Ergonomic Risk Factors

A study of heavy earthmoving machinery operators

By N. Kumar Kittusamy

ALTHOUGH MANY STUDIES HAVE SHOWN an association between operating heavy construction equipment and symptoms of musculoskeletal disorders (MSDs), little research has been performed that systematically characterizes the exposure of operating engineers to ergonomic hazards. This study evaluated: 1) vibration at the seat/operator interface; 2) transmissibility of vibration in the Z-axis; 3) psychophysical ratings of vibration level and vibration discomfort; and 4) postural requirements of the job. Results indicate that the digging operation had higher levels of total weighted acceleration than high- or low-idling conditions. Transmissibility data showed that the seat amplified vibration, particularly in the lower frequencies. Seats demonstrated that they may not be sufficient in protecting operators from long-term effects of vibration exposure. High positive correlation was found among subjective ratings (vibration discomfort and vibration level), but moderate positive correlation was found between subjective ratings and quantitative vibration levels. Postural evaluations revealed that the operators were required to assume awkward postures of the neck, shoulder and trunk while performing their jobs.

Work-related injuries and illnesses pose a continuing threat to the health and well-being of American workers. The construction industry has been historically recognized as having higher rates of fatality, injury and illness than other industries (McVittie 285+; BLS). In 1994, an estimated 218,800 lost-workday injuries were reported in the construction industry (BLS). Construction also had the second-highest incidence rate for sprains and strains. Although the industry has made progress since then, injuries and illnesses, including MSDs, continue to be cause for concern.

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Operating engineers (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 surveyors or mechanics. This equipment is used to: 1) build roads, bridges, tunnels and dams; 2) construct buildings and power plants; 3) remove earth materials and grade earth surfaces, and to replace concrete, blacktop and other paving materials; and 4) construct drainage systems, pipelines and related tasks, such as blasting (Stern and Haring-Sweeney 51+). An estimated 487,000 operating engineers (55 percent union, 45 percent nonunion) are employed in the U.S. and Canada, most of whom are exposed to whole-body vibration, albeit in concert with other occupational risk factors.

Past studies have shown that MSDs affect construction equipment operators due to awkward postures (e.g., static sitting), whole-body vibration, work intensity, high-resistance levers and repetitive motions (Kittusamy, et al; Buchholz, et al 23+). It is believed that reducing ergonomic exposures such as vibration and postural stress may be an important factor in improving operator health, comfort and efficiency.

Study Methodology

This study evaluated workers employed in the construction of the Central Artery/Third Harbor Tunnel (CA/T) in Boston. Eight journey-level (experienced) operators (seven males, one female) employed by two major contractors were studied; however, only six participated in the postural portion of the study because environmental conditions at the site were deemed unsafe for standing and videotaping the tasks being performed). Operators' ages ranged from 33 to 58 years; experience ranged from 11 to 40 years; height ranged from 5'5" (165 cm) to 6' (183 cm); and weight ranged from 115 lbs. (52 kg) to 284 lbs. (129 kg) (Table 1). Operators were briefed about the study and each signed an informed consent form.

Each operator used a different piece of earthmoving equipment including a wheeled loader, wheeled backhoe/loader, wheeled excavator and a crawler excavator. Equipment was grouped into three size categories: small, medium and large. Equipment was engaged in static tasks (i.e., low- and high-idling) and dynamic tasks (i.e., digging-related).

Whole-body vibration was assessed for each task at the seat/operator interface using a triaxial piezoresistive seat pad accelerometer (Model VT-3) and at the floor level using a single axis piezoresistive accelerometer (Model 7265A-HS), both from Endevco Corp. A field computer system (Model 2100 FCS) from Somat Corp. was used to filter and store data (Figure 1). Vibration measurements were performed in accordance with ISO 2631 (ISO; ACGIH 126+). Test equipment was calibrated and mounted according to manufacturer guidelines. Vibration data were sampled at a rate of 500Hz and filtered using a Butterworth filter with a low-pass break frequency of 100Hz.

