BIOMECHANICAL MODELING OF SPINAL LOADING DUE TO JARRING AND JOLTING FOR HEAVY EQUIPMENT OPERATORS

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This paper describes the development of a multi-body biomechanical model that can be used to assess the risk of low back disorders due to occupational exposure to jarring and jolting from operation of heavy mobile equipment (e.g., trucks, haulers, graders, tractors, etc.) The four-element dynamic spinal model is capable of providing estimates of the force and acceleration responses of the head/neck, upper, lower, and middle torso resulting from vibration input collected in field studies. The paper also presents a method for using the model output to assess an individual's risk of low back disorder due to a specific jarring and jolting exposure.

Introduction

In a comprehensive review of the literature relating whole body vibration (WBV) to low back pain (LBP), it was noted that operators of heavy equipment in occupations such as mining, construction and agriculture are repeatedly exposed to high levels of transient jarring and jolting, as well as steady state WBV (Bovenzi and Hulshof, 1998). It has been shown experimentally that repeated exposure to WBV and jarring and jolting is associated with an increased risk of developing low back disorders (LBDs). Researchers have suggested that high levels of mechanical loading to the spine due to WBV and transient jarring and jolting may cause micro-fractures of the lumbar vertebral endplates or transient pressure changes that over time may result in adverse health effects arising from material fatigue processes. Due to limitations in existing biomechanical models of spinal loading, however, it has been difficult to accurately predict the health effects to the spine associated with exposure to mechanical shock.

Noteworthy attempts to develop biodynamic models to study human response to WBV have been reported by Matsumoto and Griffin, 1998; Pankoke, Buck, and Woelfel, 1998; Amirouche and Ider, 1988; and Kitazaki and Griffin, 1997. The majority of these efforts used finite element (FE) models as opposed to finite-segment (multibody) dynamic models. Recently, however, there have been significant advances in whole-body modeling that are directly applicable to the study of human exposure to WBV and jarring and jolting. These advances are based upon modeling the human body as a multi-body system rather than a finite-element model. The principal advantage of multi-body modeling (sometimes called "lumped-parameter" modeling) is that it can simulate large-scale dynamics, which can then be used with finite element models or injury models to evaluate stresses and predict tissue damage. As with finite element models, a multi-body model can employ as many bodies as needed to study a given phenomena.

Biomechanical Model

In order to estimate the loading on the spine due to jarring and jolting, we developed a specialized multi-body biomechanical model of the human skeletal system. The jarring and jolting model is derived from a general multi-body dynamics computer simulator, called DYNOCOMBS, developed by Huston et al. 1990, 1991. The general model represents the human body by a series of connected elements simulating the limbs, torso, head and neck. Computer algorithms have been developed using 3 dimensional multi-body dynamic computer modeling to provide a dynamic analysis (kinematics and kinetics) of arbitrary collections of elements allowing for both translation and rotation between adjacent elements. These elements are connected by spring and damper elements to simulate the response of soft tissues connecting the arms, head, neck, trunk and legs. By applying equations of dynamic equilibrium to the elements of the simulation model, the model is capable of estimating the kinetic joint reaction forces and kinematic spinal responses resulting from the dynamic exposures. Figure 1 shows the configuration of a whole human body model of the heavy equipment operator at a workstation. It consists of 17 rigid bodies as illustrated, representing the lower torso, back, upper torso, head, neck, and upper arms, lower arms, hands and upper legs, lower legs and feet. The springs and dampers are placed between each adjacent body. Each body has 6 degrees of freedom.

For modeling jarring and jolting exposure, the general DYNACOMBS model was adjusted by combining elements into a simpler 4-body spinal model shown in Figure 2. In this configuration, the four elements consist of the lower torso (pelvis), the middle torso (back), upper torso (chest) and the head/neck (head and neck are combined in this model configuration).

A 4-body spinal model is more efficient than a 17 segment model for obtaining gross-motion simulation, without sacrificing accuracy. The mass and geometric

properties of the 4-body spinal system are based on the general whole body model's published anatomical data.

Other mechanical parameters are determined by comparing model responses to published experimental data. Results from the new 4-body model can be used to estimate risk of low back disorder due to jarring and jolting exposure.
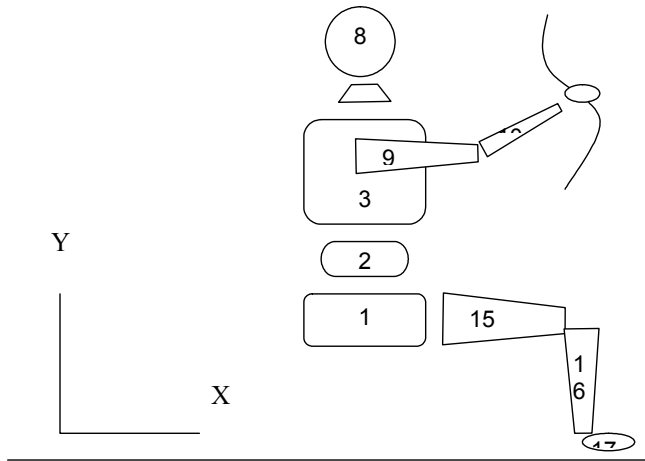

