A CALCULATION OF BACK COMPRESSIVE FORCE: IMPLEMENTING A LOAD DISPLACEMENT VELOCITY CONSTANT

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ABSTRACT

Improvement of current biomechanical models through implementation of a dynamic factor may provide greater accuracy in acquiring more realistic calculations of back compressive force (BCF) in the spine during lifting. Direct measurement of internal disk pressure is highly invasive and impractical for the purposes of job evaluations. Therefore, most widely used biomechanical models for job evaluations in industry are simplified and considered "static" models. These models neglect additional forces generated by acceleration of the body segment centers of mass and load, and therefore under predict peak back compressive force at the L5/S1. Few researchers have addressed these issues; however those that have indicate a 19-200% increase in peak force, over static BCF calculations. The purpose of this study was to address the issue of whether a current static model developed at the University of Utah to calculate BCF could be modified to include a load displacement velocity constant (LDVC) derived from lifting scenarios simulated in a laboratory. The study was designed to answer two main questions: 1. By what percentage does the BCF calculation increase during slow, medium and fast lifting speeds? 2. Can a LDVC be used to modify a static BCF model and calculate a more representative measure of BCF? Results of this study indicate that peak BCF increased as much as 42% for fast vs. slow lifting, and 32% for fast vs. normal lifting. Incorporating the LDVC into static BCF calculations will more accurately represent true BCF and should therefore improve risk estimation of back injuries from lifting tasks.

INTRODUCTION

Identifying causes of low back pain (LBP) can be especially difficult because the disorder is so common, even without workplace exposures influencing the health outcome. As with most any epidemiological study, exposure is complex in nature, varies with time, and must be summarized before it can be effectively used in a comprehensive model that predicts risk. Recent publications in Theoretical Issues in Ergonomics Science have discussed the importance of cumulative spinal loading and a need to develop models capable of accounting for cumulative stress in the spine from manual material handling (Waters, Yeung et al. 2006; Waters, Yeung et al. 2006). An important part of quantifying spinal loading is accurate estimation of back compressive force (BCF). According to the US Bureau of Labor Statistics, low back disorders are a common problem in occupational health and safety accounting for nearly one-third of all occupational injuries and illnesses. Improved quantification of BCF will improve model predictions of exposure and should help occupational ergonomists identify potentially hazardous jobs to help reduce the number of low back disorders in the workplace.

Ergonomics tools, in general, have been designed for single task jobs and have difficultly combining complex tasks to completely represent job risks, and most lack true validation. Currently used biomechanical models include the Revised NIOSH Lifting Equation (RNLE) and the University of Michigan 3D Static Strength Prediction Program (3DSSPP), and are designed to look at relatively simple jobs or an instant in time to quantify risk. The RNLE includes parameters designed to account for fatigue, but does not directly look at dynamics as a component of potential risk for developing a low back injury. Incorporating dynamic components into lifting models may improve predictive capability and the ability to detect hazardous jobs.

Researchers have reported significant differences in back compressive force calculation in dynamic vs. static models. Differences have been found ranging from 19% to 200% increases with dynamic models (Freivalds, Chaffin et al. 1984; McGill and Norman 1985; Marras and Sommerich 1991; Marras and Sommerich 1991; Waters, Putz-Anderson et al. 1993).

Biomechanical models have been created to predict compressive forces and moments during MMH, however few guidelines have been given about the spinal loads corresponding to elevated risk for developing low back musculoskeletal disorders. NIOSH does not currently have any guidelines or limits with respect to dynamic loading and cumulative lifting. Little is known about differences in spinal loading at the beginning vs. end of a lift, or how acceleration of loads affects the development of low back injuries. Traditional, static, biomechanical models look at a single instant in time during a lift, and typically focus on the origin or destination. Load acceleration and deceleration are neglected when reporting BCF using a static approach. To correct for these inadequacies, a load displacement velocity (LDV) has be defined by the researcher as the change in location of a load over time during a lift and will be discussed in further detail in the methods section.

