



Predictive equations for lumbar spine loads in load-dependent asymmetric one- and two-handed lifting activities

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ABSTRACT

Background: Asymmetric lifting activities are associated with low back pain.

Methods: A finite element biomechanical model is used to estimate spinal loads during one- and two-handed asymmetric static lifting activities. Model input variables are thorax flexion angle, load magnitude as well as load sagittal and lateral positions while response variables are L4–L5 and L5–S1 disc compression and shear forces. A number of levels are considered for each input variable and all their possible combinations are introduced into the model. Robust yet user-friendly predictive equations that relate model responses to its inputs are established.

Findings: Predictive equations with adequate goodness-of-fit (R^2 ranged from ~94% to 99%, $P \leq 0.001$) that relate spinal loads to task (input) variables are established. Contour plots are used to identify combinations of task variable levels that yield spine loads beyond the recommended limits. The effect of uncertainties in the measurements of asymmetry-related inputs on spinal loads is studied.

Interpretation: A number of issues regarding the NIOSH asymmetry multiplier are discussed and it is concluded that this multiplier should depend on the trunk posture and be defined in terms of the load vertical and horizontal positions. Due to an imprecise adjustment of the handled load magnitude this multiplier inadequately controls the biomechanical loading of the spine. Ergonomists and bioengineers, faced with the dilemma of using either complex but more accurate models on one hand or less accurate but simple models on the other hand, have hereby easy-to-use predictive equations that quantify spinal loads under various occupational tasks.

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1. Introduction

Epidemiological studies have associated asymmetric lifting activities with low back pain (Hoogendoorn et al., 2000). *In vivo* studies show that asymmetric conditions increase paraspinal muscle electromyographic (EMG) activities (McGill, 1991) and lumbar intradiscal pressure (Wilke et al., 2001). In line with these findings, biomechanical model investigations indicate increased spinal loads due to the asymmetry in lifting (Arjmand et al., 2010; Bean et al., 1988; Granata and Marras, 1993). Given the recognized elevated risk in asymmetric lifting, the National Institute for Occupational Safety and Health (NIOSH) introduced a multiplier in their Revised Lifting Equation (Waters et al., 1993) in which the allowable handled weight is reduced by ~10% for every 30° of load asymmetry in the horizontal plane with respect to the body's mid-sagittal plane.

The asymmetry multiplier in the Revised NIOSH Lifting Equation is not, however, established based on a biomechanical modeling study.

It is derived from few psychophysical investigations (e.g., Garg and Badger, 1986; Mital and Fard, 1986) which are in turn based on subjective individual perceptions/judgments of tolerance levels. Assumptions and simplifications employed in biomechanical models directly influence the accuracy of estimations and, hence, their suitability for ergonomic and biomechanical applications. For example, as an important shortcoming, model studies often estimate muscle forces and spinal loads based on the balance of net moments at a single joint; a simplification that results in violation of equilibrium at remaining levels (Arjmand et al., 2007).

Similarly, many previous computational tools that estimate spinal loads during asymmetric lifting activities have been based on simplified models; e.g., the University of Michigan's 3D Static Strength Prediction Program™ (3DSSPP) model (University of Michigan Center for Ergonomics, 2001), McGill's polynomial equation of low back compression (McGill et al., 1996), and the regression models of Fathallah and co-workers (Fathallah et al., 1999) (see Arjmand et al. (2011) for a critical review of these models). EMG-assisted modeling approach is also used to estimate trunk muscle forces during asymmetric tasks (Granata and Marras, 1993; Marras and Davis, 1998; McGill, 1991); an approach which

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due to the required input data and applied methodology, is cumbersome or even impractical for common ergonomic applications. For an effective management of risk of injury and design of safer workplaces, hence, both ease-of-use and accuracy of biomechanical models are to be considered.

For more accurate predictions, the existing kinematics-driven finite element approach accounts for passive-active trunk systems while satisfying equilibrium at different levels (Arjmand and Shirazi-Adl, 2006a; Bazrgari et al., 2008). Complex anatomy of muscles, accurate simulation of wrapping of thoracic muscles, nonlinear material properties of the thoracolumbar motion segments in different directions, and gravity distribution along the entire length of the spine are incorporated. The biomechanical fidelity of the model, however, has made it too complex and time-consuming for routine use in practical applications.

In continuation of our earlier work on symmetric lifting activities (Arjmand et al., 2011), the present study aims to employ the Response Surface Methodology (RSM) (Montgomery, 2000) to establish robust and user-friendly predictive equations that relate response (i.e., spinal loads at the L4–L5 and L5–S1 levels) of the complex kinematics-driven model to its task-related input variables (i.e., load and posture characteristics) during one- and two-handed asymmetric lifting activities. These predictive equations can serve ergonomists in the estimation of spinal loads and design of workplaces, practitioners in management of low back disorders, and biomechanical engineers in prediction of tissue stresses/strains and design of implants.

