A Review of Factors Influencing Whole-Body Vibration Injuries in Forestry Mobile Machine Operators

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ABSTRACT

Mobile machine operators in the forestry industry are subjected to long hours of whole-body vibration exposure while adopting static seated postures and performing repeated hand and foot movements to operate controls. These conditions have been found to put operators at increased risk for musculoskeletal injuries and pain in the neck, shoulders, and back, as well as decreased productivity. This paper provides a review of the individual risk factors for these musculoskeletal problems and explores the possible interactions between risk factors and their effects on injury and productivity. Gaps in the literature and directions for future research are identified and discussed.

Keywords: *forestry, mobile machine operator, vibration, posture, repetitive motion, spine stability, muscle activity, musculoskeletal injury, trunk, prevention*

Introduction

Despite ergonomic improvements, injuries and/or pain to the arm, neck, shoulder, legs, and lower back are common in mobile machine operators (MMOs) in the forest industry (Axelsson and Ponten 1990, Hansson 1990, Harstella 1990, Slappendel et al. 1993, Hagen et al. 1998, Synwoldt and Gellerstedt 2003). A survey of 215 northern Sweden forestry MMOs and 167 controls conducted in 1999 by Rehn et al. (2002) found that the forestry MMOs had an elevated prevalence of neck, shoulder, upper back (thoracic), and lower back musculoskeletal symptoms. Here, forestry MMOs reported 2.3 times more musculoskeletal symptoms in the neck than controls, 1.9 times more shoulder symptoms than controls, 2.4 times more upper back symptoms than controls, and 1.1 times more lower back symptoms than the control group (Rehn et al. 2002). The aforementioned symptoms correspond to a prevalence of 61 percent, 56 percent, 20 percent, and 47 percent of forestry MMOs for musculoskeletal symptoms of the neck, shoulder, upper back, and lower back, respectively (Rehn et al. 2002). A 2007 survey conducted by Cation et al. (2007) of seven skidder operators in northern Ontario revealed that three of the

seven operators had low level neck pain (operators gave ratings of 1 to 2 on a 5-point scale with 5 being the most severe), and two of the seven operators reported more severe back pain (operators gave ratings of 3 on a 5-point scale). These injuries financially burden employers when company subsidized health care plans are used, insurance premiums are increased, and replacement workers are hired. Employers also incur revenue loses from lost production when employees are injured (Leigh et al. 2001).

The origin and cause of musculoskeletal injuries in forestry MMOs (and MMOs in general) likely results from a combination of whole-body vibration (WBV) exposure, static driving postures, and repetitive movements associated with the operation of hand and foot controls (Axelsson and Ponten 1990, Harstella 1990, NIOSH 1997, Hagen et al. 1998, Synwoldt and Gellerstedt 2003). A more comprehensive understanding of the interactions between these risk factors will help to elucidate strategies to decrease the incidence of injuries in forestry MMOs. The following sections provide a review of musculoskeletal injury risk factors for MMOs with a focus on forestry MMOs. In addition, an in-depth discussion of the possible interactions between musculoskeletal risk factors for forestry MMOs is provided, along with the possible influences of these musculoskeletal injury risk factors on operator productivity. It should be noted that literature regarding ergonomic investigations of WBV exposures, postures, and repetitive movements among forestry MMOs is limited. As a result, this paper where appropriate incorporates vehicles from other industries to illustrate some of its points, but all discussions are provided with the forest industry in mind. The desire is to illustrate the mechanisms by which forestry MMOs could be injured, so that future vehicles and work policies can be designed with these mechanisms in mind.

Risk Factors for Operator Musculoskeletal Injury

WBV

WBV has been connected to nervous, digestive, and cardiopulmonary system problems, noise induced hearing loss, and degenerative spine changes (Wilson and Corlett 1990, Wasserman and Taylor 1992, Bovenzi 1996, Thalheimer 1996, Kroemer et al. 1999). Several studies have found WBV to be positively related to back disorders and low back pain (Frymoyer et al. 1983, Damkot et al. 1984, Hulshof and Veldhuijzen van Zanten 1987, Bongers et al. 1988, Boshuizen et al. 1988, Johann-

ing 1991, Wilder 1993, Bovenzi and Betta 1994, Bovenzi 1996, NIOSH 1997, Scutter et al. 1997, Bovenzi and Hulshof 1998, Schwarz et al. 1998, Teschke et al. 1999, Koda et al. 2000, Ling and Leboeuf-Yde 2000, Rehn et al. 2002). Elevated risks for low back disorders and vertebral disc herniation with WBV exposure range from 1.2 to 39.5 and 2 to 4.67 times, respectively, that of unexposed individuals (Kelsey 1975a, 1975b; Heliovaara 1987; Bovenzi and Betta 1994; NIOSH 1997; Hagen et al. 1998). Hagen et al. (1998) found that harvester and forwarder operators in forestry were 1.76 times more likely to develop a low back disorder than administrative workers (i.e., clerks and managers). WBV has also been linked to neck and shoulder pain in MMOs (Village et al. 1989, Johanning 1991, Scutter et al. 1997, Hagen et al. 1998, Koda et al. 2000, Rehn et al. 2002), with harvester and forwarder operators being 3.37 times more likely to develop neck and shoulder pain than administrative workers (Hagen et al. 1998).

Forestry MMOs are exposed to potentially harmful levels of WBV as they are vibrated over long time periods during which they also experience non-periodic shocks (i.e., from driving over potholes, tree stumps, and rocks). When reported, the amplitude of WBV encountered by forestry MMOs often surpasses the ride criteria proposed by various organizations and researchers (Golsse and Hope 1987; Boileau and Rakheja 1990; Neitzel and Yost 2002, 2003; Rehn et al. 2005a, Rehn et al. 2005b, Cation et al. 2007) indicating potential risks to the driver's health. These exposure levels increase with increases in driving speed, roughness of terrain, and decreases in driver and carried load weight, as seen in forestry skidders (Golsse and Hope 1987, Cation et al. 2007), forwarders (Rehn et al. 2005a), and forklift trucks (Malchaire et al. 1996).

WBV also has detrimental effects on visual acuity, balance, and dexterity and can cause muscle fatigue since exposure to WBV can result in increased muscle activity (Seidel et al. 1980, Wilder et al. 1982, Damkot et al. 1984, Seroussi et al. 1989, Village et al. 1989, Pope et al. 1998). Greater muscle activity is associated with increased muscle fatigue due to localized reductions in blood flow and impairment of normal metabolic processes (i.e., oxygen uptake and metabolite/waste removal) (Kroemer 1999). During WBV exposure, the muscles of the back (particularly the erector spinae and trapezius muscles) contract in an attempt to absorb transmitted vibrations (Wilkstrom 1993), which can result in muscle fatigue.

The wide variety of WBV effects depend on the vibration exposure characteristics. Depending on the magnitude, direction (**Fig. 1**), frequency, and duration of WBV exposure, the effects can range from sensations of pleasure, pain, or discomfort to interference with performance (reading and hand control) to acute or chronic illness with physiologic and pathologic changes (Herington and Morse 1995). The body harmlessly attenuates most vibration, but frequencies between 1 and 20 Hz cause the pelvis and spine to resonate, leading to structural damage and health problems (Thalheimer 1996, Kitazaki and Griffin 1998). When considering the magnitude of WBV, Bovenzi (1996) found that WBV vector sum root mean square (RMS) acceleration levels between 0.7 m/s² and 0.9 m/s² (using ISO 2631-1:1985) had
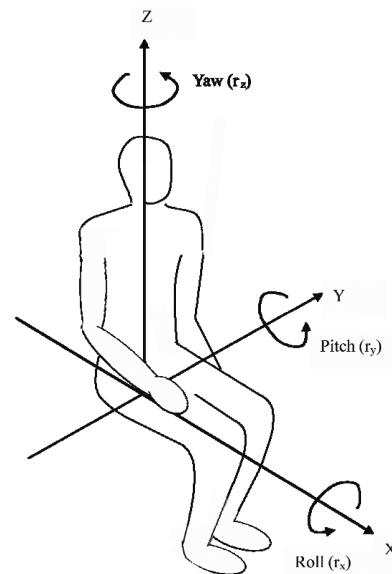
Figure 1. ~ *The basicentric orientation used to describe vibration in three translational and three rotational directions.*