Vibration data were collect-

Table 1

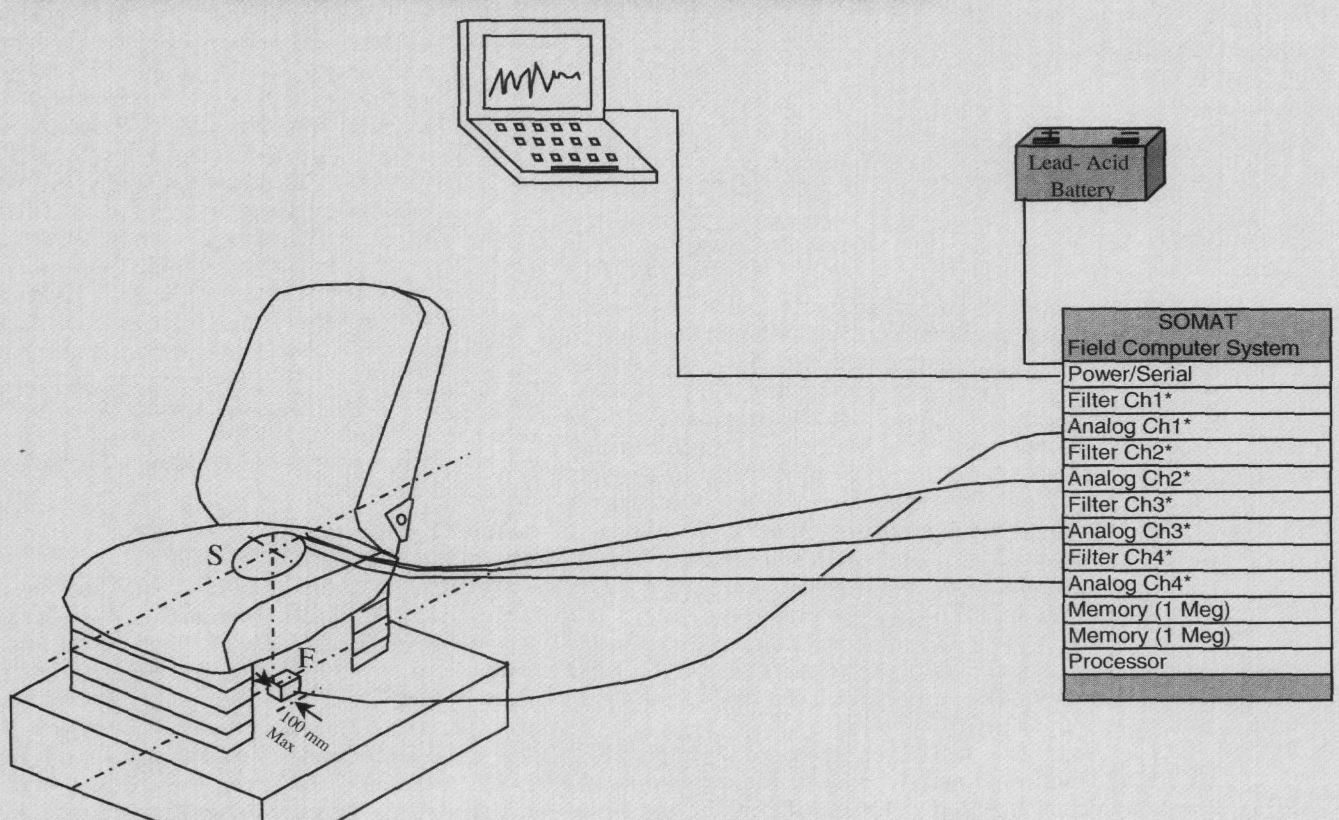
Background Data of Operators & Equipment Evaluated in the Study

Operator Characteristics					Equipment Information	
Operator*	**Height (cm)**	**Weight (kg)**	**Age**	**Years Exp.**	**Size**	**Type**
1	165	52	33	11	Small	Loader/Backhoe
2	178	129	49	30	Small	Loader/Backhoe
3	183	86	38	17	Small	Loader/Backhoe
4	165	70	58	36	Medium	Excavator
5	178	100	56	40	Medium	Excavator
6	168	86	35	15	Large	Excavator
7	170	66	35	12	Large	Excavator
8	168	84	56	30	Large	Loader
Mean	171.8	84.2	45.0	23.9		
SD	6.8	23.5	10.8	11.4		
Var	46.0	552.5	117.1	130.7		

**OE #1 is female, all others are male operators; OE #1 & OE #8 did not participate in postural studies.*

Figure 1

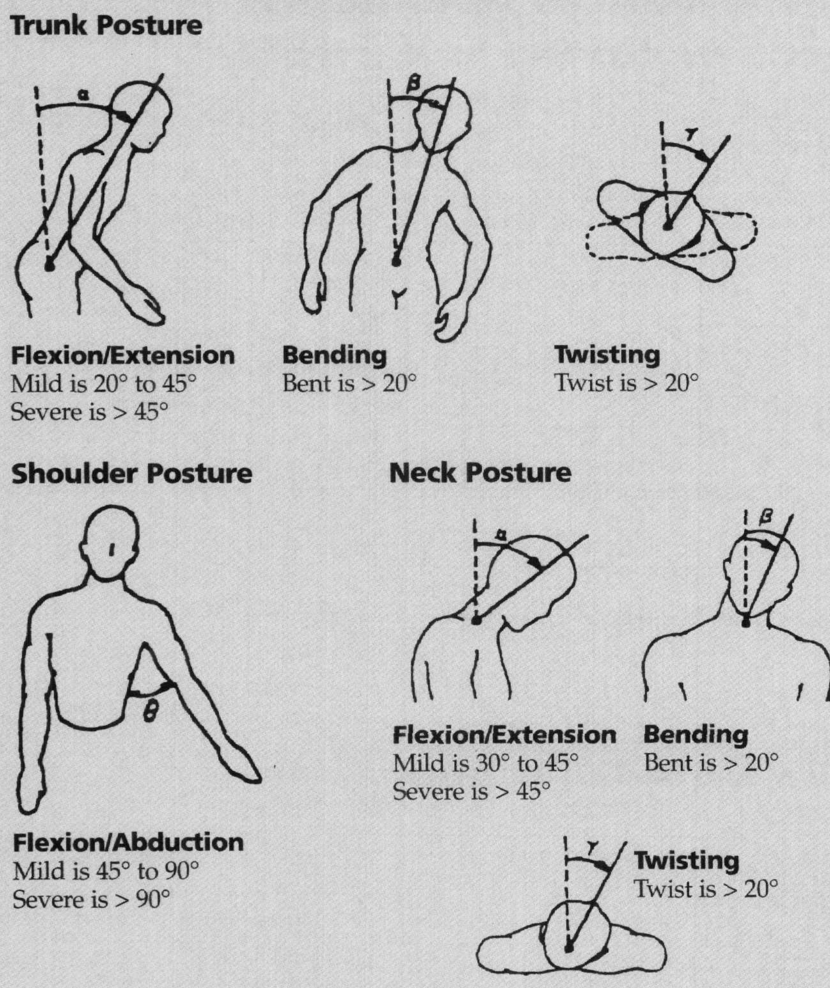
Instrumentation Used for Data Collection