The purpose of this study was to investigate the effects of dynamics on a modified static biomechanical model. The study was designed to answer two main questions: 1. By what percentage does the BCF calculation increase during slow, medium and fast lifting speeds? 2. Can a load displacement velocity constant (LDVC) be used to modify a static BCF model and calculate a more representative measure of BCF?

Biomechanical Models

Revised NIOSH Lifting Equation (RNLE)

The RNLE is an assessment tool that combines factors associated with weight, vertical and horizontal location, vertical displacement, asymmetry, frequency, and coupling to compute a recommended weight limit (RWL) for a lifting task, and an associated lifting index from which a risk is assigned. Although not explicitly, the RNLE weights heavily the biomechanical load to the spine as a function of lift origin and destination positions. The RNLE is a comprehensive assessment tool designed to assess biomechanical, psychophysical, and physiological parameters to identify job risk for musculoskeletal disorders related to manual material handling (Waters, Putz-Anderson et al. 1993; Garg 1995). The equation to compute the calculation for a single task is shown in Equation 1.

$$RWL = LC \times HM \times VM \times DM \times AM \times FM \times CM \qquad \text{Eq. (1)}$$

NIOSH defines the RWL for a specific set of task conditions as the weight of the load that nearly all healthy workers could perform over a substantial period of time without an increased risk of developing musculoskeletal disorders related to manual material handling. The ratio LW/RWL, where LW is the actual load weight of the object, represents the Lifting Index (LI). NIOSH has established recommendations for these lifting indices. Generally a LI < 1.0 is safe for most workers and a LI > 3.0 will be hazardous to most workers and requires changes to be made (Garg 1995).

University of Michigan 3D Static Strength Prediction Program (3DSSPP™)

Increased axial compression in the spine has been associated with low back pain (LBP). The 3DSSPP is a 3-Dimensional biomechanical model developed to incorporate posture and loads into an inverse dynamics calculation to determine joint loads. As implied with the title of the model, it is purely static and neglects any contributions from movement. BCF predictive capability of static models alone has been questioned by many researchers, and underestimates true BCF (Marras and Granata 1997).

The single most important factor that appears to affect the model's calculation of BCF is the distance of the load from the L5/S1 vertibral disk. The kinematics model incorporates the load moment about the L5/S1 and other moments created by body segment weights and center of mass distances from the L5/S1. Authors of the 3DSSPP suggest that a complex musculoskeletal model drives its results, although it would appear that for purely sagittal lifts, a simplification of the model can be justified as was found by Bloswick, Loertscher, and Merryweather (Bloswick and Villnave 2000; Loertscher, Merryweather et al. 2006; The University of Michigan Center for Ergonomics 2007).

Revised Utah Back Compressive Force Estimation Model (UBCF)

The purpose of the UBCF was to estimate static back compressive force at the L5/S1 during lifting tasks. The UBCF is a simple hand-calculation method for BCF (HCBCF) based on the original Utah Back Compressive Force Calculation model developed by Bloswick (Bloswick and Villnave 2000). The UBCF was developed to create a more accurate HCBCF adjusting the error-inducing assumptions made in the previous model. BCF estimations from the current and improved UBCF models were compared to computer-based BCF values to determine overall accuracy.

Validation of the UBCF was performed and found to be highly accurate with r^2 equal to 0.97 compared to the 3DSSPP™ (Loertscher, Merryweather et al. 2006). It was concluded that the UBCF would be an excellent candidate for the purposes of this study.

METHODS

Subjects and Tasks

The study included 2 male participants as a subset of a larger proposed study to consist of 10 subjects. Both participants gave written consent and the study was approved as part of a larger study by the University of Utah's Institutional Review Board (IRB). Neither participant had any current low back pain during the study period.

Approach

A customized 3D model was developed and data were captured using Peak Motus 9.0. Four camera video acquisition with reflective markers placed according to a modified Helen Hayes marker set for gait analysis with an upper body model was used to capture 3D coordinate data for each joint center and segment used in the model. Each participant was instrumented with reflective markers and performed 12 trials with a single load using two randomly assigned lifting techniques. A squat lift (leg lift) and stoop lift (back lift) were demonstrated to each participant by the researcher. Each lift consisted of a lift and hold. A box weighing 7 lbs was used for each lift. Each participant was asked to lift "fast", "slow" and "normal" based on his personal selection of lifting speed.

