Characterization Of The Health Hazard Associated With Exposure To Repeated Mechanical Shock

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1. INTRODUCTION

Occupational exposure to whole-body vibration (WBV) is associated with an increased incidence of low back pain and degenerative disorders of the spine (Wikström et al., 1994). The International Organization for Standardization (ISO) provides a standard for the measurement and analysis of WBV exposure using frequency weighting and rms averaging (ISO 2631-1, 1997). Occupational WBV exposure often involves repeated mechanical shocks that are not appropriately considered by the rms method. This standard recommends the use of a running rms average to identify the maximum transient vibration value (MTVV) or a fourth power vibration dose value (VDV) to characterize exposure that includes repeated mechanical shocks. However, these methods have been criticized as lacking physiological or biomechanical origin, and no guidance is provided to relate VDV or MTVV with potential health effects.

An alternate approach has been developed based on the concept of a material fatigue process that ultimately results in tissue failure or injury. This approach differs from that of the VDV or MTVV in that exposure is related to the repeated stress levels in the lumbar spine rather than directly to the acceleration response.

Allen (1977) and Payne (1978) explored the use of simple mechanical analogues to predict spinal loading in response to mechanical shocks, and developed the Dynamic Response Index (DRI) to account for the health effects of multiple shocks. The Air Standardization Coordinating Committee (ASCC, 1982) adopted their approach as a standard.

Sandover (1986) hypothesized that dynamic loading of the vertebral end-plates and annulus could lead to material fatigue of these tissues; therefore, the Palmgren-Miner hypothesis could be applied to predict the number of cycles required to generate damage for a known stress level. Combining the approach of Allen, Payne and Sandover allows for the generation of a dose-response model that relates input acceleration at the seat to injury in the spine. The current paper describes an approach that expands on the earlier work of Allen, Payne and Sandover to allow an estimation of health risk from exposure to repeated mechanical shocks. This approach was developed on contract DAMD17-91-C-1115 for the U.S. Army Aeromedical Laboratory, Fort Rucker, Alabama, and is mathematically described in Morrison et al. (1997).

2. OVERVIEW OF APPROACH

Figure 1 provides a schematic overview of the proposed health hazard assessment approach and the flow of data between sequential models that are applied to the seat acceleration to estimate health risk.

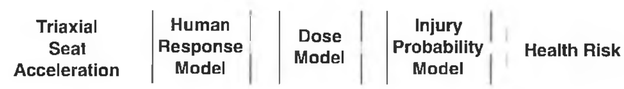

Figure 1. Schematic of proposed health hazard assessment method.

The Human Response Model is comprised of dynamic response models for the x, y and z axes that estimate lumbar spine acceleration from seat acceleration, and regression equations based on biomechanical data that transform the lumbar spine acceleration to compressive force at the L4-L5 intervertebral joint.

The lumbar spine response in the x and y directions was modeled as a second order linear system, similar to the DRI, with a natural frequency of 2.125 Hz and critical damping ratio of 0.22. The response to z-axis shocks was found to be non-linear (Morrison and Robinson, 2001) and a recurrent neural network was used to establish a non-linear difference equation that adequately represented the measured response (Nicol et al., 1997).

Regression equations were derived from a biomechanical model that utilized measurements of spinal posture, acceleration, and internal pressure to estimate the peak compressive and shear forces acting at the L4-L5 lumbar joint and the peak acceleration response in each axis.
The Dose Model is based on the Palmgren-Miner hypothesis that the degree of material fatigue is related to the ratio of the cumulative number of stress cycles to the total number of cycles for failure at that stress level. The Dose Model calculates a sixth power root mean sum of the lumbar compressive forces (or stresses) estimated by the Human Response Model for each shock. The exponent of 6 was selected as a conservative estimate of the rate of fatigue in bone, based on a reported range of 5 to 7.7 (Sandover, 1986). The output of the Dose Model for a series of mechanical shocks is an equivalent static load that can be compared with the ultimate

strength of the L4-L5 joint, as determined by material testing of cadaveric tissue (Hutton and Adams, 1982; Morrison et al., 1997).

