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THE EFFECT OF A VARIABLE LUMBAR ERECTOR SPINAE SAGITTAL PLANE MOMENT ARM ON PREDICTED SPINAL LOADING

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Recent research indicates that the sagittal plane moment arm of the erector spinae decreases at the L_5/S_1 level during torso flexion. The objective of this study was to assess the predicted L_5/S_1 spinal loading from a lifting task when allowing the erector spinae sagittal plane moment arm to vary during torso flexion. Nineteen male subjects lifted three loads from two origin locations to an upright neutral posture. Spinal loading was predicted from an EMG-assisted biomechanical model that allowed the erector spinae moment arm to vary during torso flexion. The predicted lateral, anterior-posterior shear and compression forces increased by 7.4%, 11.1% and 6.6%, respectively, when compared to using a biomechanical model that kept the erector spinae moment arm constant. These results suggest that models that account for the varying erector spinae moment arm predict greater spinal loads, especially for motions that involve a large degree of torso flexion.

INTRODUCTION

Biomechanical models of the torso have been developed to evaluate muscle function and spinal loading during various manual materials handling activities such as lifting and lowering. The validity of the estimates of muscle force and spinal loading, however, are dependent upon the anatomical geometric representation of the torso musculature in relation to the spine as well as their action during motion of the spine. Anatomical parameters that have been shown to affect the predicted spinal loading include the physiological cross-sectional area (Brand et al. 1986), muscle force line-of-action (Nussbaum et al. 1995), and the moment arms of the trunk extensor muscles in single equivalent muscle biomechanical models (McGill and Norman 1987; van Dieen and de Looze 1999). The moment arms of the torso extensor muscles are utilized to predict the internal moments the torso generates to offset the externally applied moments, as well as the estimates of spinal loading. Additionally, spinal load estimates from biomechanical torso models are used to assess the magnitude of loading in relation to tolerance estimates of these torso structures to provide an indication of risk of injury. Thus, accurate geometric estimates of the torso muscle moment arms and their affects during torso motion are necessary. Recent evidence suggests that the moment arm of the primary torso extensor muscle changes as a function torso flexion. Utilizing magnetic resonance imaging (MRI), the lumbar erector spinae sagittal plane moment arm at L_5/S_1 was found to decrease by 9.7% for males as their torso went from neutral to 45° torso flexion (Jorgensen 2001). It is hypothesized that reflecting the changing moment arms in biomechanical models of the torso will alter the predictions of spinal loading compared to models that do not allow the erector spinae sagittal plane moment arm to vary. Thus, the objective of this study was to evaluate the impact on predicted spinal loading utilizing a three dimensional biomechanical model that allowed the sagittal plane L_5/S_1 moment arm of the erector spinae to vary as a function of torso flexion.

METHODS

Subjects

The subjects for this study consisted of nineteen male subjects chosen from the local community (age 23.5 +/- 3.6 years; height 177.3

+/- 9.0 cm; mass 74.8 +/- 13.4 kg; BMI 23.8 +/- 3.8 kg/m^2).

Experimental Design

The subjects lifted a wooden box with handles from near the floor to an upright standing position. The independent variables consisted of load mass (6.8 kg, 13.6 kg and 22.7 kg) and lift origin location (sagittally symmetric and 60° to the right). Each combination of the independent variables was performed twice by each subject, and was randomly presented to the subjects. The dependent variables consisted of the predicted spinal loading on the L_5/S_1 intervertebral disc (compression and lateral and anterior/posterior shear force) from a three-dimensional electromyography-assisted biomechanical model of the torso.

Equipment

A lumbar motion monitor (LMM) was used to collect the torso kinematic variables (Marras et al. 1992). Electromyographic (EMG) activity was collected using bipolar silver-silver chloride surface electrodes (4 mm diameter) from ten trunk muscles (right and left pairs of the latissimus dorsi, erector spinae, rectus abdominis, external obliques, and internal obliques). The electrodes were spaced 3 cm apart over the muscle in the direction of the line-of-action for each muscle. The electrodes were connected to preamplifiers located close to the body, where they were preamplified, high- and low-pass filtered at 30 Hz and 1000 Hz, respectively, rectified and integrated via a 20 ms sliding window hardware filter.

The subjects performed the free-dynamic lifting trials while standing on a force plate (Bertec 4060A, Worthington, OH, USA), without moving their feet. The three-dimensional forces and moments measured at the force plate were translated and rotated to the L_5/S_1 disc utilizing electrogoniometers to measure the position the L_5/S_1 in space relative to the center of the force plate, as well as the subjects' pelvic/hip orientation (Fathallah et al. 1997).