estimated odds ratios for low back pain varying from 1.6 to 2.0, with risk estimates increasing for exposures greater than 1 m/s². A 2002 study of forestry worker exposures to WBV in the state of Washington by Neitzel and Yost (2002), which used the same ISO weightings as Bovenzi (1996), reported WBV acceleration levels for mobile forestry equipment that would be associated with an increased risk for low back pain. Neitzel and Yost (2002) found that workers employed in logging related activities have substantial overexposures to vibration using the ISO 2631-1:1985 standard. These overexposures are also evident in a 2003 report by Neitzel and Yost (2003), where several forestry machines and job tasks in Washington State, Alaska, and Idaho forestry operations exceeded the upper limit (indicating a likely health risk) of the ISO 2631-1:1997 health caution zone for a 4-hour day (**Tables 1 and 2**). In 2004, a research group in Ireland (Sherwin et al. 2004a) investigated the vibration levels of a cut-to-length timber harvester while felling, processing (delimbing and cross-cutting trees), and traveling (along an ISO 5008;1979 test track). The cut-to-length timber harvester was found to have ISO 2631-1:1997 weighted X-, Y-, and Z-axes, and vibration total values below the ISO 2631-1:1997 health caution zone for an 8-hour day during all three operating tasks investigated (**Table 3**). While traveling, however, the vibration total values determined would be associated with some discomfort according to ISO 2631-1:1997. A 2005 study by Rehn et al. (2005b) found that forwarders in northern Sweden logging operations had average ISO 2631-1:1997 RMS weighted accelerations of 0.5, 0.78, and 0.6 m/s² in the X-, Y-, and Z-axes, respectively. These forwarders also had an average vibration total value of 1.5 m/s² (Rehn et al. 2005b), which would exceed the upper limit of the ISO 2631-1:1997 health caution zone for a 4-hour day. A second 2005 study by Rehn et al. (2005a) reported that northern Sweden forwarders had average ISO 2631-1:1997 vibration total values that ranged from 0.41 m/s² while unloading logs to 1.69 m/s²

Table 1. ~ *WBV exposure levels reported in the forestry industry by machine.*

	RMS accelerations (m/s²)				Daily exposure limit[c]	
Machine	X-axis[a]	Y-axis[a]	Z-axis[a]	Summary equivalent[b]	Lower limit[d]	Upper limit[e]
Dump truck	0.8	0.7	1.5	2.0	30 minutes	2 hours
Excavator	0.5	0.3	0.3	0.5	8 hours	24 hours
Feller/buncher	1.0	0.9	0.9	1.6	1 hour	4 hours
Forwarder	0.7	0.6	0.7	1.1	2 hours	8 hours
Front end loader	0.2	0.1	1.3	1.2	2 hours	4 hours
Grader	1.1	0.9	1.1	1.7	1 hour	2 hours
Harvester	2.0	1.9	1.9	3.4	10 minutes	1 hour
Logging truck	0.1	0.1	1.0	1.0	2 hours	8 hours
Processor	2.1	2.0	2.1	3.4	10 minutes	1 hour
Shovel	1.2	1.1	1.8	2.3	30 minutes	2 hours
Skidder	1.6	1.4	1.4	2.5	30 minutes	1 hour
Stacker	0.1	0.1	0.7	0.6	8 hours	24 hours
Yarder	1.1	1.2	1.3	1.4	1 hour	4 hours

[a] Constant bandwidth (1 to 80 Hz range) accelerations using ISO 2631-1:1997 frequency weightings. Data compiled from values presented in Neitzel and Yost (2003).
[b] A vector sum of the three orthogonal axes accelerations determined from vibration dose values by removing the time component. Data compiled from values presented in Neitzel and Yost (2003).
[c] Exposure limits are based on summary equivalent exposures and the ISO 2631-1:1997 health caution guidelines.
[d] Indicates a potential health risk with daily exposures that exceed the indicated time (ISO 2631-1:1997).
[e] Indicates a likely health risk with daily exposures that exceed the indicated time (ISO 2631-1:1997).

Table 2. ~ *WBV exposure levels reported in the forestry industry by task.*

	RMS accelerations (m/s²)				Daily exposure limit[c]	
Task	X-axis[a]	Y-axis[a]	Z-axis[a]	Summary equivalent[b]	Lower limit[d]	Upper limit[e]
Cutting wood	0.1	0.1	1.4	1.4	1 hour	4 hours
Processing logs	2.6	2.5	2.7	4.5	10 minutes	30 minutes
Skidding logs	3.3	3.4	3.6	4.9	10 minutes	30 minutes
Sorting/stacking logs	1.0	1.0	1.6	1.8	1 hour	2 hours
Yarding logs	1.8	2.0	2.2	2.3	30 minutes	2 hours

[a] Constant bandwidth (1 to 80 Hz range) accelerations using ISO 2631-1:1997 frequency weightings. Data compiled from values presented in Neitzel and Yost (2003).
[b] A vector sum of the three orthogonal axes accelerations determined from vibration dose values by removing the time component. Data compiled from values presented in Neitzel and Yost (2003).
[c] Exposure limits are based on summary equivalent exposures and the ISO 2631-1:1997 health caution guidelines.
[d] Indicates a potential health risk with daily exposures that exceed the indicated time (ISO 2631-1:1997).
[e] Indicates a likely health risk with daily exposures that exceed the indicated time (ISO 2631-1:1997).

Table 3. ~ *WBV exposure levels reported during three cut-to-length timber harvester tasks.*

	RMS accelerations (m/s²)				Daily exposure limit[d]	
Task	X-axis[a]	Y-axis[a]	Z-axis[a]	VIbration total value[b]	Lower limit[e]	Upper limit[f]
Felling trees	0.060	0.107	0.135	0.219	> 24 hours	> 24 hours
Processing trees[c]	0.050	0.082	0.102	0.169	> 24 hours	> 24 hours
Traveling	0.088	0.146	0.219	0.324	24 hours	> 24 hours

[a] Constant bandwidth (1 to 80 Hz range) accelerations using ISO 2631-1:1997 frequency weightings. Data compiled from values presented in Sherwin et al. (2004a).
[b] A vector sum of the three orthogonal axes accelerations with ISO 2631-1:1997 multiplication factors (k-values) applied to each axis. Data compiled from values presented in Sherwin et al. (2004a).
[c] Includes delimbing and cross-cutting trees.
[d] Exposure limits are based on vibration total values and the ISO 2631-1:1997 health caution guidelines.
[e] Indicates a potential health risk with daily exposures that exceed the indicated time (ISO 2631-1:1997).
[f] Indicates a likely health risk with daily exposures that exceed the indicated time (ISO 2631-1:1997).

while traveling unloaded (travel loaded was associated with a 1.1 m/s² WBV exposure, and loading logs was associated with a 0.55 m/s² exposure).

Except for unloading logs, all of the aforementioned forwarder tasks had vibration exposures that exceeded the lower limit of the ISO 2631-1:1997 health caution zone for an 8-hour

day, with traveling loaded and unloaded exceeding the upper exposure limit after 2 hours and 1 hour, respectively. A recent study conducted in the summer of 2007 by Cation et al. (2007) found that northern Ontario skidder operators exceeded the upper limit of the ISO 2631-1:1997 health caution zone for a 4-hour day while driving with and without a load (**Table 4**).

Bovenzi and Betta (1994) found the duration of WBV was related to low back disorders to a greater extent than the WBV acceleration magnitude. Consistent trends are seen in Bovenzi and Betta's (1994) study, with increasing WBV exposure in terms of driving hours, driving years, and cumulative vibration dose (i.e., WBV exposure levels multiplied by the years of exposure) being associated with increased prevalence and odds of general back and low back pain. The influence of exposure duration on health outcomes is also reflected in current health guidelines with a given WBV exposure level being associated with elevated risks for adverse health effects as the duration of that exposure increases (BS 6841:1987, ISO 2631-1:1997). Thus the duration of exposure is also very important.