S = seat; F = floor; S & F denote the location of accelerometer.
**Ch1 = Z axis—floor; Ch2 = Y axis—seat; Ch3 = Z axis—seat; Ch4 = X axis—seat*

Figure 2

Standard Postures Used to Classify Trunk, Shoulder & Neck Position



Adapted from Keyserling, 1986.

ed on 50 tasks performed by all operators. Of these, 16 (four low-idling, four high-idling, two chipping concrete, four digging and two driving) were perfomed by small-size equipment; 18 (three low-idling, three high-idling, 10 digging and two spreading rocks) were performed by medium-size equipment; and 16 (three low-idling, three high-idling, eight digging and two loader functions) were performed by large-size equipment. Results were summarized as 1) total vector sum (X, Y and Z axes) at the seat; 2) weighted acceleration in the Z axis at the seat; and 3) nonweighted acceleration in the Z axis at the seat and cab floor. Static tasks were evaluated for a period of two minutes each, while dynamic tasks were evaluated for periods ranging from three to five minutes.

After each task, operators rated their perceived vibration level and discomfort. They were asked to rate the amount of vibration felt from the equipment through the seat and the level of discomfort felt due to this vibration by placing a straight vertical line on a continuous visual analog scale (VAS). The VAS consisted of a four-inch (10 cm) line with word anchors on each extreme (McDowell and Newell). For the vibration discomfort scale, the extremes were "no discomfort" and "intolerable discomfort"; for the vibration level scale, the extremes were "no vibration" and "high vibration." Rating scales were scored for each task by measuring the distance from the left end of the VAS to the operator's vertical line and obtaining a value from 0 to 10.

Perceived ratings were collected from operators who performed 36 different tasks (20 static, 16 dynamic). Of these tasks, 12 (four low-idling, four high-idling, two digging, one driving and one chipping concrete) were performed by small-size equipment; 13 (three low-idling, three high-idling, five digging and two spreading rocks) were performed by medium-size equipment; and 11 (three low-idling, three high-idling, four digging and one loader function) were performed by large-size equipment. The evaluation period for the vibration measurement and the work time considered for the psychophysical ratings were identical. This was done to allow for a more-direct comparison of perceived ratings and quantitative vibration level.

Postural recordings of the operator performing dynamic tasks (i.e., digging-related) were obtained. Then, postural analysis was performed by observing the videotaped job in simulated real-time (Figures 2 and 3). Thirteen tasks were taped and analyzed using the computer-aided system developed by Keyserling (569+). Interobserver variability was eliminated by having an experienced analyst perform all analyses. To avoid the need to observe and analyze multiple joints simultaneously, a tape was played three different times with different joints—such as trunk, left or right shoulder, and neck—studied during each playback. Since it was not possible to videotape both shoulders, at least one shoulder was videotaped for each job. In addition, at least one cycle of each job was recorded; where feasible, additional cycles were taped and analyzed.

