Predictive Equations for Spinal Loads in Symmetric Lifting Using a Complex Biomechanical Model

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INTRODUCTION

Accurate estimation of spinal loads in recreational and occupational activities of daily living is essential for the effective rehabilitation, treatment, and performance enhancement programs as well as the design of safer workplace and occupational tasks. 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 models assuming single equivalent flexor/extensor moment generators are simple but inaccurate, rigorous detailed models are much more reliable but too complex and time-consuming for use in the industry and practical applications. Present study aims to establish robust and user-friendly predictive regression equations that relate dependent response variables (spinal compression and shear forces at the L4-L5 and L5-S1 levels) to independent task-related input variables (load and posture characteristics) during sagittal static lifting activities. To generate the required data for the full factorial design of experiments, the complex finite element kinematics-driven approach [1] is employed.

METHOD

In the predictive equations and in order to simulate a wide range of lifting activities, four independent input variables (thorax flexion angle with respect to the upright posture ***T*** in deg, lumbar/pelvis rotation ratio ***L/P*** where *T*=*P*+*L*, weight lifted ***M*** *in kg*, and horizontal distance of the center of the mass held in hands with respect to the shoulder joint ***D*** in cm) and four dependent model output responses (disc compression **C** and anterior-posterior shear **S** forces in N at both L4-L5 and L5-S1 levels) are considered. A number of levels for each input variable over its physiologically relevant region of interest is selected; *T* = 10° to 110° at 10° intervals, *L/P* = 0.5 to 3 at 0.25 intervals, *M* = 0 to 20 kg at 2.5 kg intervals, and *D* = 0 to 30 cm at 10 cm intervals). To improve accuracy, equations for the lifting tasks in the upright posture are developed separately from foregoing ones in the forward flexion employing 9 levels for *M* (0 to 20 kg) and 5 levels for *D* (20 to 60 cm). All combinations of input variable levels (full factorial design of experiment) within a full quadratic regression model are considered; $Y = f(T, M, L/P, D, T^2, M^2, (L/P)^2, D^2, T \times M, T \times L/P, T \times D, M \times L/P, M \times D, D \times L/P)$. Output variables *Y* are computed for each combination of input variables. A total of 4401 combinations (4356 runs for the forward flexion and 45 runs for the upright lifting) was analyzed using the rigorous iterative finite element Kinematics-driven model [1] resulting in the determination of the function f by regression on predictions.

For each set of input variables, the corresponding sagittal thorax T and pelvis *P* rotations along with external loading (*M* applied at *D* position) and upper body mass distribution are applied onto the nonlinear finite element model of the thoracolumbar spine [1] that accounts for nonlinear passive properties of the ligamentous spine and musculature. Gravity loading and geometry of the model are individualized for a healthy male (52 years, 174.5 cm, and 68.4 kg) who participated in prior in vivo phase of this study. In the model and under prescribed rotations, the net moment is estimated iteratively at each spinal level and used along with an optimization method (min $\sum\sigma^3$) to resolve the redundancy at the corresponding level. Calculated muscle forces are fed back as updated loads onto the model at the level to which they are attached and iteration is repeated till convergence is reached.

RESULTS

Predictive equations for the spinal compression and shear forces at two disc levels (L4-L5 and L5-S1) and two postures (flexed and upright) yielded $R^2 > 99.4\%$, root-mean-squared-errors *RMSE* < 88 N, and $p < 0.0001$ in all regression models (e.g., $C_{L4\text{-}L5} = -29.0 + 54.9\,T + 19.6\,M - 141.0\,L/P + 9.6\,D - 0.32\,T^2 + 0.26\,M^2 + 38.2\,(L/P)^2 + 0.03\,D^2 + 0.67\,T \times M - 0.65\,T \times L/P - 0.06\,T \times D - 3.4\,M \times L/P + 2.2\,M \times D - 1.1\,D \times L/P$ for forward flexed postures). Peak compression and shear forces of 5940 N and 2138 N were computed at the L5-S1 level, respectively. Based on the predictive equations, contour plots can be constructed (e.g., Figs. 1 and 2 when varying mass M from 0 to 20 N and trunk rotation T from 0 to 110°) to identify unsafe combinations of input levels that yield spinal loads beyond the tolerance levels (for example, 3400 N compression limit based on the revised lifting guidelines of the National Institute of Occupational Safety and Health, NIOSH [2]).