WBV Transmission Through the Spine

While vibration has a localized source, it may also be transmitted to other areas of the body through soft tissues, and more readily through bone tissue which is assumed to be rigid (Dietrich et al. 1991). How that vibration is transmitted through the body determines the body parts affected as well as the severity. Since vibration is more readily transmitted through a rigid structure, conditions that increase the rigidity or stability of a structure will increase vibration transmission. In the case of the human body, increased rigidity and vibration transmission can be the result of posture and muscle activity, or a combination of the two (Cholewicki and McGill 1996, McGill and Cholewicki 2001). Spinal tissues become stiffer the more they are deformed (Adams 1995), leading to greater passive tissue resistance and muscle activity to overcome that resistance when adopting a bent and/or twisted posture (Bottoms and Barber 1978, Boden and Oberg 1998, Chaffin et al. 1999, Bluthner et al. 2001, Toren 2001). The greater the stiffness of a motion segment, the greater the stability (McGill and Cholewicki 2001). As well, Cholewicki and McGill (1996) found that stability of the spine increased with increased joint compression and muscle activity indicating a stiffer spine. Therefore, altered postures cause increased muscle activity, compressive loads, and stiffness probably leading to

an increase in vibration transmission. Pope and Hansson (1992) stated that postures with lateral bending and axial rotations should be avoided as they can cause greater vibration transmission. Griffin (1990) also lends support to the argument that postures with increased trunk muscle activity and rigidity will increase WBV transmission. Griffin (1990) reported elevated seat-to-head WBV transmission as a more erect posture is adopted (i.e., in more rigid posture with greater muscle activity than a relaxed or slumped posture [O'Sullivan et al. 2002]). Several other studies support the notion of posture influencing vibration transmission with reported changes in transmission and attenuation peak magnitudes and changes in the frequency at which those peaks occur when different postures were adopted (Seidel et al. 1980, Wilder et al. 1982, Wilder et al. 1994, Pope et al. 1990, Zimmerman and Cook 1997, El-Khatib et al. 1998, Pope et al. 1998, Matsumoto and Griffin 2002). A general pattern displayed by these studies is that conditions with higher compressive spinal loading, a flattening of the lower back curvature (decreased lumbar lordosis), increased muscle activity, and increased stiffness/stability had transmission peaks at higher frequencies and greater vibration transmission. It has also been observed that WBV exposure frequency can mediate how posture affects vibration transmission. Zimmerman and Cook (1997) found that for frequencies of 6 Hz and above, posture changes that produce increased stiffness increased transmissibility, while at frequencies below 6 Hz, posture changes that produced increased stiffness decreased transmissibility. A similar result was also reported by Seidel et al. (1980).

Extremity location can also affect vibration transmission. Holding a weight in front of the body causes an increase in vertebral disc and intra-abdominal pressures and muscle tension (Dietrich et al. 1991). These conditions will increase rigidity and vibration transmission. Leg positions can also affect the rigidity of the spine. Knee and hip angles affect spinal posture due to the muscles that insert on the pelvis and legs (Anderson et al. 1979, Chaffin et al. 1999). When the lower extremity joints are moved, these muscles rotate the pelvis, thus influencing lumbar spine posture (Chaffin et al. 1999). Postures that flatten the lower back curvature (decrease the lumbar lordosis), such as a flexed knee and hip (Chaffin et al. 1999), and increase muscle activity while sitting will increase vertebral disc pressure and vibration transmission.

Table 4. ~ *WBV exposure levels reported during northern Ontario skidder operations.*

Task	RMS accelerations (m/s²)				Daily exposure limit[c]	
	X-axis[a]	Y-axis[a]	Z-axis[a]	Vibration total value[b]	Lower limit[d]	Upper limit[e]
Driving unloaded	0.86	1.12	0.73	2.10	30 minutes	2 hours
Driving loaded	0.72	0.96	0.72	1.83	1 hour	2 hours

[a] Constant bandwidth (1 to 80 Hz range) accelerations using ISO 2631-1:1997 frequency weightings. Data compiled from values presented in Cation et al. (2007).
[b] A vector sum of the three orthogonal axes accelerations with ISO 2631-1:1997 multiplication factors (k-values) applied to each axis. Data compiled from values presented in Cation et al. (2007).
[c] Exposure limits are based on vibration total values and the ISO 2631-1:1997 health caution guidelines.
[d] Indicates a potential health risk with daily exposures that exceed the indicated time (ISO 2631-1:1997).
[e] Indicates a likely health risk with daily exposures that exceed the indicated time (ISO 2631-1:1997).

Finally, larger accelerations have greater load magnitudes and the fact that the spine stiffens with increased load (Cholewicki and McGill 1996, Panjabi 2003) supports the idea that larger accelerations could be transmitted more readily. Griffin (1990) reports a general trend toward an increase in seat-to-head WBV transmission with an increase in vibration exposure acceleration levels, particularly at lower frequencies. Matsumato and Griffin (2000) also found greater exposure accelerations were associated with greater vibration transmission at lower frequencies. It is, therefore, evident that posture, muscle activity, and WBV can influence vibration transmission. The postures and WBV exposures in the available literature, however, are not industry specific and are limited with respect to the postures and WBV patterns studied.

Rotational Vibration

Driving environments expose operators to translational vibrations in the X-, Y-, and Z-axes, and rotational vibrations about each of these axes in roll, pitch, and yaw (Shoenberger 1988). Actual rotational vibrations, however, are not considered in health guidelines and little research has been conducted to investigate their effects on health due to measurement technology limitations.

MMOs exposed to WBV (which includes rotational vibration) can have torques about spinal motion segments due to applied loads and muscle activation in an attempt to stabilize the body and maintain operator field of view. Repeated lateral bend, axial twist, and flexion/extension operator movements can also be expected, while subjected to compressive loading from WBV, body weight, and muscle activity. These conditions have been associated with vertebral disc herniation (Hardy et al. 1958, Callaghan and McGill 2001, Kuga and Kawabuchi 2001). Vertebral disc herniation can occur with a high number of 1 Hz flexion/extension cycles in combination with static compressive loading (Callaghan and McGill 2001). Wilder (1993) found that vertebral disc herniation can result from cyclic vibration loading, but it has yet to be seen if similar loading conditions with frequencies and accelerations from field WBV exposures could affect vertebral disc herniation. Terrain-induced vibrations in forestry vehicles (i.e., skidders, forwarders, and cut-to-length timber harvesters) are predominantly in the 0.5 to 8.0 Hz range (Boileau and Rakheja 1990, Sherwin et al. 2004a, Sherwin et al. 2004b, Rehn et al. 2005b, Cation et al. 2007). Also, compressive loading of the spine while seated can be around 700 N (Magnusson and Pope 1998) and will likely be higher while driving due to the increased muscle activity associated with WBV (Seidel et al. 1980, Seroussi et al. 1989, Village et al. 1989, Wilkstrom 1993, Pope et al. 1998, Bluthner et al. 2001). Interestingly, using a porcine (pig) spine model Callaghan and McGill (2001) reported higher incidences of vertebral disc herniation while repeatedly flexing and extending (at 1 Hz) their specimens under 867 N of compressive loading.