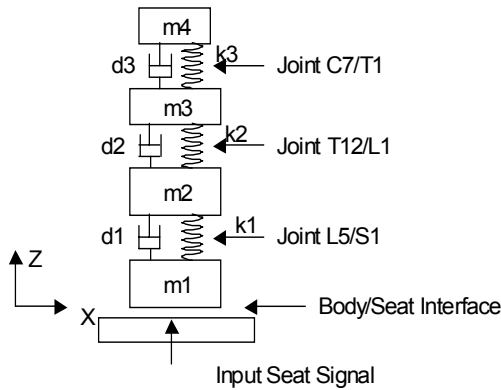Figure 1. DYNACOMBS Multi-body lumped parameter model.

Figure 2. New 4-body model of spine/neck, and head.

The USAF has published some values for the spring and damping parameters for specific lumped parameter models (USAF, 1970), but special algorithms were developed for calculating these variables for the proposed model. Due to space limitations, it is not possible to provide details of the algorithm development, however, they were based a series of linearization, scaling, and modal parameter analyses.

Given suitable initial conditions and input seat accelerations profiles, the DYNOCOMBS model solves the governing dynamic equations by using a fourth-order Runge-Kutta integrator. The output then presents the kinematics and kinetics results of the system. For each body of the spinal system DYNOCOMBS computes the displacement, rotation angle, velocity and angular velocity, acceleration and angular acceleration as well as mass center positions, and internal force and moment.

Estimating Risk of LBDs

Based on the output of the jarring and jolting model, spinal health effects can be estimated in two ways. First, potential tissue damage can be estimated by comparing the predicted spinal forces directly to assumed spinal tissue tolerance limits. Second, the model output can be used to calculate the ISO 2631-5 exposure limit values (i.e, Part 5: Method for evaluation of vibration containing multiple shocks). These exposure limit values include the Daily Equivalent Static Compression Stress (S_{ed}) and the Cumulative Adverse Health Effects Factor (R). These measures provide an estimate of the daily and cumulative exposure limit for exposure to jarring and jolting.

In order to evaluate the effects of internal pressure changes, the Palmgren-Miner fatigue approach is applied. Essential exposure-related factors are the number and magnitudes of the peak compression in the spine. The peak compression in the spine is affected by anthropometrics data (body mass, size of endplates) and posture. The assessment is based on the person subjected to the vibration in a seated upright posture.

The procedures for determining the spinal response to an acceleration dose and subsequent risk assessment requires the following steps:
(1) Obtain experimental seat accelerations in the field
(2) Use DYNOCOMBS to calculate the spine accelerations
(3) Use custom software to identify and count peak values
(4) Calculate the acceleration dose (D_k) from Equation 1 below.

$$D_k = \left[\sum_i A_{ik}^6 \right]^{1/6} \quad \text{(Equation 1)}$$

where A_{ik} is the ith peak of the response acceleration, and k is the direction.
(5) Calculate average daily dose by normalizing the acceleration dose as shown in Equation 2 below.

$$D_{kd} = D_k \left[\frac{t_d}{t_m} \right]^{1/6} \quad (m/s^2), \quad \text{(Equation 2)}$$

where t_d is the duration of the daily exposure, and t_m is the period over which D_k has been measured.
(6) Calculate the daily equivalent static compression dose using Equation 3 below.

$$S_{ed} = \left[\sum_{k=x,y,z} (m_k D_{kd})^6 \right]^{1/6} \quad (Mpa), \quad \text{Equation (3)}$$

where

$$m_x = 0.015 Mpa/(m/s^2)$$
$$m_y = 0.035 Mpa/(m/s^2)$$
$$m_z = 0.032 Mpa/(m/s^2)$$

If S_{ed} is below $0.5Mpa$, then the probability of an adverse health effect at lifetime exposure is low. If S_{ed} is above $0.8Mpa$, then probability of an adverse health effect at lifetime exposure is high.

(7) Calculate the cumulative adverse health effects factor (R) using Equation 4 below.

$$R = \left[\sum_{i=1}^{n} \left(\frac{S_{ed} \cdot days^{1/6}}{S_{ui} - c} \right)^6 \right]^{1/6}$$ Equation (4)

where: *days* is the number of exposure days per year (typically, *days*=240 days/year), *n* is the number of years of exposure, *c* is a constant representing the static stress due to gravitational force (a value of $c = 0.25Mpa$ is normally used for driving posture) and $S_{ui} = 6.75 - 0.066(b+i)Mpa$, S_{ui} is the ultimate strength of the lumbar spine for a person of age $(b+i)\,years$ with b being the age at which the exposure starts. Since the value S_{ui} varies with the bone density of the vertebrae, it is normally reduced with age. When $R < 0.8$, then probability of an adverse health effect is considered to be low. When $R > 1.2$, then the probability of an adverse health effect is considered to be high.