The Injury Probability Model relates the equivalent static load (dose) to a probability function that accounts for the population variance in ultimate strength of the L4-L5 joint.

3. DISCUSSION

The proposed approach for characterizing the health hazard associated with exposure to repeated mechanical shocks is theoretically based in that it can be related to known characteristics of the human dynamic response to shocks, the physical properties of tissue at risk of injury, and population variance with respect to those properties.

An advantage of this approach is that it can be used to assess the health hazard of a single exposure to repeated shocks, intermittent exposures over a prolonged period, or a lifetime of daily exposure. Although the model is designed for a male population in the age range of 20 - 40 yr., it can be modified to account for age and gender related changes in the biomechanical properties of tissue. This approach is now being considered by ANSI and ISO working groups as a draft standard for exposure to repeated shocks.

Validation of the proposed approach requires epidemiological data that relate mechanical shock exposure to the incidence of spinal injury. At present, data required to perform this validation is limited, since most studies characterize the rms WBV rather than the occurrence of shocks. However, analysis of the predicted probability of injury has been performed for a variety of simulated shock exposures (Morrison et al., 1999). Exposure to WBV of 0.63 $m \cdot s^{-2}$ rms with 32 shocks of 0.3 g and 0.6 g every 5 minutes results in a probability of injury of 1% after 10 years of daily exposure. Increasing the shock amplitudes to 0.5 g and 1.0 g elevates risk of injury to 11%, while 2.0 g shocks at the same rate (rms =1.6 $m \cdot s^{-2}$) results in an injury risk of 95% after only 1 year. By comparison exposure to steady state WBV of 1.6 $m \cdot s^{-2}$ rms results in an injury risk of 52% after 10 years of daily exposure. This increase in predicted degenerative injury as WBV increases from 0.63 $m \cdot s^{-2}$ to 1.6 $m \cdot s^{-2}$ is consistent with the epidemiological literature for WBV exposure (Wikström et al., 1994). However, the further increase in injury risk due to repeated shocks is not well defined by current assessment measures.

While more complex to implement than the frequency weighting filters and VDV or MTVV of ISO 2631-1 (1997), the current power of computers allows for greater complexity in computational approaches to the analysis of exposure to repeated mechanical shock.

4. REFERENCES

Allen, G. (1977) Human tolerance of repeated shocks. Proceedings of the European Space Agency Life Sciences Research in Space, Germany, pp 343-349.

ASCC (1982) Human tolerance to repeated shock. ASCC Advisory Publication 61/25, Air Standardization Coordinating Committee.

Hutton, W., and Adams, M.A. (1982) Can the lumbar spine be crushed in heavy lifting? Spine Vol 7, No 6, pp 586-590.

ISO 2631-1 (1997) Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1: General Requirements. International Organization for Standardization, Geneva, Switzerland.

Morrison, J. et al. (1997) Development of a standard for the health hazard assessment of mechanical shock and repeated impact in army vehicles – Phase 5. U.S. Army Aeromedical Research Laboratory, Contract No. DAMD17-91-C-1115.

Morrison, J., et al. (1999) A biomechanical approach to evaluating the health effects of repeated mechanical shocks. Models for Aircrew Safety Assessment: Uses, Limitations and Requirements, NATO, RTO-MP-20, pp 24-1 to 24-8.

Nicol, J., et al. (1997) Modelling the dynamic response of the human spine to shock and vibration using a recurrent neural network. Heavy Vehicle Systems, Special Series, International Journal of Vehicle Design, Vol. 4, Nos 2-4, pp. 145-165.

Payne, P. (1978) Method to quantify ride comfort and allowable accelerations. Aviation Space and Environmental Medicine, Vol. 49, pp 262-269.

Sandover, J. (1986) Vehicle vibration and back pain. AGARD conference proceedings No. 378, NATO, pp 13-1 – 13-8.

Wikström, B-O., et al. (1994) Health effects of long-term occupational exposure to whole-body vibration: A review. International Journal of Industrial Ergonomics, Vol. 14, pp 273-292.