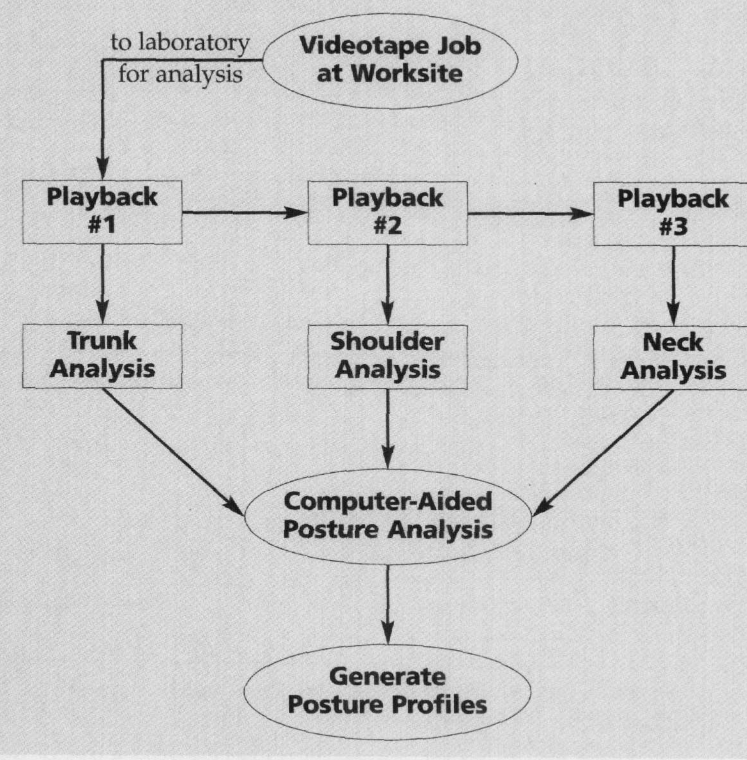
Results & Discussion

Whole-Body Vibration

Examination of the ⅓-octave band values in the range of 1 to 80Hz revealed that all equipment demonstrated a marked increase in amplitude in the critical frequency range for the Z axis (4 to 8 Hz), and for the X and Y axes (1 to 2 Hz) (Figures 4, 5 and 6). When total vector sum accelerations were compared for the different size equipment and tasks, it showed significance for size, tasks and interaction ($p < 0.05$). In addition, the mean values for digging-related tasks were higher than low- or high-idling tasks. The total vector sum value for the digging tasks were always higher than the 0.5 m/s^2 eight-hour action level established by the European Commission (ACGIH 126+). However, total vector sum accelerations for low- or high-

Figure 3

Principal Steps in Evaluating Equipment Operator Posture



idling tasks were consistently lower than the limit set by the European Commission.

A comparison of the total transmissibility ratio was performed for the different size equipment and tasks. The transmissibility of the seating system was not significant for size, tasks and interaction. However, higher transmissibility was noted in the lower frequencies for all tasks (Figure 7).

Psychophysical Rating

Before performing the correlation among the variables, data from similar tasks performed by the same operator and equipment were averaged. This was done to smooth the data so that each operator would have one data point representing each task (e.g., low- and high-idling). Then, quantitative vibrations were logged and compared to the ratings. This was done because visual examination revealed a logarithmic relationship in the way the operators rated the ratings when compared to the quantitative vibration values. Correlation was performed between several factors of concern (e.g., rating of vibration level, rating of vibration discomfort, quantitative vibration-vector sum, quantitative vibration-weighted acceleration in Z axis, and quantitative vibration-nonweighted acceleration in Z axis).

Another correlation was performed that encompassed all tasks observed for this study (static, dynamic and miscellaneous). This analysis revealed 1) a high positive correlation between ratings of vibration level and vibration discomfort ($r=0.70$; $p<0.05$); 2) a moderately high positive correlation between ratings of vibration level and any type of quantitative vibration ($p<0.10$); and 3) a positive association between vibration discomfort and any type of quantitative vibration ($p>0.10$).

A two-way analysis of variance (ANOVA) was conducted using size of equipment (small, medium, large) and task performed (low-idling, high-idling, digging) as the independent variables and rating of vibration level as the dependent variable. A significant main effect was only found for task ($p<0.05$). An examination of the means (0.75 for low-idling, 1.1 for high-idling and 2.26 for digging) revealed that operators performing digging tasks rated higher levels of vibration than other tasks. A post-hoc comparison using Scheffe's test did not find any significant differences between the tasks. However, the largest difference in means were recognized between low-idling tasks and digging tasks and between high-idling tasks and digging tasks.

A two-way ANOVA was conducted using equipment size and task performed as independent variables and rating of vibration discomfort as the dependent variable. A significant main effect was only found for size of equipment ($p<0.05$). Examination of the means for size—0.61 for small, 0.77 for medium, 2.5 for large—indicates that operators using large-size equipment reported higher levels of vibration discomfort. A post-hoc comparison using Scheffe's test found a significant difference between 1) small- and large-size equipment; and 2) medium- and large-size equipment.

High positive correlation was observed between the ratings of vibration level and vibration discomfort. Moderate correlation was evident between the ratings (vibration level or vibration discomfort) and the quantitative vibration. Higher ratings were seen for both dynamic tasks and larger equipment. This can be explained by the inherent nature of the dynamic job and the size of equipment. Larger equipment is involved in more-demanding tasks.

Postural Analysis

The percentage of time an operator assumed a neutral posture was calculated using the computer-aided system. Only dynamic jobs were studied ($n=15$). The percentage of time the back was in a neutral posture ranged from 32 to 100 percent (Figure 8); the shoulder (left or right) from 29 to 99 percent (Figure 9); and the neck from 55 to 97.5 percent (Figure 10).

This showed that operators were required to assume awkward postures in the course of performing their jobs. In general, these postures were notable for the neck, shoulder and back (descending order). Deviation of the back can be explained by the inherent nature of the job—workers must bend over to see the ground that they are digging or moving. Deviation of the shoulder can be explained by the requirements of operating various controls (i.e., levers and gears) located inside the cab. Deviation of the neck was mainly due to the operator maintaining eye contact with the work, which was located at or below ground level.