Static Postures

A greater risk of back problems and discomfort in the buttocks, legs, and feet has been associated with extended periods of sitting (Floyd and Roberts 1958, Bottoms and Barber 1978, Frymoyer et al. 1983, NIOSH 1997, Boden and Oberg 1998, Chaffin et al. 1999). When the body remains in a static position, blood flow throughout the body is reduced causing the muscles and tissues holding the body in a selected position to receive insufficient amounts of nutrients to keep them functioning optimally. Intervertebral discs (which do not have a direct blood supply) also do not receive nutrients due to reduced circulation but also because of a lack of change in intradiscal pressure (Stokes and Iatridis 2005). This may play a role in the disc degeneration seen in MMOs with increased muscle activity due to static postures and WBV exposure further reducing localized blood flow. There is strong evidence that occupations with high levels of static contraction and prolonged static loads or extreme postures involving the neck and shoulder muscles will place workers at increased risk for neck and shoulder musculoskeletal injuries (NIOSH 1997). Neck and shoulder pain has been reported in forestry MMOs such as forwarder and harvester operators (Hagen et al. 1998). Harvester operators have also been reported to adopt static and twisted postures (Gellerstedt 2002). Rehn et al. (2005b) reported that forwarder operators in Sweden spend 10 percent of their time with their neck twisted greater than 15° to the left and 19 percent of their time with their neck twisted greater than 15° to the right with durations lasting 1 to 22 seconds. In the experience of the current authors, northern Ontario skidder operators who report neck pain associate that pain with the repeated twisting to view the skidder grapple.

Static postures can also affect trunk muscle activity (Bluthner et al. 2001). When sitting, muscle activity of the lower back (lumbar erector spinae) muscles decreases when the back is in full flexion, the arms are supported, or a backrest is used (Chaffin et al. 1999). Tilting a tractor cab (10°) and inducing a lateral bend in a seated subject was found to increase muscle activity in the shoulder and back (trapezius, latissimus, and lumbar erector spinalis) muscles in a laboratory setting (Bottoms and Barber 1978). Twisted postures often adopted by MMOs (i.e., harvester and forwarder operators in forestry [Gellerstedt 2002, Rehn et al. 2005b]) also increase trunk muscle activity to overcome the passive resistance of the trunk tissues which increase the more the trunk is twisted (Boden and Oberg 1998, Toren 2001). Twisting in the range of 10° to 15° involves little muscle effort, but beyond this region, increased muscle effort is required (Boden and Oberg 1998, Toren 2001). The increased muscle activity and subsequent fatigue associated with adopting non-neutral static postures likely plays a role in the reporting of pain and musculoskeletal injuries in MMOs.

Repetitive Movements

Forestry MMOs often perform repeated trunk, neck, arm, and leg movements. Rehn et al. (2005b) found that Swedish forwarder operators twist their neck greater than 15° two to three times per minute. Gellerstedt (2002) reported that Swedish harvester operators preformed 4,000 control inputs per hour (note that this is a total for both the right and left hand controls). Using data presented in Hansson (1990), Swedish pro-

cessor operators conduct between 1,380 to 3,240 hand movements per hour (again this is a total for both the right and left hands). The repetitive movements of the arms and legs (to operate controls) in forestry MMOs has been found to increase trunk muscle activity (Hansson 1990). The amount of muscle activity depends on the magnitude, direction, and amount of repetition. These fatiguing movements may contribute to the back injuries and pain seen in forestry MMOs (and MMOs in general), as they increase spinal loading and discomfort (Haslegrave 1995). Repetitive arm movements have also been associated with neck and shoulder musculoskeletal injuries (NIOSH 1997). Movement span, shoulder and arm strength, dexterity, speed, work motivation, health, the location of armrests and controls, and work technique have all been associated with differences in forestry MMO neck and shoulder health (Hansson 1990, Haslegrave 1995). The forces involved in operating controls can also cause distress on the body while driving (Haslegrave 1995, NIOSH 1997). MMOs reporting neck and shoulder problems tend to have greater control resistances than healthy MMOs (Hansson 1990).

Spine Stability

The spinal stabilizing system is composed of the spinal column (which carries loads and provides information about the position, motion, and loads of the spinal column), the muscles surrounding the spine and a motor control unit (that takes information about the spine and provides necessary adjustments in posture and stiffness via the muscles) (Panjabi 2003). Under normal conditions, these components work together and provide the needed mechanical stability (Panjabi 2003). But, low muscle activity may result in instability, thus causing unexpected vertebral body displacement whereas high muscle activity increases the system stiffness but may result in excessive loading and subsequent tissue failure (Cholewicki and McGill 1996, Brown and Potvin 2004). In the case of low muscle activity, the resulting instability may induce a sudden need to regain stability thus resulting in muscle spasm and potential tissue overload (Cholewicki and McGill 1996).

Research has indicated that the muscular response to WBV tends to get out of phase with the vibration input, and, therefore, rather than absorb the effects of vibration, the forces from muscle contractions add to the effects of vibration (Wilder 1993). Additionally, the inappropriate muscle activation patterns resulting from muscle activity becoming out of phase with the vibrational load input could lead to moments of instability and injury. As well, the terrain related transient shocks forestry MMOs experience can overload spinal tissues and may also result in a sudden need to regain spine stability.

Work Duration

A survey of northern Ontario skidder operators revealed that these operators worked between 8 hours and 14 hours a day. In New Zealand, a majority (72.7%) of forestry MMOs reported working between 8 hours and 10 hours a day, and 24.2 percent of forestry MMOs reporting working over 10 hours a day (Lilley et al. 2002). Long work days can create problems

with the accumulation of fatigue, decreased ability to maintain attention, and increased tendencies to take unsafe short cuts (Spurgeon et al. 1997). Fatigue contributes significantly to performance deterioration and leads to increased risks of human error and accidents (Spurgeon et al. 1997, Lilley et al. 2002). Lilley et al. (2002) found that close to 80 percent of New Zealand forestry MMOs report a low level of fatigue at work, and 28 percent of workers felt fatigue affected their safety sometimes, while 4 percent felt it often or always affected their safety. Additionally, a significant association between reported accident near-misses and fatigue level was found, with a high level of fatigue at work having a 9.29 times increased risk for accident near-misses (Lilley et al. 2002). What's more, long hours act as a stressor increasing the demands on a person who attempts to maintain performance levels in the face of increasing fatigue (Spurgeon et al. 1997). Long work days also increase the time that a worker is exposed to other sources of workplace stress such as WBV, repetitive movements, and static postures (Spurgeon et al. 1997). Consequently, forestry MMOs can be at greater risk of injury due to increased exposure to musculoskeletal injury risk factors as well as an increased risk of a fatigue-related accident occurring.

WBV Risk Factor Interactions

WBV, static postures, repetitive movements, spine stability, and work duration all play a role in the health of forestry MMOs. Consideration of the interactions between these risk factors, however, is necessary for understanding how forestry MMOs are being injured.

Cab Design and Operator Posture

MMOs are typically seated with a "slumped" posture achieved by a backward rotation of the pelvis and simultaneous rounding (kyphosis) of the spine (Chaffin et al. 1999). Twisted or bent postures are frequently adopted by forestry MMOs (Gellerstedt 2002, Rehn et al. 2005b), and these postures are often influenced by cab design (Eklund et al. 1994, Gellerstedt 2002). The positions adopted are a function of the seat design, control locations, and vision requirements where MMOs bend and twist to view driving routes and attachments as well as to reach controls (Bottoms and Barber 1978, Eklund et al. 1994, Boden and Oberg 1998, Gellerstedt 2002, Mansfield et al. 2002).

Operator Posture and WBV

Holding seated postures for extended periods of time has been associated with increased risk for musculoskeletal problems in the neck, back, shoulders, legs, and buttocks (Floyd and Roberts 1958, Bottoms and Barber 1978, Frymoyer et al. 1983, Village et al. 1989, Zacharkow 1990, Pope and Hanson 1992, NIOSH 1997, Boden and Oberg 1998, Chaffin et al. 1999). As these postures become extreme, the passive loading of joints can cause sensations of discomfort and pain, and the risk for spinal disorders increases (Toren 2001). WBV on top of these prolonged static seated postures increases the risk of back, neck, and shoulder disorders (NIOSH 1997). Several studies comparing MMOs to controls report a higher incidence of low back

pain, vertebral disc herniation or ruptures of the annulus fibrosus, sciatic pain, headaches, neck pain, and low back pain with WBV (Village et al. 1989, Johanning 1991, Bovenzi and Betta 1994, Bovenzi 1996, Scutter et al. 1997, Hagen et al. 1998, Rehn et al. 2002). Moreover, WBV has increased harmful effects when combined with adverse postures. The muscle fatigue from prolonged contractions to maintain a static posture coupled with increased muscle activity resulting from WBV (Seidel et al. 1980, Seroussi et al. 1989, Village et al. 1989, Wilkstrom 1993, Pope et al. 1998) could lead to discomfort and pain in forestry MMOs.