Figure 1 was developed to describe BCF characteristics during each phase of a lift. Similar phases have been described for gait analysis and provide a means of standardizing results for comparison across studies. Although lifting is not as regular as normal walking, lifting also has distinct events that occur during a lift cycle. No generally used or accepted method for standardization is published among occupational biomechanists and ergonomists with respect to lifting analyses and lift phases. Because of this lack of standardization, Figure 1 is the author's description of a fundamental lift cycle. Each lift cycle has distinct events that can be analyzed. This approach may prove more critical when quantifying cumulative spinal loading as a function of time, and will not be discussed in greater detail for this study.

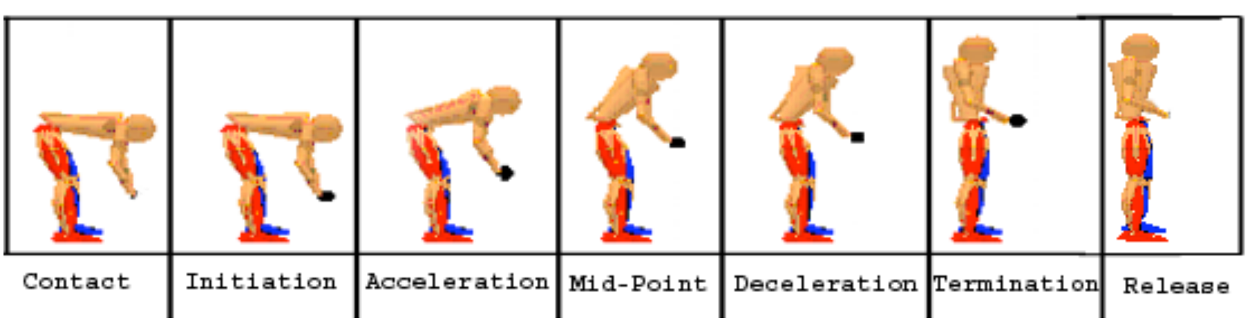

Figure 1 Lift Cycle Events

The load displacement velocity was determined according to equation 2:

$$\text{LDV} = \frac{d_f - d_o}{t_f - t_o} = \frac{\text{Äd}}{\text{Ät}}$$

Eq. (2)

and is illustrated in Figure 2, where d = displacement and t = time. For the purpose of this study, a full lift cycle was not analyzed including a lower; however the general profile for each lift should follow a very similar pattern no matter where the destination of a lift occurs. A total of 24 trials were analyzed. Lifting velocity and acceleration were defined from marker position data.

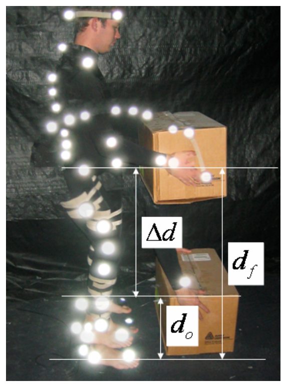

Figure 2 Load Displacement Velocity

Research Hypotheses

1. There is a significant difference between load displacement velocities and self selected lifting speeds that can be determined by observation.

2. The UBCF model can be modified using a LDVC to better account for peak BCF during lifting.

Experimental design

A 3D model developed using Peak Motus 9.0 was created to capture motion data of each participant during lifting. A 6 channel AMTI force platform was also used to verify that ground reaction force profiles were consistent with BCF calculations determined using the UBCF model described elsewhere (Loertscher, Merryweather et al. 2006). Data were collected at 60 Hz for marker data and 600 Hz for analog force platform data. Comparisons between the UBCF model and the 3D motion model (3DMM) implementing body segment center of mass locations and mass as a function of stature and body weight respectively, were performed. Additionally, the accelerations of the center of mass of each segment were included to represent additional force generated by mass acceleration during the lift initiation phase. Figures 3 and 4 represent the 3D computer model used for comparison and the differences between model assumptions (static vs. dynamic).