DISCUSSION

Simple predictive equations between output and input variables of interest are developed based on 4401 analyses of a complex kinematics-driven nonlinear trunk finite element model [1]. The independent input variables are chosen to explicitly allow for the commonly-observed alterations in the crucial parameter of lumbar posture (lordosis versus kyphosis) during lifting by introducing both trunk T and pelvic P rotations as independent variables. This is more robust and accurate as compared with the choice of weight height as an input variable made in some earlier works. Full quadratic regression model with coupled terms results in excellent quality-of-fit. A linear regression model, often used in earlier studies, would have deteriorated results yielding smaller R^2 and larger *RMSE* (e.g., R^2 and *RMSE* of 87.8% and 384 N rather than 99.4% and 88 N, respectively, for the L5-S1 compression). The estimated intradiscal pressures at the L4-L5 disc are in close agreement with available *in vivo* data measured under similar loadings and postures [3].

Combinations of input (posture and loading) variable levels that yield spine loads beyond the NIOSH tolerance compression limit of 3400 N can easily be identified using contour plots. 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 predictive equations to quantify spinal loads and risk of injury under different activities. Attempts to incorporate additional independent input variables such as individualized weight/height, lifting speed, and asymmetry in movement as well as output variables such as trunk stability margin is currently underway.

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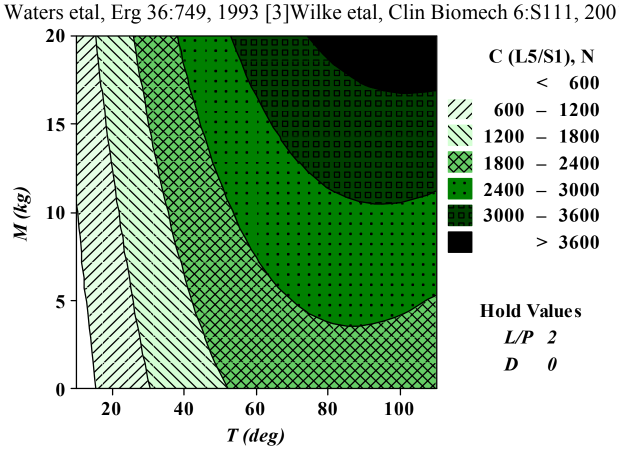

Fig 1. Contour plot of the compression force at the L5-S1 level taking L/P =2 and D =0 cm fixed while varying weight M and trunk rotation T.

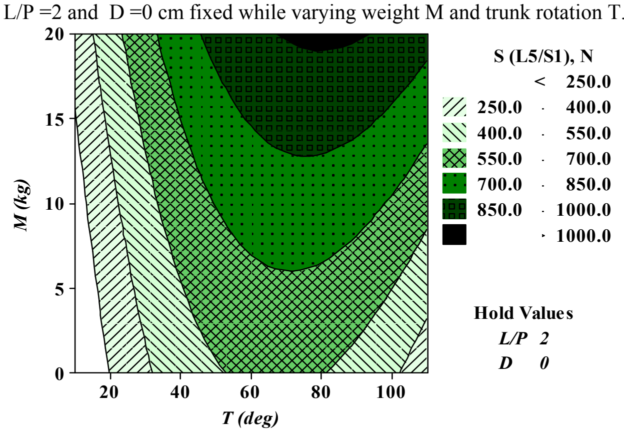

Fig 2. Contour plot of the shear force at the L5-S1 level taking L/P = 2 and D = 0 cm fixed while varying carried weight M and trunk rotation T.