Muscle Activity, Repetitive Movements, and Risk of Disk Herniation

Increased muscle activity has implications for vertebral disc herniation and disc degeneration, which is often seen in MMOs exposed to WBV (Kelsey 1975a, Kelsey 1975b, Heliovaara 1987, Hulshof and Veldhuijzen van Zanten 1987, Wilder 1993, Bovenzi and Betta 1994, Teschke et al. 1999). Vertebral disc herniation has been associated with repetitive movements (Hardy et al. 1958, Adams and Hutton 1982, Callaghan and McGill 2001, Kuga and Kawabuchi 2001), particularly when compressive loading is involved (Adams and Dolan 1996, Callaghan and McGill 2001, Kuga and Kawabuchi 2001). Increasing the magnitude of compressive load increases the likelihood and severity of a vertebral disc herniation (Callaghan and McGill 2001). In MMOs (including forestry MMOs), these repetitive movements can result partly from postural control to stabilize the spine and maintain a visual field while operating machine controls under X- and Y-axis accelerations and rotational vibration exposures. Compressive loads can result from combined bodyweight and Z-axis accelerations, passive tissue tension, and muscle activity. It has yet to be seen, however, how exposures with frequencies, rotations, and accelerations found in field operating conditions would affect vertebral disc herniation, but the conditions associated with operating mobile equipment in forestry and other industries are conducive to the development of this type of injury.

Transient Loading and Vertebral Disc Herniation

WBV also contains sudden unexpected transient accelerations (i.e., hitting a stump or pothole), which are associated with greater risk of injury (BS 6841:1987). Vertebral fractures or dislocations, ligament stretch or rupture, and intervertebral disc/end-plate lesions have been reported, with the structure affected depending on the load magnitude, direction, application point, loading rate, and spinal posture (Oxland et al. 1991, Tsai et al. 1998). The vertebral disc herniations seen in MMOs could also be the result of a sudden transient acceleration while driving as bending and a rapid compressive load can herniate a vertebral disc (Adams and Hutton 1982).

Interactive Effects of Repetitive and Sudden Loading on Vertebral Disc Herniation

An interaction between repetitive and sudden loading with respect to vertebral disc herniation is apparent from the litera-ture. It appears that the degenerative changes seen with repetitive movements can decrease the forces needed to herniate a disc with a sudden load (Callaghan and McGill 2001). In laboratory experiments, degenerated discs herniated at much lower applied loads (Brinckmann 1986, Simunic et al. 2001) and intradiscal pressures (Iencean 2000) than did undamaged discs.

Muscle Activity, Compressive Loading, Repetitive Motion, Posture, Spine Stability, and Vibration Transmission

Active muscle force (McGill and Cholewicki 2001), inherent joint stiffness (McGill and Cholewicki 2001), posture (Hardy et al. 1958, Cholewicki and Van Vliet 2002), and resulting joint compression (Panjabi 2003) all contribute to the stability of the lumbar spine. Here, increased muscle force and joint compression (Cholewicki and McGill 1996, McGill and Cholewicki 2001) and more extreme postures (bending or twisting) display greater stability. WBV also affects the rigidity of the spine with the frequency and magnitude of the loads it applies to the body. The spine becomes stiffer when exposed to greater load magnitudes (Cholewicki and McGill 1996, Panjabi 2003) and with increased loading frequencies (Simunic et al. 2001). Therefore, high frequencies and accelerations increase spine rigidity. Since vibration is transmitted through a rigid structure more readily, and natural frequency of a structure is determined by its stiffness, the way a person sits in a seat, the WBV exposure pattern, and the associated muscle activity can affect vibration transmission through the body because of the influence those factors have on the stiffness of the spine (Wilson and Corlett 1990, Michida et al. 2001).

An injury causing losses in passive tissue stiffness, such as the degenerative changes in vertebral discs seen with WBV exposure, result in joint laxity that necessitate higher levels of muscular activation and stiffness to ensure sufficient stability (Oxland et al. 1991, McGill and Cholewicki 2001). An injury such as the degenerative changes in vertebral discs seen with WBV exposure can, therefore, necessitate higher levels of muscular activation and stiffness to ensure sufficient stability (Oxland et al. 1991, McGill and Cholewicki 2001). This may lead to muscle fatigue, possibly resulting in pain and discomfort, which may explain the high prevalence of low back pain in MMOs (Bovenzi and Betta 1994, Bovenzi 1996, Koda et al. 2000) and forestry MMOs (Hagen et al. 1998, Rehn et al. 2002, Cation et al. 2007) exposed to WBV.

Trunk postures are not the only variable that can affect the rigidity of the spine or the only risk factor for back and neck disorders. Static arm positions can influence spine stability and trunk muscle activity (Cholewicki and McGill 1996, Kitazaki and Griffin 1998). Repetitive movements of the arms can also increase the muscle activity in the trunk (Hansson 1990). As well, the position of the legs can have an effect on the rigidity of the spine through resultant muscle activity and spinal loading. For example, a flexed knee and hip will rotate the pelvis backwards, flattening spinal curvature and increasing back muscle activity (Chaffin et al. 1999).

Work Duration, Posture, Fatigue, and Vibration Transmission

Forestry MMOs work long hours with the majority spent exposed to seated WBV (Golsse and Hope 1987, Harstella 1990). Since the duration of vibration exposure is an important factor in the health effects seen with WBV (Bovenzi and Betta 1994, BS 6841:1987, Herington and Morse 1995, Bovenzi 1996, ISO 2631-1:1997) and damage to vertebral discs is cumulative (Callaghan and McGill 2001), these long hours of operation pose an increased risk for vibration-related problems. The long duration of static driving postures and repeated movements to operate controls also cause distress on the body (Haslegrave 1995) and can lead to localized muscle fatigue and subsequent discomfort and pain.

Long hours of work and fatigue affect posture with the back having a tendency to round as time goes on (Michida et al. 2001). These postural changes while exposed to vibration over time have implications for vibration transmission since different postures can create conditions that more readily transmit and attenuate vibration (in this case they may increase vibration transmission). Interestingly, fatigue affects posture, but posture can also affect fatigue. Wilder et al. (1994) found that low back (L3 erector spinae) muscle fatigue during a simulated truck drive was greatest in an upright posture when compared to a forward lean posture and a posture where the subject leaned against a backrest. Thus, some postures may be more fatiguing and lead to posture changes that can affect vibration transmission.

Productivity and WBV Risk Factors

The bottom line of any forestry operation is economics and productivity becomes perhaps the most important issue. Discomfort, fatigue, and WBV exposure during forestry equipment operation can all affect the productivity of forestry MMOs. Discomfort in MMOs is influenced by WBV, operator posture, the forces required to operate controls, seat design, pressure distribution on the buttocks and thighs, and noise (BS 6841:1987, Witheford 1994, Haslegrave 1995, ISO 2631-1:1997, Park and Kim 1997, Shen and Vertiz 1997, Park et al. 1998, Mehta and Tewari 2000, Tewari and Prasad 2000, Pope et al. 2002). The aforementioned variables also affect the level of discomfort of forestry MMOs, and when discomfort is present there is an increased likelihood of reduced productivity (Love et al. 1992, Haslegrave 1995).

