related industries with operators using similar equipment will be reviewed as applicable.

A pilot study by Kittusamy and Buchholz (2001) evaluated postural stress during excavating operations. They evaluated postural requirements of the operators performing trench digging operations on two different pieces of construction equipment. For both pieces of equipment, they found that the trunk was either flexed or twisted for at least 25% of the cycle time. The right shoulders were elevated a majority of the cycle time and the neck was either flexed or twisted for at least 22% of the cycle time for operators of either pieces of equipment.

A study by Bovenzi and Betta (1994), already discussed in the WBV section of this paper, indicated a linear trend of increasing prevalence of low back pain (LBP) among tractor drivers that had an increasing perceived postural load. Perceived postural load was assessed in terms of frequency and/or duration of awkward posture at work. Furthermore, the tractor drivers with excessive WBV and postural stress had more than a three-fold increased risk for chronic LBP than the unexposed subjects.

In a recent study, Bovenzi, Pinto, and Stacchini (2002) investigated the occurrence of LBP among a group of 219 port machinery operators (straddle carrier, fork-lift, and crane operators) exposed to both WBV and postural load, and a control group of 85 maintenance workers employed at the same company. The 12-month prevalence of low back symptoms was significantly greater in the forklift truck drivers than in the controls or the other two groups of port machinery operators. An excessive risk for lumbar disk herniation was also observed among port machinery operators that had prolonged driving experience. Even though this cross-sectional study does not allow for definitive conclusion on the relationship between exposure and low back disorders, the findings of this investigation provide additional evidence that suggest that seated WBV exposure and non-neutral trunk postures can have adverse long-term health effects on the lower back.

Bottoms and Barber (1978) evaluated a tractor seat with a swivel of up to 20 degrees from the normal forward facing position. The results of this study showed a decrease in muscle activity in the shoulder and neck regions when the seat was swiveled up to 20 degrees. Measured angles of the body twist showed that the full potential benefit of the swiveling seat was not used by the subjects, although the mean twist between the shoulders and hips was reduced significantly with increased swivel angle. This study confirmed that a swiveling seat was of benefit to the tractor driver specifically performing tasks that required rearward visual monitoring.

In a more recent study, Torén and Öberg (2001) investigated whether the exposure to twisted trunk posture was affected when driving an agricultural tractor in the field using freely swiveling saddle chairs. Ten subjects employed as tractor drivers volunteered for this study. The results of this study showed that the exposure to extreme twisted trunk posture was slightly reduced during harrowing using the saddle chair than the conventional chair. But for plowing, the exposure to extreme twisted postures was reduced by about 50% in comparison to the conventional chair. Thus, it can be concluded that the use of a freely swiveling mechanism and enough space to swivel would be beneficial in reducing postural stress.

Courtney and Chan (1999) performed an ergonomic study to evaluate the workplace and workspace design of a cab of grab unloaders for bulk material in ships. Their results demonstrated that the drivers adopted poor postures, partially due to the basic geometry of the situation and in part due to using only the central lower front window for downward vision and control boxes that obstructed operator's vision. All of the drivers complained that they had to maintain and perform their work in an awkward posture. The main body parts that were problematic included the neck (81%), the lower back (88%), mid-back (50%), and shoulders (50%). About 56% of the drivers indicated that they sought medical advice for these problems. It was found that the operators spent 50% of the cycle time looking vertically down. This resulted in static loading of the neck and back with the trunk flexed forward 30 to 40 degrees and the neck flexed forward about 60 to 70 degrees from vertical to ensure proper viewing of the work vertically below the cab. Similar results were found in a previous study by Courtney and Evans (1993), albeit they evaluated much older cabs than this study. Thus both of these studies concluded that static loading of the trunk and neck contributed to the various aches and pains experienced by the drivers. The authors of these studies made recommendations for improving cab design to address these concerns.

Gustafson-Söderman (1987) evaluated the effect of a seat with an adjustable sitting angle and perceived discomfort in the back, neck, and shoulder regions among crane operators. The crane operators had previously indicated that discomfort was mainly contributed by a forward flexed sitting position that happened during lifts close to the crane. The seat with adjustable sitting angle (test seat) was installed in one of the three cranes that were evaluated, while the other two had an ordinary type of seat. The highest estimated discomfort values were obtained from operators using the ordinary seat and the lowest discomfort values were obtained from the use of test seat with adjustable sitting angle.

Sjøflot (1980) evaluated the use of big mirrors to improve tractor driver's posture and quality of work. Big rearview mirrors make it possible for the driver to adopt a good working posture. By using the big mirrors, the operator's time spent in twisted posture was reduced from 48% to less than 4% of the driving time when operating a forage harvester. The hip-shoulder and neck angles were considerably less awkward with the use of big mirrors than without mirrors. There was no change in the chair-hip angle with or without the use of big mirrors. When plowing, the operator's time spent in a twisted posture was reduced from 40% to 3.5% of the total driving time. In another study by Nielsen (1986), the use of big mirrors was beneficial in reducing the time required to view rearward work from 35% to 6% while driving the precision chopper and beet harvester.

In summary, awkward postures during the operation of heavy construction equipment are a consequence of improper cab design and work procedures. Poor visibility of the task, limited room in the cab, excessive forces required to operate levers/pedals, and improper seat designs are some of the characteristics of a poorly designed cab. If not controlled, awkward posture of any body part can result in increased risk of fatigue, pain, or injury. Exposure to awkward postures either repetitively or for prolonged periods can lead to a variety of musculoskeletal disorders. Thus, cab evaluations and improvements in cab design are necessary for reducing the adverse health effects experienced by these operators (Kittusamy, 2003). Several of the studies that were reviewed evaluated and discussed controls for awkward posture. These studies have demonstrated that postural requirements of work can be minimized with the use of big mirrors, swivel seats, and seats with an adjustable sitting angle. These and other controls can be incorporated in the cab design to reduce exposure to awkward posture when operating construction equipment.

4. Summary

Previous studies have indicated that operators of heavy construction equipment (or other related equipment) are afflicted by musculoskeletal injuries of the arms, shoulders, neck, and lower back. From this review, it is shown that WBV and the postural requirements of work (both static and awkward postures) are important risk factors that contribute to the development of musculoskeletal disorders among OEs. In spite of this, very little research has been performed that systematically characterizes the exposure of operating engineers to these ergonomic hazards. The quantification of vibration and postural requirements in practical settings is necessary for developing a better comprehension of the exposure levels that are present in different construction equipment performing various tasks.

Acknowledgements

This work was performed when the corresponding author was at the University of Massachusetts Lowell as a Research Assistant on the Construction Occupational Health Project. This project was funded by the National Institute for Occupational Safety and Health (NIOSH) through the Center to Protect Workers' Rights (CPWR) (Grant # U02/CCU312014). The authors would like to thank Drs. David Wegman and Michael Ellenbecker for providing helpful comments on earlier drafts. The authors also thank Emmett Russell (from the International Union of Operating Engineers) and Danny Thiemens (from the Associated General Contractors of America) for their valuable comments.

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