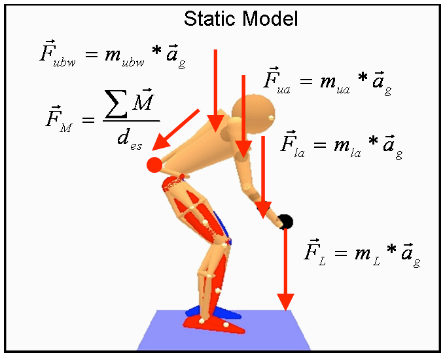

Figure 3 Static BCF Model

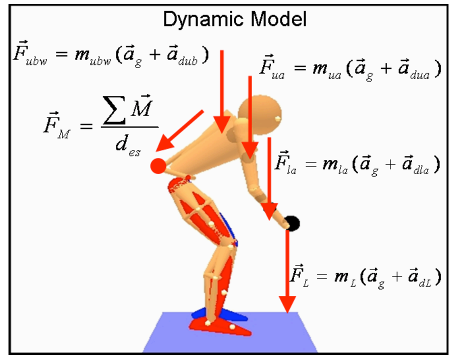

Figure 4 Dynamic BCF Model

RESULTS

Comparisons were made for two lifting techniques: Squat and Stoop. The percent difference between each self selected lifting speed are reported in Table 1. Although multiple trials were recorded for each condition, the statistical significance of these values was not computed. The author felt because of limited sample size, only comparative statistics were needed to report the findings from this pilot study. When compared, an obvious distinction is present among lifting speeds, with the largest difference occurring between Fast and Slow, which was expected. Similar differences were found from the resultant ground reaction forces measured with the force plate.

For the 3DMM comparing all three self selected lifting speeds performed by each worker in a randomized order, there was a 25% increase of fast compared to slow squat lifting, and a 38% increase in BCF for fast compared to slow stoop lifting.

Next, comparisons were made for each posture during the lift to demonstrate the difference between the original UBCF static model and the 3DMM. The results are displayed in Table 2. No significant difference was found between squat and stoop lifting when compared to the static model. Nearly a 40% increase in BCF was calculated for the fast dynamic model over UBCF model. A 31% increase in BCF was found for normal speed dynamic over static, and nearly a 17% increase was found for slow dynamic over static.

The plot in Figure 5 is a graphical representation of BCF over time. This represents a lift where the origin and destination are the same. The importance of cumulative spinal loading was not explored in this work; however LDV appears to be an important component to accurately describe BCF throughout the duration of a lift. The peak area highlighted above the static curve accounts for the acceleration of the load and body at lift initiation, and load and body deceleration at lift termination.

Table 1 Lifting Speed Percent Difference BCF

		SQUAT			STOOP				
		Slow	Moderate	Fast	Slow	Moderate	Fast		
	BCF (N)	3722	4334	4799	3504	4103	5168	BCF (N)	
Slow	3722	0.00%	15.19%	25.28%	0.00%	15.75%	38.38%	3504	Slow
Moderate	4334	15.19%	0.00%	10.18%	15.75%	0.00%	22.97%	4103	Moderate
Fast	4799	25.28%	10.18%	0.00%	38.38%	22.97%	0.00%	5168	Fast

Table 2 Dynamic vs. UBCF Static Model

		Dynamic Model		
		Slow	Moderate	Fast
Utah Model	BCF (N)	3504	4103	5168
Slow	3145	16.81%	31.80%	41.64%
Moderate	3179	15.74%	30.75%	40.61%
Fast	3200	15.08%	30.10%	39.98%