Data Analysis

In a recent MRI study on the affect of torso flexion on the lumbar erector spinae, the sagittal plane moment arm of the erector spinae at L_5/S_1 was shown to decrease 9.7% between neutral and 45° torso flexion, whereas no significant changes between neutral and 45° torso flexion were observed between the L_1/L_2 and L_3/L_4 levels (Jorgensen 2001). To assess the effect of the changing moment arm, an existing EMG-assisted biomechanical model (Marras and Granata 1997) was modified to account for the varying sagittal plane erector spinae moment arm as a function of torso flexion (Figure 1), where the sagittal plane moment arm was allowed to decrease by 9.7% between neutral and 45° torso flexion. The resulting predicted spinal loading was compared with the spinal loading predictions from the biomechanical torso model while keeping the moment arm constant.

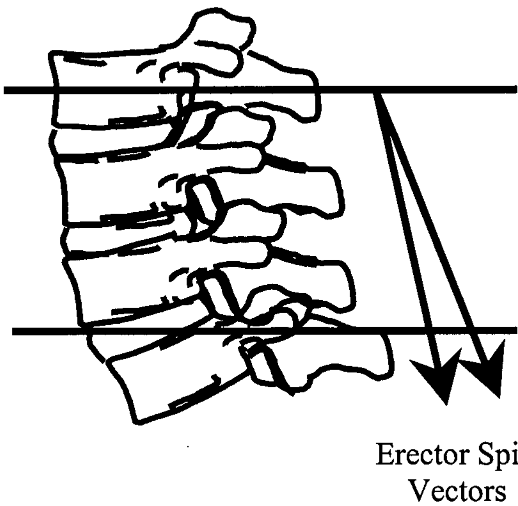

Figure 1. Geometrical representation of the variable erector spinae vector at the origin as a function of torso flexion.

Statistical Analysis

The effect of utilizing a variable erector spinae moment-arm as a function of torso flexion was assessed by performing a repeated-measures three-factor repeated measures Analysis of Variance (ANOVA). The independent variables included the model type (variable moment arm and constant moment arm), lift origin location, and load mass.

Table 1. Mean (SD) peak spinal loading (Newtons) as a function of model type (constant or variable erector spinae moment arm), load mass and lift origin location.

Independent Variables		Lateral Shear		A/P Shear		Compression	
		Constant	Variable	Constant	Variable	Constant	Variable
Load Mass (kg)	6.8	150.3 (147.5)	161.6 (157.9)	564.8 (241.3)	630.8 (269.3)	3106.3 (1023.3)	3317.9 (1090.1)
	13.6	193.7 (175.0)	208.2 (188.2)	749.4 (334.9)	834.8 (372.0)	4006.7 (1355.1)	4274.9 (1436.4)
	22.7	223.8 (194.0)	239.6 (208.2)	941.5 (385.3)	1040.5 (417.3)	5018.5 (1695.0)	5341.3 (1776.9)
Lift Origin Asymmetry (deg)	0	124.9 (98.0)	134.1 (104.5)	688.3 (313.1)	761.0 (340.7)	3783.6 (1424.6)	4038.3 (1511.2)
	60	252.7 (208.6)	271.2 (224.2)	813.1 (390.6)	907.3 (429.3)	4293.3 (1695.9)	4573.0 (1675.9)

The dependent variables included the predicted L_5/S_1 spinal loading (lateral and A/P shear force, and compression force). Significant main effects and interactions involving the model variable from the ANOVA were followed up by an LSD post-hoc test, with comparisons made between the models for the level of each independent variable. A Bonferroni adjustment was applied to the $\alpha=0.05$ significance level to guard against a Type I error.

RESULTS

The predicted mean (SD) peak spinal loading as a function of the experimental variables is shown in Table 1. The ANOVA indicated that the model type main effect and the interactions including the model type all significantly affected ($p \leq 0.05$) all three measures of the predicted spinal loading. Post-hoc tests on the significant interactions indicated that the variable moment arm model resulted in significantly greater predicted spinal loading in all three directions than the constant moment arm model at all three load mass levels ($p \leq 0.0167$) and both lift origin locations ($p \leq 0.0250$). The predicted lateral shear increased between 7.1% and 7.5% when using the variable model, the predicted A/P shear force increased between 10.6% and 11.7% when using the variable model, and the predicted compression force increased significantly between 6.4% and 6.7% when using the variable model. To gain insight as to where the differences occur in the spinal loading estimates of the two types of models, the time dependent predicted A/P shear force is shown in Figure 2. The predicted A/P shear force for the variable model was greater at the beginning of the lift when the subject had their torso flexed and in an asymmetric posture to start the lift, and the difference decreased as the subject became more upright and symmetric.