Conclusion

This study was performed to evaluate ergonomic exposures among operators of heavy construction equipment. Results reveal that operators performing dynamic tasks are exposed to whole-body vibration higher than the allowable limit established by the European Commission. Seats can be improved to attenuate the levels of vibration at the lower frequencies. Job location (at, above or below ground) and operator placement within the cab makes it difficult for him/her to assume a neutral posture while working. This can be addressed by designing cabs that consider both factors. Use of psychophysical ratings to evaluate vibration dis-

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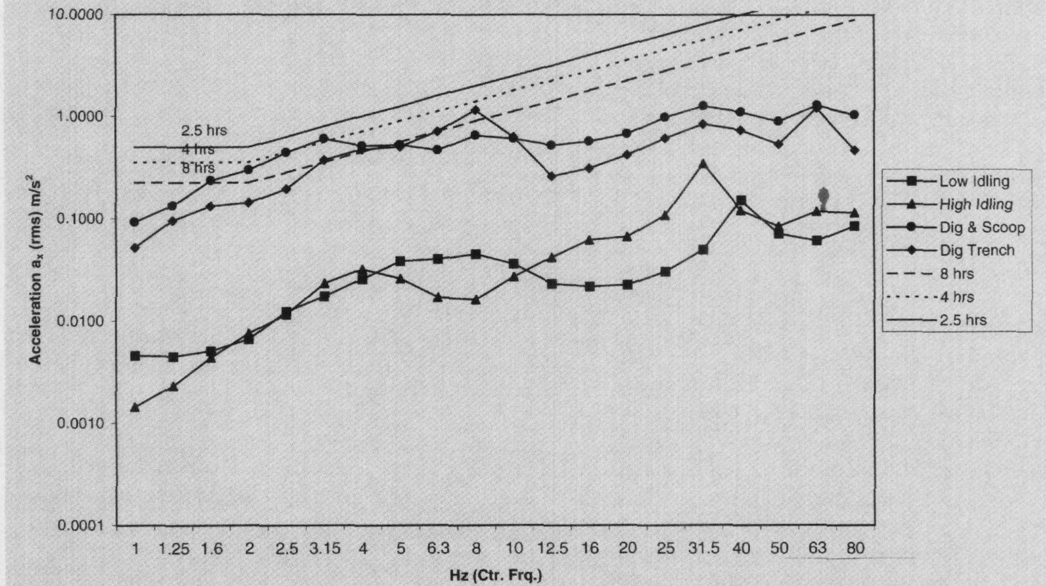
Figure 4

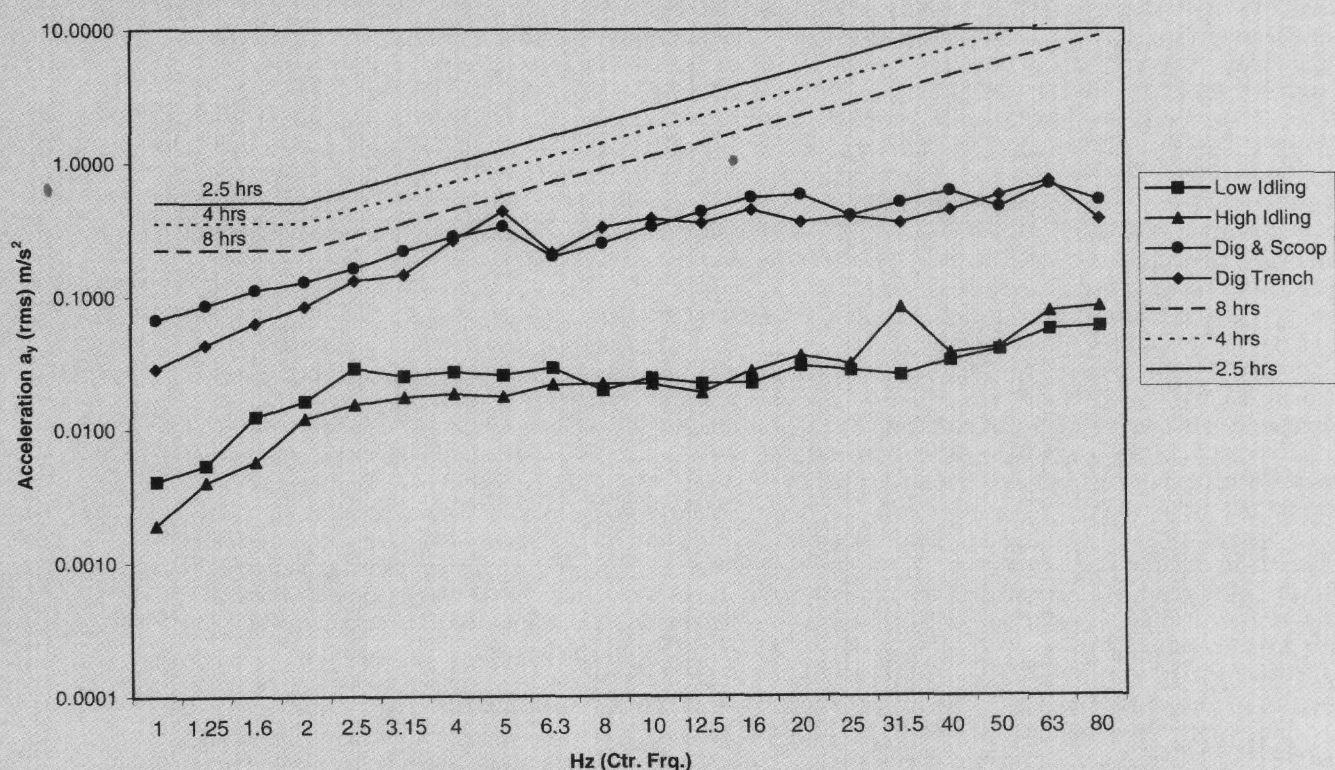
Whole-Body Vibration from Medium-Size Excavator*