Fatigue can contribute to poor performance and increase human error (Slappendel et al. 1993, Spurgeon et al. 1997, Lilley et al. 2002). WBV, repetitive movements, and long work days can all be fatiguing and diminish productivity. Vibration exposure can produce a cardiopulmonary response similar to that during moderate exercise (Wasserman and Taylor 1992, Kroemer et al. 1999) and can lead to higher rates of fatigue (Pope and Hanson 1992). Many drivers view WBV as fatiguing and feel that it affects work performance (Hansson 1990). Additionally, WBV acceleration levels greater than 0.5 m/s^2 in any axis can decrease an individual's visual acuity, dexterity, and hand manipulation abilities (BS 6841:1987, Village et al. 1989, Slappendel et al. 1993). Seidel et al. (1980) found that with increased time of WBV exposure, subject reaction times to a stimulus increased as did the number of errors in stimulus recognition. These authors found that an 8 Hz exposure was more detrimental than a 4 Hz exposure. Lewis and Griffin (1980) found similar results, with increased WBV acceleration levels resulting in a greater percentage of reading errors and longer reading times. In contrast to Seidel et al. (1980), these authors found that 11.2 Hz was the most sensitive frequency, resulting in more errors and a longer reading time. Consequently, WBV exposure can result in inefficient and inaccurate operation of equipment, once again leading to decreases in productivity.

Longer work days have also been shown to decrease performance (Spurgeon et al. 1997), with the effects being greater at night (Lilley et al. 2002). This is likely due to the accumulation of fatigue from WBV exposures, repetitive movements, and static postures throughout the work day. Night work may also affect performance due to the disruption of normal circadian rhythms (daily sleep/rest cycles). When asked to assess the effect of fatigue on work quality and output, 38 percent of forestry workers in New Zealand felt that their work quality and output were affected by fatigue some of the time, while 8 percent reported it often or always affecting work quality and output (Lilley et al. 2002).

Overview and Recommendations

Ultimately, research is focused on reducing injuries so that workers do not have to suffer through any ill health, but also to decrease health care and injury-related costs to companies and society as a whole. In addition to decreasing injury-related costs to employers, increased production and higher profits are a primary goal of any company. This paper discussed several factors which can influence the health of forestry MMOs, along with how those factors can interact, and the effects of those factors on operator productivity. The synthesis of the large body of literature provided in this paper indicates that reductions in injury and subsequent injury cost can be accomplished by reducing biomechanical risk factors, thus resulting in concomitant productivity improvements. The following sections discuss some methods for reducing the aforementioned biomechanical risk factors.

Postural Improvements

There are several guidelines available indicating which postures are less harmful than others, but little is known about which postures are optimal, particularly when considering interacting factors such as WBV exposure and transmission, spinal stability, muscle activity, repetitive forceful movements, as well as health and productivity outcomes. Determining postures that minimize WBV transmission while optimizing spinal stability can lead to improved operator cab designs. For example, it has been established that visibility requirements and control locations influence the operator's posture. The repositioning of controls, cab frame components, working attachments, or any other object which would cause an operator to bend or

twist in order to obtain the necessary field of view or operate the necessary controls for the task being preformed can help improve operator postures. The use of a swiveling seat and self leveling cabs have been suggested by operators to be a benefit and aid in providing a comfortable working posture (Bottoms and Barber 1978; Gellerstedt 1998, 2002), as well as a decrease in head and trunk rotations (Eklund et al. 1994, Gellerstedt 1998).

Gellerstedt (1998) provided a review of the design and ergonomic studies of a Pendo™ self-leveling and swiveling cab manufactured in Sweden. The cab is suspended from an arched column that is in turn connected to a swiveling socket that can be controlled by the operator. This gives the operator the ability to adjust the cab for optimum visibility at all times, alleviating skewed and twisted work positions. When compared to a conventional cab, the operator's head rotation while operating a harvester with a Pendo cab was reduced. Gellerstedt (1998) reported that the amount of time that harvester operators spend with their head rotated beyond 22.5° was reduced by 10 to 28 minutes per hour when a Pendo cab was used. Although the swivel seat and self-leveling or swiveling cab may not be a viable solution for all forms of forestry equipment, they demonstrate how operator postures can be improved through cab design.

Reductions in Repetitive Movements

There are significant differences between operators with and without neck and shoulder health problems with respect to arm movement span and speed, control resistance, as well as the location of armrests and controls (Hansson 1990, NIOSH 1997). Limiting the magnitude of the movement span can lead to a decline in muscle activity (Hansson 1990). Therefore, a reduction in the magnitude of these repeated motions (through control location and operational requirements) may help reduce musculoskeletal injuries. This has been demonstrated in musculoskeletal injury intervention studies that found reductions in task repetition coupled with the adoption of less extreme working postures resulted in a reduced incidence of neck musculoskeletal disorders and an improvement in symptoms in those who were experiencing neck problems (NIOSH 1997).

Reductions in WBV Exposure

Posture and repeated movements are only one important factor in the health and productivity of forestry MMOs. WBV exposures which can influence muscle activity and potentially influence spine stability are also an important concern. Currently interventions for WBV exposure focus on designing seat suspensions to attenuate vibration and shift exposures to less harmful frequencies (below the resonant frequency of the operator's trunk). In addition to seat suspension systems, seat cushioning, cab/chassis and axel/chassis suspension systems, and the vehicle tires can all be used in combination to help minimize operator WBV exposures.

Seat Suspensions

Donati (2002) stated that the majority of suspension seats are designed to ensure isolation only in the vertical (Z-) axis. This was demonstrated in a study by Malchaire et al. (1996), where a mechanical anti-vibration suspension was found to significantly reduce Z-axis vibrations in forklift trucks, but there was no influence on vibration levels in the X- and Y-axes. The vertical vibration isolation is done most often with scissor linkage seats that utilize a spring/damper system or an air bladder and compressor to provide vibration attenuation. Donati (2002) notes that the suspension travel should be sufficient to prevent bottoming or topping at end stops, and that the lower the input frequency, the larger the required suspension travel to dampen the input. Thus the low frequency vibration seen in forestry vehicles requires sufficient space for suspension travel, which is likely limited and may result in a risk for impacts when high vibration input levels are present. This will result in transient loading of the spine as well as increase the overall vibration exposure levels if these impacts are repeated. In order to minimize these impacts, some suspension manufacturers will highly damp their suspensions to prevent end-stop impacts, but this is usually detrimental to suspension performance (Donati 2002). One suggestion by Donati (2002) was to utilize soft end stops, but Donati (2002) further stated that such end stops require space, which may affect the capacity of the suspension system to reduce input vibrations. Weight adjustments are also provided so that the seat suspension sits at its mid-travel point when the operator sits on the seat. A proper weight adjustment for a seat helps to reduce the amount of end stop impacts as it provides the suspension system with the greatest travel distance to dampen input vibrations before the endstops are reached.

Paddan and Griffin (2002) measured vertical accelerations on the floor and seat base of 100 vehicles fitted with both conventional (67 vehicles) and suspension (33 vehicles) seats. These authors reported lower median seat vibration transmission (using both RMS and vibration dose values calculated in accordance with ISO 2631-1:1997 and BS 6841;1987) with vehicles that were fitted with a suspension seat (Paddan and Griffin 2002). Several suspension seats, however, amplified the vibration they were supposed to attenuate. Seat suspensions can be described as a second-order system where frequencies above the resonance of system (1.4 times the resonance frequency [Donati 2002]) are attenuated. Thus, the stiffness of a suspension seat is adjusted such that its resonance for a given supported weight is below the dominant input frequency of the chassis. If the seat suspension stiffness/resonance is not properly adjusted and overlaps with the chassis input frequencies, then the vibration inputs will be amplified. The amplification of vibration seen with suspension seats generally happens when the suspension seat used was not designed for the dynamic properties of the vehicle it is mounted on, under the conditions that the vehicle is being used. Paddan and Griffin (2002) found that 94 out of the 100 vehicles investigated might benefit from changing the seat to one having the dynamic performance of a different vehicle, demonstrating how the seats used need to be appropriate for the vehicle and driving conditions.

A lightly damped and soft suspension is considered desirable for effective attenuation of continuous vibration of low-to-medium levels, provided that the excitation occurs at frequencies

well above the seat's natural frequency (McManus et al. 2002). The attenuation of high-magnitude vibration and shock, on the other hand, requires suspension designs with higher damping and stiffness to prevent end-stop impacts from occurring (McManus et al. 2002). In environments involving combinations of low, medium, and high levels of continuous vibration and shocks (as seen in forestry), means of achieving variable damping are, therefore, desirable to adapt the seat attenuation performance accordingly (McManus et al. 2002). This can be achieved through the incorporation of active or semi-active damping within the suspension (McManus et al. 2002). Active suspension systems can help improve low-frequency vibration attenuation of seats, but because active suspensions require a continuous power source and associated electronics, they have a high manufacturing cost, complexity in control, and poor reliability (Sankar and Afonso 1993). On the other hand, semi-active suspension systems (which perform relatively well in comparison to active control designs) require less power than active control systems, are more reliable, and are less costly as a result of their simpler design (Guglielmino et al. 2005).