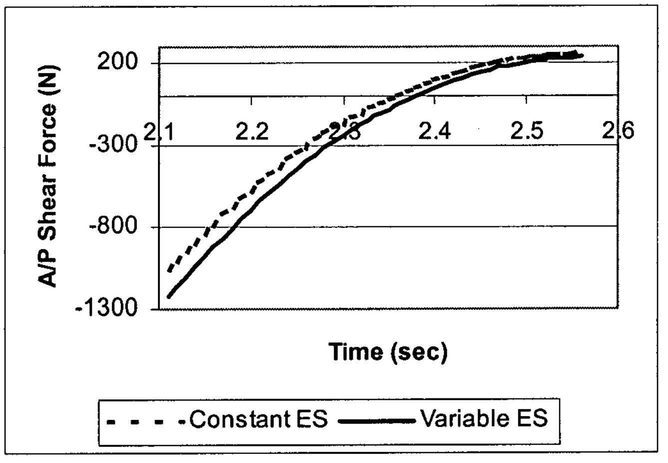

Figure 2. Predicted A/P shear force (N) from the variable and constant moment arm biomechanical model for a subject lifting a 22.7 kg load starting 60° to the right to sagittally symmetric upright.

DISCUSSION

The impact of the variable moment arm model in contrast to leaving the erector spinae moment arm constant as in most other biomechanical models can be assessed by the increase in predicted spinal loading, although the increase was not consistent.

The overall mean peak increase was 7.4%, 11.1% and 6.6%, for the lateral shear, A/P shear and compression force, respectively. The larger increase in the A/P shear force is consistent with observations from other studies that indicated that as the torso bends forward, the muscle fibers of the erector spinae become more aligned with the flattening lumbar spine, and are less capable of opposing externally generated shear forces (Macintosh et al. 1993; van Dieen and de Looze 1999).

Although the increases in the predicted spinal loading as a result of allowing the erector spinae vector orientation to vary are modest in magnitude, one must consider the magnitude of the resulting spinal loads in relation to estimated structural tolerance limits. Estimates of compression force limits on the vertebral end-plates have been presented by NIOSH (1981). Compressive loads of 3400 N on the vertebral end-plates are believed to be the level for which micro-fractures to the vertebral end-plates begin to occur. Compressive loads greater than 6400 N are believed to contribute to microfractures of the vertebral end-plates in 50% of the working population. Evaluation of the predicted mean peak compression forces of the lifting trials indicated that the constant erector spinae model resulted in 59.5% and 8.4% of the lifting trials above 3400 N and 6400 N of compression force, respectively.

Modeling the lifting trials with the variable erector spinae vector model, the percentage of lifting trials above 3400 N and 6400 N increased to 68.3% and 12.8%, respectively. Thus, modeling of the lifting trials of the load weight and asymmetry as used in this study, one could conclude that there was a slight increase in the risk of LBD based on the NIOSH compressive force limits.

The risk of injury to the intervertebral disc from shear forces is believed to increase when these forces exceed 1000 N (McGill 1997). Allowing the moment arm to remain constant, 20.3% of the trials were above 1000 N of A/P shear force. Allowing the erector spinae moment arm to vary as a function of torso flexion resulted in 26.0% of the lifting trials above 1000 N of A/P shear force. The increase in the magnitude of the shear force over that predicted by the constant moment-arm model indicates that the decrease in the moment arm as a function of torso flexion serves to increase the risk of LBD related to loading on the disc.

The increase in the A/P shear force and compression force between the two models was typically the greatest at the beginning of the lift, where the torso was flexed to its maximum. Practically, this indicates that lifts originating between the floor and knee are slightly higher in risk for LBD than our modeling efforts have previously indicated. This is consistent with a previous study that indicated the probability of high-risk group membership for low back disorders for palletizing and depalletizing tasks increased as the height lifted from or to approached the floor (Marras et al. 1997). Previous *in vitro* research on failure of intervertebral discs from motion segments has shown that sustained torso flexion combined with compressive loading (Adams and Hutton 1982), or torso flexion performed repetitively with compressive loading (Adams and Hutton 1983) resulted in prolapse of the posterior annulus fibrosis fibers. Thus, there is consistent epidemiological, *in vitro*, and biomechanical modeling evidence that manual materials handling of loads requiring large magnitudes of torso flexion, such as lifts originating near the floor, results in predicted spinal loading levels near the tolerance levels for some individuals, which would increase the risk of LBD.

One methodological consideration must be considered when interpreting these results. The predicted spinal loading was obtained from lifting tasks performed while standing on a force plate, where the subjects could not move their feet during the lifting exertion. Thus, these tasks are not completely reflective of typical MMH tasks that would allow foot movement during the lifting exertions. However, the design of the lifting task, including standing on the force plate, was chosen to demonstrate the sensitivity of the biomechanical model and the impact of allowing the erector spinae moment arm to vary, and the use of the force plate allowed quantification of the external moments.

CONCLUSIONS

Several conclusions can be presented from the demonstration of the variable erector spinae moment arm biomechanical model. First, utilizing results from an MRI study and allowing the sagittal plane erector spinae moment arm to vary as a function of torso flexion, significant increases in peak spinal loading resulted as opposed to using a constant moment arm model to model symmetric and asymmetric free-dynamic lifting exertions. Second, consistent with observations that the risk of LBD increases as the torso flexes forward, the increased spinal loading above that predicted from a constant moment arm model indicates that these types of MMH tasks, which originate near the floor, may result in higher loading than previously thought, and may pose higher risk for LBD than previously thought.

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