Example Output

Figure 3a depicts the graph of the force estimated at the seat for a typical 2 second sample of data for a fork-truck driver over smooth pavement and Figure 3b depicts the graph of the L5/S1 spinal force for the same exposure event.

Figure 4a depicts a plot of the cumulative adverse health effects factor (R) for a low risk jarring and jolting exposure obtained in a field study and Figure 4b depicts and a plot of the cumulative adverse health effects factor (R) for a high risk jarring and jolting exposure obtained in a field study.
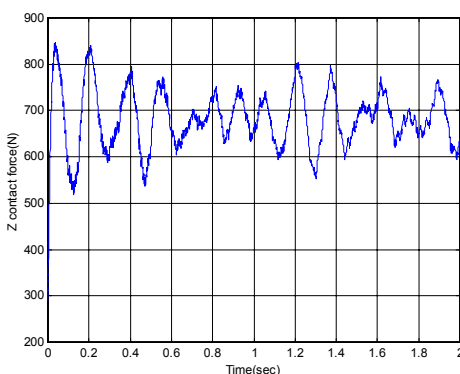

Figure 3a. Contact force between buttocks and seat surface, both static and dynamic components, 75% male, sitting upright, no backrest.
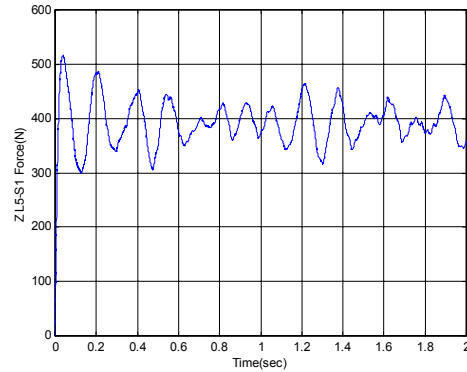

Figure 3b. Compression force between L5 and S1, both static and dynamic components, 75% male, sitting upright, no backrest.
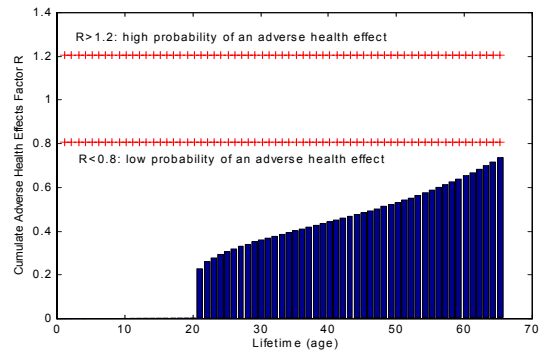

Figure 4a. Cumulative adverse health effects factor (R) for a low risk jarring and jolting exposure.
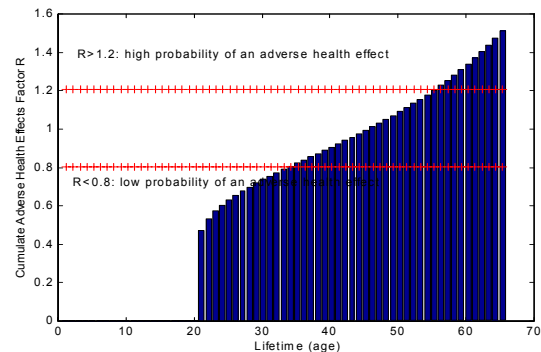

Figure 4b. Cumulative adverse health effects factor (R) for a high risk jarring and jolting exposure.

Model Validation

Validation and tuning of the model will be accomplished by comparing actual acceleration values collected from the head of an operator driving a vehicle over a rough road to the predicted head accelerations obtained from the model using the seat acceleration data from the vehicle as input. Correlation coefficients for peak accelerations will be compared, as well as temporal shifts in spinal response acceleration peaks to insure that the model is behaving properly.

Conclusions

Based upon our preliminary analysis, the model appears to adequately respond to acceleration inputs from the seat, however, further validation testing is needed to determine its ultimate accuracy. Used of the model in conjunction with the ISO method appears to provide a meaningful way of evaluating the potential health impacts of jarring and jolting exposure on the health of the low back, but it remains to be tested in an epidemiological study. Finally, it is likely that the proposed model and evaluation methods will provide a satisfactory way of evaluating the effectiveness of various interventions, such as new seat designs and new material properties that can be used to reduce exposure to levels that will be considered safe for nearly all heavy equipment operators.

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