McManus et al. (2002) compared the vibration and shock attenuation characteristics of a suspension seat fitted with a conventional damper and one which was fitted with a semi-active magnetorheological fluid (MR) damper designed for use in heavy road vehicles. It was found that the conventional suspension had a natural frequency near 1.48 Hz and a corresponding peak acceleration transmissibility of 1.51, while the MR damper suspension when set to 'medium' and 'firm' had natural frequencies near 1.37 Hz and 1.49 Hz, respectively, with corresponding peak acceleration transmissibility values of 1.63 and 1.59 (McManus et al. 2002). These results suggest that at the optimal mid-ride position, the seat with a conventional damper offered higher damping capabilities than that provided with the MR damper, for both medium and firm settings (McManus et al. 2002). Under a transient (pot-hole) excitation, however, the MR damper with a firm setting performed the best with respect to end-stop impacts as it required the most energy in terms of ISO 2631-1:1997 weighted RMS Z-axis accelerations and vibration dose values to induce an end-stop impact (McManus et al. 2002). The MR damper with the medium setting required the next most energy to induce an end-stop impact followed by the conventional damper (McManus et al. 2002). When increasing the vibration inputs by 150 percent, McManus et al. (2002) found that at mid-ride height, only the MR dampers (medium and firm) prevented end-stop impacts. Here, the firm setting provided the lowest Z-axis transmissibility with regards to RMS accelerations, vibration dose values, and crest factors.

Seat suspensions designed with MR dampers have a quick dynamic response, but the fast switching of the damper characteristics results in ocassional acceleration and jerk peaks that degrade ride quality (Guglielmino et al. 2005). To overcome the fast switching problem, Guglielmino et al. (2005) incorporated the use of fuzzy logic controls to smooth the control action without using low-pass filters that would reduce the system bandwidth (Guglielmino et al. 2005). Using a random vibration input and a 1998 Wei and Griffin lumped parameter seat and driver model, Guglielmino et al. (2005) found that a MR damper with fuzzy logic control reduced the RMS accelerations transmitted to the body by 21 percent, as well as lowered the peak acceleration frequency when compared to the same suspension system with a traditional viscous damper. It should be noted that the MR damper was found to reduce RMS accelerations by an extra 6 percent when a 'crisp' controller was used instead of the fuzzy logic control, but the fuzzy logic controller reduced acceleration peaks and improved ride quality (Guglielmino et al. 2005).

The above seat suspension systems were designed for the Z-axis; however, the Z-axis is not the only direction of vibration exposure that designers should be concerned with (as indicated in previous sections of this paper). The attenuation of X- and Y-axis vibrations is also desired, and some attempts to attenuate these horizontal vibrations have been made. X-axis suspensions have been used with articulated and agricultural tractor seats where they were found to be particularly useful when these tractors were pulling a trailer (Donati 2002). These X-axis suspensions allow the driver's body to move in phase with seat motion (Donati 2002). Without an X-axis suspension, at about 2 Hz, a driver may move backwards while the seat moves forwards resulting in the seat striking the driver in the back (Donati 2002). This may result in injuries to the back and neck as the impact could cause the neck to extend rapidly.

Sankar and Afonso (1993) investigated the performance of a combined Y- and Z-axis suspension system during off-road vehicle use. The Y-axis isolator consists of a platform supported on a set of linear bearings with springs and a shock absorber, and the Z-axis isolator was a scissor linkage bounce suspension system (Sankar and Afonso 1993). In a laboratory test, Sankar and Afonso (1993) found reductions in Y-axis vibration magnitudes that were greater than 30 percent when vibration inputs had a frequency above 1Hz (the suspension resonance was tuned to 0.5Hz). When the vibration inputs were greater than 1.5 Hz the Y-axis vibration magnitudes were reduced by more than 50 percent (Sankar and Afonso 1993). With a field test (using a dump truck on a test track), Sankar and Afonso (1993) found that their lateral suspension system improved the vibration exposures at the seat. The same Y-axis suspension system could also be used in the X-axis. A combination of a tuned X-, Y-, and Z-axis suspension system would then provide triaxial translational damping of vibrations to the seat.

Saddle Seats

In addition to seat suspensions, different seat designs to improve ride quality have been investigated. One design that has shown some promise is the saddle seat. Mansfield et al. (2002) compared a standard suspension seat (typically used in forwarders) to a saddle type seat (with an identical suspension mechanism). The saddle seat height was selected such that the operator's relative trunk/thigh angle was 130° (Mansfield et al. 2002). Both seats were mounted on a forwarder which drove over a test track (Mansfield et al. 2002). The two seats were both found to have a peak vibration transmission between 1.5 Hz and 2 Hz with the saddle seat having a slightly lower peak value

and fewer impact occurrences (Mansfield et al. 2002). Subjectively, the operators in the study had no clear preference between seats when simply driving, but the operators preferred the saddle seat when driving over rough tracks as fewer end-stop impacts were experienced (Mansfield et al. 2002). In addition, Mansfield et al. (2002) reported that ISO 2631-1:1997 weighted RMS accelerations measured on the seat were significantly lower in the Y- and Z-axes for the saddle seat. The vibration dose values were also significantly lower for the saddle seat in the Z-axis, but the saddle seat had significantly greater vibration dose values in the X-axis (Mansfield et al. 2002). Further investigations into the seat design's affect on contact pressure distribution between the seat, buttock, and thigh should be conducted, coupled with investigations into the affect of the thigh angles on pelvic and spinal postures and concomitant influences on muscle activity and vibration transmission through the spine.

Seat Cushioning

Seat cushioning can also be used to reduce vibration exposure levels and improve operator comfort ratings for the seat. Mayton et al. (2005) investigated the effects of differed seat cushion configurations in mid-coal seam shuttle car haulage vehicles. There were three seat cushions used: the original seat cushion (well worn), a seat with 13 cm of Sun-Mate Extra-Soft foam padding, and a seat with a combination of Sun-Mate Extra-Soft foam and Pudgee padding that totaled 13 cm in thickness (Mayton et al. 2005). Subjectively, the operators preferred the seat with just the Sun-Mate Extra-Soft foam padding (Mayton et al. 2005). When considering vibration exposure levels, Mayton et al. (2005) found that the Sun-Mate Extra-Soft foam and Pudgee padded seat performed the worst while driving fully loaded with an average daily exposure limit of 201 minutes and an average vector sum RMS acceleration of 2.19 m/s^2 (using 2002 ACGIH TLV guidelines for vibration exposures and analyses which are based on ISO 2631-1:1985). Mayton et al. (2005) attribute the poor performance of this seat while driving loaded to a frame mounted horizontal spring on which the foam padding was mounted. The Sun-Mate Extra-Soft foam and Pudgee padded seat, however, performed the best when driving unloaded, with an average daily exposure limit of 503 minutes and an average vector sum RMS acceleration of 1.53 m/s^2. The seat with just Sun-Mate Extra-Soft foam padding had average values as follows: a vector sum RMS acceleration of 2.21 m/s^2 with a daily exposure limit of 243 minutes while driving loaded, and a vector sum RMS acceleration of 1.41 m/s^2 with a daily exposure limit of 463 minutes while driving unloaded (Mayton et al. 2005). Finally, the original seat had an average vector sum RMS acceleration of 1.62 m/s^2 and 1.98 m/s^2 with a daily exposure limit of 492 minutes and 233 minutes while driving loaded and unloaded, respectively (Mayton et al. 2005).