2. Methods

2.1. Input (task) and output (response) variables

Asymmetric loading of upper trunk is described by three independent input variables; mass (M) of the handled object and its anterior (Dx) and right lateral (Dy) distances with respect to the middle of the shoulder joints under lifting posture. In general for a given asymmetric lifting task, the three dimensional position of the trunk is not usually independent of the position of handled load and, hence, a posture prediction algorithm maybe required. Similar to the work of Bean et al. (1988) in the current study only load asymmetry is considered assuming that the lifting tasks are performed without trunk out-of-sagittal plane movements. Trunk position is thus governed by its (T1–T12) sagittal angle (T) with respect to the neutral upright posture. For a given trunk flexion angle (T), the accompanied pelvis rotation (P) is determined based on available *in vivo* data on the T – P rhythm in flexion (Arjmand et al., 2011) while the total lumbar flexion (L) can, subsequently, be calculated as $L = T - P$.

Since regression-fitted equations produce maximal errors at the border of regions of input variables (i.e., $T = 0$ that corresponds to the neutral upright posture) (Arjmand et al., 2011), separate predictive equations are developed for lifting activities in the upright posture. Moreover in the upright posture, the lumbar lordosis likely varies as a function of load in hands (Arjmand et al., 2009, 2011; Wilke et al., 2001). For lifting activities in upright postures, therefore, while only three independent loading variables (M , Dx , and Dy) are considered, the lumbar lordosis is linearly increased (by up to 15° with respect to that in the relaxed upright posture) as a function of the load in hands (M) (Arjmand et al., 2009). Output variables predicted by the model are taken as axial compression (C) and posterior–anterior shear (S) forces at both the L4–L5 and L5–S1 disc mid-heights in their respective local directions.

2.2. Regression procedure

Response Surface Methodology is used to empirically relate output (response) variables (Y) to input variables (T , M , Dx and Dy)

through regression on predictions (Montgomery, 2000). A full quadratic regression model is considered:

$$Y = b_0 + b_1T + b_2M + b_3Dx + b_4Dy + b_5T^2 + b_6M^2 + b_7(Dx)^2 + b_8(Dy)^2 + b_9T \times M + b_{10}T \times Dx + b_{11}T \times Dy + b_{12}M \times Dx + b_{13}M \times Dy + b_{14}Dx \times Dy \quad (1)$$

where b_0 to b_{14} are regression coefficients estimated through design of experiments (DOE) as explained below. T , M , Dx and Dy are in degree, kg, cm and cm, respectively and the spine loads are calculated in N. As for the tasks in upright posture for which only three input variables (M , Dx and Dy) are incorporated the regression models take the following form:

$$Y = b_0 + b_2M + b_3Dx + b_4Dy + b_6M^2 + b_7(Dx)^2 + b_8(Dy)^2 + b_{12}M \times Dx + b_{13}M \times Dy + b_{14}Dx \times Dy \quad (2)$$

A number of levels for each input variable over its region of interest are taken. For one-handed lifting activities, 11, 5, and 47 levels are considered for T (10, 20, 30, 40, 50, 60, 70, 80, 90, 100, and 110° associated with 3, 7, 9, 12, 14, 17, 22, 28, 35, 41, and 47° of pelvis rotation with respect to the neutral upright posture, respectively), M (0, 5, 10, 15, and 20 kg), and position of load (combinations of Dx and Dy within the reach distance), respectively (Fig. 1a). The analysis of all possible combinations of input variable levels (full factorial DOE) requires a total of $11 \times 5 \times 47 = 2585$ analyses. Each combination of input variable levels is inputted into the model (described below) and the corresponding outputs are predicted. For one-handed lifting tasks in the upright postures, the same 5 levels for M and 47 levels for position of load are considered yielding a total of 235 analyses. Likewise, for two-handed lifting tasks 49 positions of load (Fig. 1b) are considered yielding 2695 and 245 analyses for lifting activities in flexed and upright postures, respectively.

A total of 5760 ($2585 + 235 + 2695 + 245$) values for each output variable are predicted by the kinematics-driven finite element model and are subsequently used to evaluate the coefficients b_0 to b_{14} through regression on predictions. The adequacy of the regression models is verified by assessment of the model significance ($P < 0.05$), coefficient of determination (R^2), adjusted R^2 , and root-mean-squared-error (RMSE) values. ANOVA analyses ($P < 0.05$) are performed to investigate the significance of each of the regression coefficients in the polynomial equations. All regression analyses are carried out using the MINITAB® Statistical Software (Minitab Inc, PA, USA).

2.3. Kinematics-driven model

A nonlinear finite element (FE) model (ABAQUS, Simulia Inc., Providence, RI) of the thoracolumbar spine along with the kinematics-driven algorithm is employed to predict spine loads for each combination of input variable levels (Fig. 2). The model consists of 6 deformable beams (T12–S1 levels) with nonlinear properties (Shirazi-Adl, 2006). The upper body weight is distributed and applied eccentrically at different vertebral joints (Pearsall et al., 1996) resulting in a total load of 344.4 N for the upper trunk, head, and arms. The weights of upper arms (35.6 N), forearms/hands (29.3 N) and head (46 N) are estimated based on available anthropometric data (de Leva, 1996). Gravity loading and geometry of the model are individualized for a healthy male (52 years, 174.5 cm, and 68.4 kg) (Arjmand et al., 2009, 2010).

A sagittally-symmetric muscle architecture with 46 local (attached to lumbar vertebrae) and 30 global (attached to thoracic cage) muscle fascicles is considered (Stokes and Gardner-Morse, 1999) (Fig. 2). To simulate curved paths of global extensor muscles (ICPT and LGPT), they are restrained to wrap around vertebrae in between their insertion points (Arjmand et al., 2006). Abdominal

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