Regression Equations for Spinal Loads in Asymmetric Lifting Tasks Using a Finite Element Biomechanical Model

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INTRODUCTION:

Accurate estimation of spinal loads in recreational and occupational activities of daily living is essential for clinical and ergonomics applications. Towards this goal, the crucial role of biomechanical models of the human trunk is recognized as direct *in vivo* measurements remain invasive, costly and limited. While deterministic trunk models assuming single equivalent flexor/extensor moment generators are simple but inaccurate, rigorous detailed models are more reliable but too complex and time-consuming for routine use in the industry/practical applications. Besides, existing models often estimate muscle forces/spinal loads based on the balance of net moments only at one lumbar level; a simplification that violates equilibrium at the remaining levels [1]. The present study aims to establish, for the first time, robust/user-friendly predictive equations that relate response variables (spinal compression and shear forces at the L4-S1 levels) to input variables (load and posture) during one- and two-handed asymmetric lifting tasks. To generate the required data for the full factorial design of experiments, the finite element (FE) kinematics-driven approach [1] that satisfies equilibrium at all spinal levels is employed.

METHODS:

Asymmetric loading of the upper trunk is described by three independent input variables; mass (M) of the object carried and its anterior-posterior (Dx) and lateral (Dy) distances with respect to the middle of shoulder joints. Similar to an earlier work [2], asymmetry in the current study is limited and due only to the load positioning and not the posture; lifting tasks are performed with minimal 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 [1] while the total lumbar rotation (L) is calculated as $L = T - P$. Four dependent model output responses (disc compression C and anterior-posterior shear S forces at both L4-L5 and L5-S1 levels) are considered. A number of levels for each input variable over its physiologically relevant range of interest is selected; $T = 10°$ to $110°$ at $10°$ intervals, $M = 0$ to 20 kg at 5 kg intervals, and 47 load positions (combinations of Dx and Dy within the reach distance, $0 \le Dx \le 64$cm, $0 \le Dy \le 84$cm) for one-handed and 49 load positions ($0 \le Dx \le 60$cm, $0 \le Dy \le 84$cm) for two-handed lifting activities (Fig. 1). To improve accuracy, equations for the lifting tasks in the upright posture are developed separately employing similar levels for M, Dx and Dy. All possible combinations of input variable levels (full factorial design of experiment) within a full quadratic regression model are considered; $Y = f\,(T, M, Dx, Dy, T^2, M^2, (Dx)^2, (Dy)^2, T \times M, T \times Dx, T \times Dy, M \times Dx, M \times Dy, Dx \times Dy)$. Output variables Y are computed for each combination of input variable levels (total of 5760 combinations) by regression on model predictions.

For each set of input variables (T, M, Dx, Dy), external loads and upper body masses are applied onto the nonlinear FE model of the trunk [1] that accounts for nonlinear passive properties of the ligamentous spine and musculature as well as wrapping of global extensor muscles. Gravity loading and geometry of the model are individualized for a healthy male (52 years, 174.5 cm, and 68.4 kg). The weights of upper arms and forearms/hands are positioned at the midway between the center of mass M in hands and the corresponding shoulder joint (for one-handed lifting the opposite hand remains in the gravity direction).

RESULTS:

Regression equations for the spinal loads (compression and shear forces) at two disc levels (L4-L5 and L5-S1) and two postures (flexed and upright) yielded $R^2 > 97\%$, small root-mean-squared-errors (*RMSE* < 189 N for flexed and <99 N for upright posture), and $p < 0.001$ in all regression models (e.g., $C_{L4\text{-}L5} = 41.2 + 47.2\,T + 7.3\,M - 0.64\,Dx + 2.4\,Dy - 0.29\,T^2 + 0.69\,M^2 + 0.03\,(Dx)^2 + 0.04\,(Dy)^2 + 0.50\,T \times M + 0.05\,T \times Dx - 0.07\,T \times Dy + 2.2\,M \times Dx + 1.2\,M \times Dy - 0.04\,Dx \times Dy$ for one-handed lifting in flexed postures and $C_{L4\text{-}L5} = 286.1 + 12.0\,M - 1.0\,Dx + 32.1\,Dy - 0.17\,M^2 + 0.17\,(Dx)^2 - 0.30\,(Dy)^2 + 1.4\,M \times Dx + 0.90\,M \times Dy - 0.40\,Dx \times Dy$ for two-handed lifting in upright posture). For all the simulated tasks in the flexed and upright postures the ANOVA analyses showed that most of linear, interaction, and quadratic effects were significant ($p<0.05$). Peak compression and shear forces of 6000 N and 1811 N were computed at the L5-S1 level, respectively. Based on the regression equations, contour plots can be constructed (Fig. 2) to identify unsafe combination of input levels that yield spinal loads beyond the tolerance levels (for example, ~3400 N compression limit set for the young healthy workers by NIOSH [3]).

DISCUSSION:

Sixteen (one-/two-handed styles, L4-L5/L5-S1 levels, compression/ shear forces, and flexed/upright postures) simple regression equations between output and input variables are developed based on the multiple analyses of a complex nonlinear trunk FE model. Full quadratic regression model with coupled terms results in excellent quality-of-fit. The estimated intradiscal pressure at the L4-L5 disc (1.1 MPa) for side-lifting of a 19.8 kg object is in close agreement with available *in vivo* data (1 MPa) measured under similar loading and posture [4]. Previous models estimating spinal loads in asymmetric lifting are based either on simplified and thus inaccurate or on complex (e.g., EMG-assisted) approaches that are cumbersome for common ergonomic applications. Apart from the biomechanical fidelity of the model, an important advantage of the current study is that the variables defining load asymmetry (i.e., T, M, Dx and Dy) are easy to measure or estimate in the workplace. In contrast, the NIOSH asymmetry multiplier [3] is difficult to calculate in applied settings due to the required measurement of the angle of load asymmetry. Unsafe load handling conditions that yield spine loads at and beyond the tolerance compression limit (3400 N) can be identified using contour plots (Fig. 2). Alternatively, such contour plots may be used to investigate the effect of uncertainties in the measurements of an input variable (e.g., load asymmetry angle in NIOSH approach) on the model response (i.e., sensitivity analyses).

SIGNIFICANCE:

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, can use such novel predictive equations to quantify spine loads and risk of injury in different activities.

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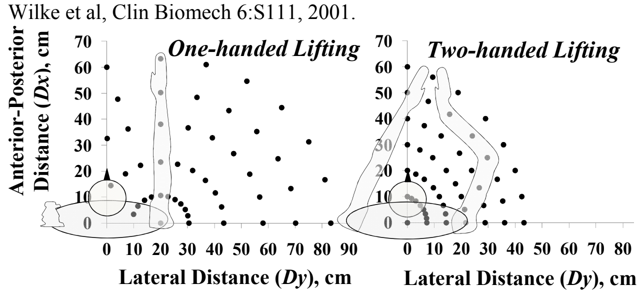

Fig 1. Positions of load considered in the design of experiments

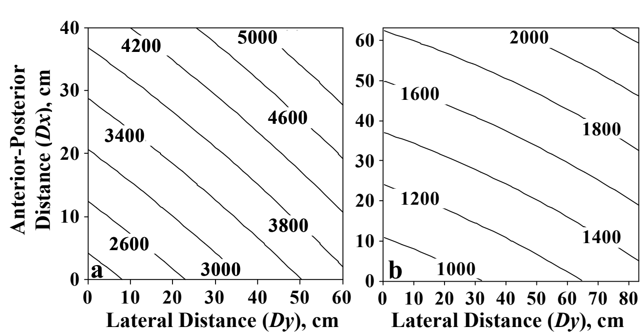

Fig 2. Contour plots of the L5-S1; **a)** compression force taking $T = 30°$ and $M = 20$ kg (one-handed) fixed, **b)** shear force taking $T = 70°$ and $M = 15$ kg (one-handed) fixed while varying load positions.