Cab Suspensions

Vehicle cab suspensions are another option for the reduction of operator exposures to WBV. Here, low-frequency suspension systems are incorporated between the driving cab and chassis. Donati (2002) stated that only low-frequency suspension cabs (preferably fitted with a four-point suspension) are efficient enough to reduce the vibration transmitted to the operator. The advantage of a low-frequency suspension cab over a suspension seat is that the operator's whole-body is protected from WBV with respect to several degrees of freedom (Donati 2002). Low-frequency suspension cabs can be designed to ensure isolation in all three linear axes but the main purpose is to reduce vertical movement as well as rolling and pitching. These cabs have been shown to reduce vertical vibration transmitted to the operator (Donati 2002, Lemerle et al. 2002). Lemerle et al. (2002) designed a cab suspension to isolate Z-axis, pitch and roll vibrations, and reported reductions in the Z- and X-axis vibrations during simulated driving. Lemerle et al. (2002) further validated the use of their cab suspension design during a field trial with the system mounted on a forklift truck. Pendo cabs described by Gellerstedt (1998) are also equipped with vibration-reducing and shock-absorbing features that provided vibration isolation for the cab in the X-, Y-, and Z-axes. These Pendo cabs have demonstrated the ability to lower vibration exposure levels (although not at a statistically significant level) when compared to conventional cabs (Gellerstedt 1998). The improvements in vibration exposures levels were seen in the X- and Y-axes of harvesters (note that here there was no Z-axis suspension), the Y- and Z-axes of forwarders while driving empty, and the X- and Z-axes of forwarders while driving loaded (Gellerstedt 1998).

Axle Suspensions

Axle suspensions are another possible means of reducing operator WBV exposures. But, most all-terrain construction, agricultural, and forestry vehicles are designed with no suspension at the axles (Sankar and Afonso 1993, Donati 2002). Donati (2002) commented on the benefits of axle suspensions in the vertical, pitch, and roll axes, but investigations into the effectiveness and feasibility of axle suspensions for use in forestry machines should be conducted.

Tire Inflation

Tire pressure levels can also be used to help reduce operator WBV exposure levels. Oguz and de Hoop (1998) stated that both empirical evidence and truck driver testimonials indicate that lowered tire pressures improve the ride quality for the driver. Sherwin et al. (2004b) found that increased tire pressures (20 psi increased to 60 psi) were associated with significantly increased X- and Z-axis WBV exposures in a cut-to-length timber harvester driven on an ISO 5008;1979 test track. The ISO 2631-1:1997 comfort weighted vibration total values that were reported for these tire pressures are associated with no discomfort at 20 psi (vibration total value = 0.277 m/s^2) and fairly uncomfortable at 60 psi (vibration total value = 0.527 m/s^2), using ISO 2631-1:1997 comfort guidelines. As well, the ISO 2631-1:1997 health weighted vibration total value for the 20 psi tire pressure (0.324 m/s^2) was associated with no health risk for an 8-hour day, while the 60 psi vibration total value

(0.561 m/s^2) was associated with a potential health risk for an 8-hour day according to ISO 2631-1:1997 health guidelines. Thus, lower tire pressures were associated with improved comfort and reduced injury risk for cut-to-length timber harvester operators.

Knowledge gained from further investigations into the interactive effects of tire inflation with driving surfaces, carried loads, and driving speeds for specific vehicle makes and models can be used to help minimize vibration exposure levels further through the aid of central tire inflation (CTI) technology. CTI technology allows operators to adjust individual tire pressures while the vehicle is in motion (Oguz and de Hoop 1998). This can help minimize WBV exposures as operators adjust tire pressures for a given load, speed, or driving condition. CTI can also assist in improving vehicle traction, decreasing tire bounce on hard surfaces and reducing wash-boarding on soft surfaces (Oguz and de Hoop 1998). In addition, reductions in vibration levels through the tire pressure adjustments can help reduce vehicle maintenance costs in addition to the operator comfort and health benefits.

The Operator and Suspension Systems

Although both the attenuation of vibration and the shifting of exposures to less harmful frequencies are desired, the shifting of frequencies needs to account for more than the general biodynamic response of trunk. Shifting the frequency may benefit one level of the spine but be detrimental to another. The design of these seats needs to consider how the body responds to vibration under various conditions, and currently, research that focuses on the body's response to real-life vibration exposures and adopted postures seen in the field is limited. There is also little focus on how a wide array of risk factors for back and neck injuries in forestry MMOs interact. Designing an efficient seat or vehicle for reducing WBV exposures may not be effective if static sitting postures and repetitive manipulation of controls are not considered.

Operator Training

Well-designed equipment does not provide a viable solution if operators do not use it properly. Driver WBV exposure levels have been shown to increase with increases in driving speed (Golsse and Hope 1987, Malchaire et al. 1996, Rehn et al. 2005a). On the other hand, proper and timely maintenance of vehicle systems can reduce vibration and noise exposure (Neitzel and Yost 2002), and proper combinations of tire inflation and seat suspension can also help reduce vibration exposure acceleration levels (Malchaire et al. 1996, Oguz and de Hoop 1998, Sherwin et al. 2004b). Thus, proper operator training (regarding speeds, maneuvering over rough terrain, tire inflation, and proper suspension seat adjustment) and vehicle maintenance can help to reduce musculoskeletal injury risk factors. Experienced operators also display fewer control movements during the day (Gellerstedt 2002), which can help reduce fatigue and improve productivity. Even though operators can be instructed on how to drive, sit, and operate controls, produc-

tion demands and long work days will likely be counter productive to efforts to reduce musculoskeletal complaints.

Another point to consider is the operator turnover associated with musculoskeletal injury complaints. Kirk et al. (1997) reported high employee turnover in the New Zealand forestry industry, which can create problems for the forestry industry when worker skills and the costs of their training are lost. An additional problem with high turnover is employers may discourage employee training which aims to reduce injury risks and improve productivity, since experience may affect operator efficiency and ride smoothness (Golsse and Hope 1987). It has also been reported that there is a considerable difference between trained and untrained New Zealand worker turnover rates (Kirk et al. 1997), with higher turnover in untrained workers. Thus training and experience can help mitigate some of the risk factors for musculoskeletal injuries associated with mobile machine operation, potentially reduce costs, improve productivity, and decrease operator turnover.

Rest Breaks

Properly scheduled rest breaks may also benefit operators by reducing operator fatigue and exposure to musculoskeletal risk factors (i.e., WBV, static postures, and repetitive movements). Lilley et al. (2002) reported that the odds of forestry workers experiencing high levels of fatigue were decreased when rest breaks were taken. A literature review by Tucker (2003) suggested that sufficient rest breaks may be an efficient means of avoiding fatigue-related decrements in driving performance. Tucker (2003) went on to indicate that fatigue is managed best when drivers take their rest breaks whenever they feel fatigued, and that the benefits of a rest break are enhanced when food is consumed, a short nap is taken, and a caffeine drink is consumed. Tucker (2003) continued with a discussion regarding how the optimal frequency, timing, and duration of breaks for various job tasks are unknown, as research tends to focus on the overall amount of rest taken within a duty period. Optimum rest schedules are likely to be specific to the nature of the work activity being undertaken (e.g., task demands, worker's control of pacing) as well as differences in both the individual's state (e.g., ability, motivation, sleep debt) and trait (e.g., circadian type, for example, a morning person vs. a night person) (Tucker 2003). In addition to fatigue issues, Lilley et al. (2002) stated that forestry workers working short intensive periods without adequate rest breaks were at higher risk of accidents and lost-time injury. Thus, properly scheduled rest breaks have the potential to reduce fatigue, accidents, and musculoskeletal injuries, while improving driver performance. Job/employee specific rest break schedules, however, need to be investigated so that the benefits can be optimized.

Conclusions

In conclusion, guidelines based on WBV exposures and adopted postures associated with the operation of mobile equipment in industry, which optimize spine stability, reduce WBV transmission, and minimize fatigue will ultimately reduce musculoskeletal injuries while improving productivity.

The implementation of these guidelines in the design or improvement of cabs coupled with proper forestry MMO training and work-rest schedules can help to reduce musculoskeletal injuries and costs to employers and society.

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