**Whole-body vibration from a medium-size excavator (OE #4) in the transverse (X-axis) compared to the ISO/TLV limit.*

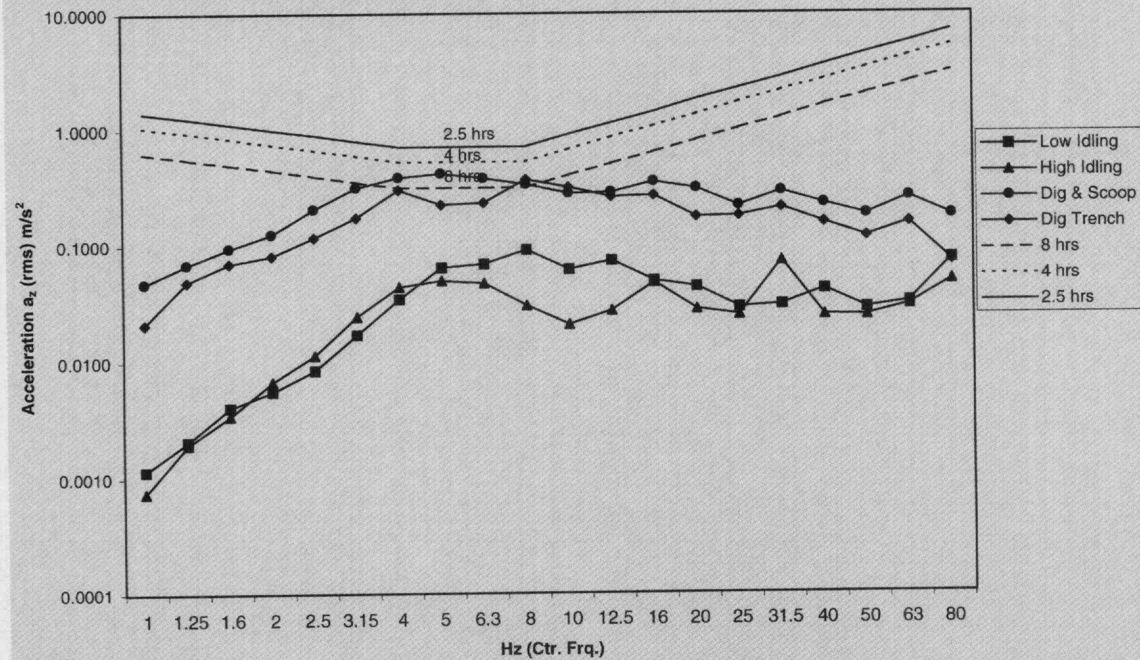
Figure 5

Whole-Body Vibration from Medium-Size Excavator*



**Whole-body vibration from a medium-size excavator (OE #4) in the transverse (Y-axis) compared to the ISO/TLV limit.*

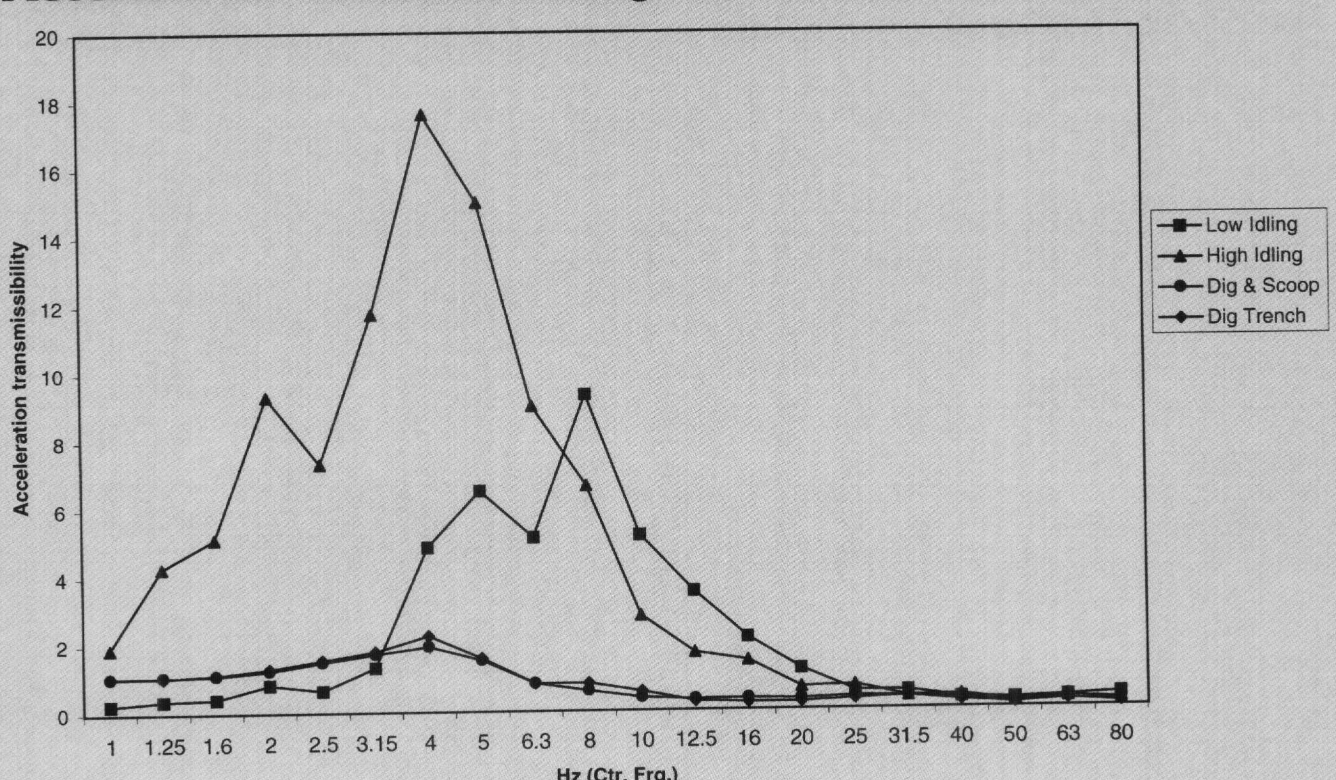
Figure 6
Whole-Body Vibration from Medium-Size Excavator*