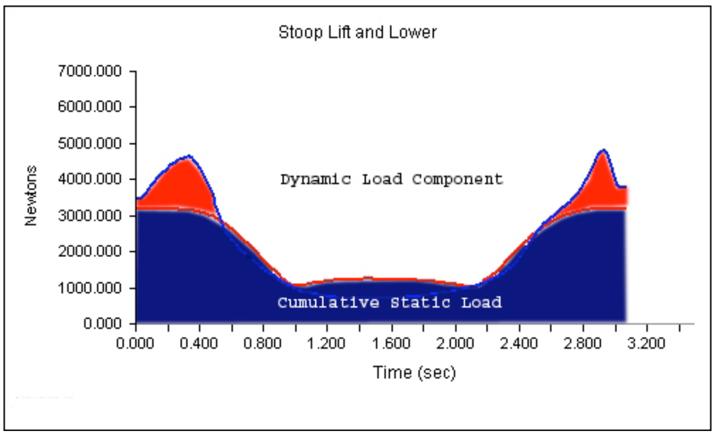

Figure 5 Dynamic BCF vs. Static BCF for Lift Duration

The load displacement velocity constants (LDVC) were determined for each self selected lifting speed. Only a small difference was found for stoop vs. squat lifting, resulting in a combined LDVC. A summary of the LDVC is found in Table 3. The equation for determining a dynamic BCF using the UBCF as the baseline is found in Eq. 3.

Table 3 Summary of Load Displacement Velocity Constants

LDVC			
	Slow	Moderate	Fast
Squat	1.14	1.29	1.39
Stoop	1.16	1.31	1.41
Average	*1.15*	*1.3*	*1.4*

$$UBCF_d = UBCF_s * LDVC \qquad \text{Eq. (3)}$$

DISCUSSION

The LDVC combined with the UBCF should give analysts the ability to quickly determine what peak BCF values exist for a lift. $UBCF_d$ is a quasi-dynamic calculation from a modified statically determined BCF. These are only preliminary results, and other questions about LDV need to be addressed before LDVC is used for risk assessments. The ability of an analyst to determine Slow, Moderate and Fast lifting movements is questionable, but critical to decide which LDVC is required. Additional studies need to be performed to verify if LDVC values calculated for this pilot study are valid for more generalizable lifting scenarios.

Accuracy

No direct measurement was made of the actual BCF developed in the spine, and was not practical for this study as stated earlier. The results are comparable to other results reported on the differences in force estimations between static and dynamic models (McGill and Norman 1985; Jager and Luttmann 1989; Menzer and Reiser 2005). There does appear to be a general pattern in the force profile for each lift that should be explored further with more numerous trials and study participants.

Limitations

The lifts analyzed for this study were restricted based on two lifting styles and a partial lift cycle. The static model modified for BCF calculations was only designed for 2D, although 3D coordinate data were collected for the experiment. The lifts were assumed to occur in the sagittal plane only and complied with the original model assumptions. Only a single muscle (erector spinae) was accounted for in the model. More complex musculoskeletal models include additional muscles that contribute to the resultant BCF calculation. All contributions to BCF from co-contractions were neglected for this model, and may result in residual under prediction of true BCF. The load weight was not varied during the study, and an important relationship may exist between LDVC and load magnitude.

CONCLUSION

Occupational biomechanics provides a means of quantifying physical stress on the body during work. Dynamic biomechanical models can improve estimation of peak BCF over static models. A LDVC can be easily implemented into currently used static models based on analyst judgment of LDV for improved estimation of BCF. Persons exposed to increased levels of BCF are usually at a higher risk for developing injuries to the low back and spine than workers without these risk factors. These new guidelines should help provide additional information about the nature of physical demands of a job and implications about protecting workers susceptible to low back injuries. The LDVC is a simple approach to solve the problems arising from neglecting movement during lifting when using a static model.

Future Work

Cumulative spinal loading (CSL) could be used as a more accurate exposure assessment of low back disorder risk than back compressive force (BCF) alone. Estimating the dose over time from a CSL model may provide valuable information about quantification of job risk. As part of a more comprehensive assessment of BCF, integration of force profiles throughout the duration of lifting task must be addressed. Dose modeling as a function of CSL should also incorporate the important effects of load displacement velocity (LDV) on BCF calculations. Can CSL for a lift be determined solely from looking at statically adjusted BCF by LDVC at lift initiation and lift termination? The answer to this question would determine if workplace design and load location influence the development of low back disorders through a CSL dose-response mechanism.

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