*Whole-body vibration from a medium-size excavator (OE #4) in the longitudinal (Z-axis) compared to the ISO/TLV limit.

Studies have shown that MSDs affect construction equipment operators due to tasks that require awkward postures and expose them to whole-body vibration.

Figure 7
Acceleration Transmissibility for Medium-Size Excavator*



*Acceleration transmissibility for a medium size excavator (OE #4) in the longitudinal (Z-axis).

On this site, operators were required to assume awkward postures in the course of performing their jobs. These postures were notable for the neck, shoulder and back.

Figure 8

Percentage of Cycle Back in Neutral Posture for Specific Digging Tasks

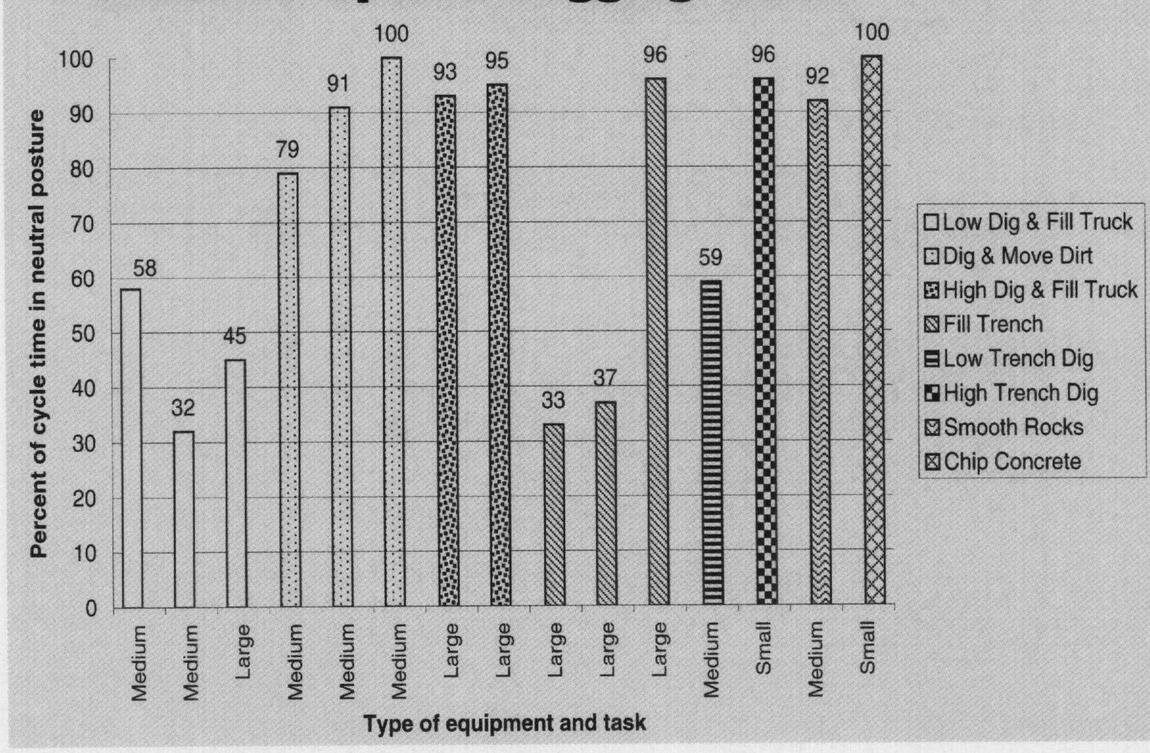
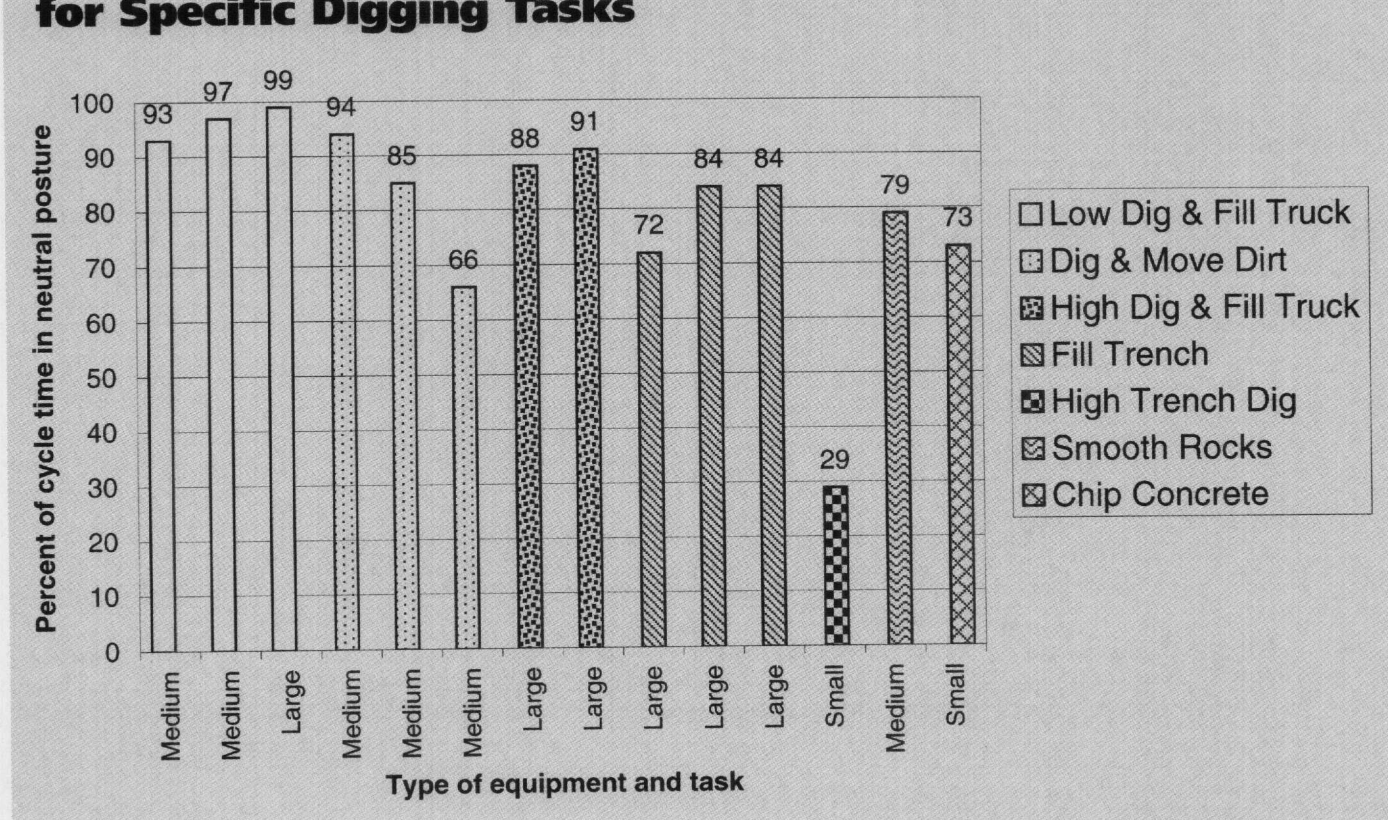


Figure 9

Percentage of Cycle Time Shoulder in Neutral Posture for Specific Digging Tasks



(continued from page 42)

comfort and vibration level appears to be a useful tool for quantifying operator perceptions (Kittusamy and Buchholz). However, more field application of this process is needed to evaluate its full potential.

Recommendations

Engineering controls are the preferred approach as they focus on workstation/job design or redesign to accommodate the operator. When these controls are not feasible or during their implementation, administrative controls may be used to limit exposures.

Whole-Body Vibration

1) Design and select seats based on the transmissibility characteristics and not just on the immediate comfort of the operator.

2) Design and select seats that will adequately dampen vibration at all frequencies, but importantly in the lower frequencies (1 to 8 Hz).

3) Properly maintain equipment to reduce wear and tear that could result in increased vibration.

4) Limit the speed of the equipment when driven, especially over bumpy or irregular surfaces.

5) Workers should not jump off equipment when exiting, since this introduces a shock to the body that has just been vibrated for several hours.

Awkward Posture

1) Redesign cabs to accommodate better upward and/or downward visibility.

2) Have a coworker guide the operator (hand signals) when visibly challenging jobs are performed.

3) Install mirrors to provide better visibility (sideways and below ground). ■

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40	Somewhat
41	No

Acknowledgments

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Figure 10

Percentage of Cycle Neck in Neutral Posture for Specific Digging Tasks