

Spine loading in patients with low back pain during asymmetric lifting exertions

William S. Marras, PhD^{a,*}, Sue A. Ferguson, PhD^a, Deborah Burr, PhD^b,
Kermit G. Davis, PhD^c, Purnendu Gupta, MD^d

^a*Biodynamics Laboratory, The Ohio State University, 210 Baker Systems Engineering, 1971 Neil Avenue, Columbus, OH 43210, USA*

^b*Department of Epidemiology and Biostatistics, The Ohio State University, 320 West 10th Avenue, Columbus, OH 43210, USA*

^c*Department of Environmental Health, The University of Cincinnati, 3223 Eden Avenue, Cincinnati, OH 45267-0056, USA*

^d*Section of Orthopaedic Surgery and Rehabilitation Medicine, University of Chicago, 5841 South Maryland Avenue, MC3079, Chicago, IL 60637, USA*

Received 3 February 2003; accepted 6 July 2003

Abstract

BACKGROUND CONTEXT: Recurrent low back pain (LBP) is a common and costly problem that might be related to increased spine loads in those with LBP. However, we know little about how the spine is loaded when those with LBP perform lifting exertions.

PURPOSE: Document spine loading patterns of patients with LBP performing symmetric and asymmetric lifting exertions compared with asymptomatic individuals performing the same tasks.

STUDY DESIGN: Spine loadings during lifting exertions that varied in asymmetric origin as well as horizontal and vertical distance from the spine were compared between asymptomatic subjects and patients with LBP.

METHODS: Sixty-two patients with LBP and 61 asymptomatic individuals performed a variety of lifting exertions that varied in lift origin horizontal and vertical position (region), lift asymmetry position and weight lifted. An electromyography-assisted model was used to evaluate spine loading in each subject during the lifting exertions. Differences in spine loading between the LBP and asymptomatic subjects were noted as a function of the experimental variables.

RESULTS: Patients with LBP experienced greater spine compression and shear forces when performing lifting tasks compared with asymptomatic individuals. The least taxing conditions resulted in some of the greatest differences between LBP and asymptomatic individuals.

CONCLUSIONS: Greater levels of antagonistic muscle coactivation resulted in increases in spine loading for patients with LBP. Specific lifting conditions that tend to exacerbate loading can be identified by means of physical workplace requirements. These findings may impact acceptable return-to-work conditions for those with LBP. © 2004 Elsevier Inc. All rights reserved.

Keywords:

Spinal loads; Low back pain; Low back disorder; Electromyography; Lifting biomechanics; Musculoskeletal; Rehabilitation; Recurrent low back pain; Secondary low back pain

Introduction

A continuing dilemma for those treating low back pain (LBP) has been the treatment and prevention of recurrent LBP. It has been well documented that one of the strongest predictors of future LBP is a previous history of LBP [1,2]. A recent review of LBP risk factors found that 80%

of the studies reviewed concluded that previous history of LBP was associated with an increased risk of symptoms [3]. Papageorgiou et al. [4] have estimated that those with a history of previous LBP have twice the rate of new LBP episodes compared with those without a history of LBP. It has also been reported that the more frequently back pain occurs, the greater the risk of new back pain. Specifically, van Poppel et al. [5] reported that the odds ratio was 9.8 for new episodes of LBP in those material handlers reporting back pain more than twice in a year. However, it is unclear whether reports of “new episodes” in these studies were truly new or reoccurrences of previous episodes [6]. One might speculate that patients who do not fully recover from a LBP episode might be predisposed to further exacerbation of an LBP event.

FDA device/drug status: not applicable.

Support in whole or part was received from Ohio Bureau of Workers' Compensation Grant 737825. Nothing of value received from a commercial entity related to this research.

* Corresponding author. Biodynamics Laboratory, The Ohio State University, 1971 Neil Avenue, Columbus, OH 43210, USA. Tel.: (614) 292-6670; fax: (614) 292-7852.

E-mail address: marras.1@osu.edu (W.S. Marras)

Although multiple injury pathways are believed to be potentially responsible for recurrent LBP [7–9], a biomechanical source of low back disorders has historically been accepted as one potential pathway [7]. Studies [10–12] have suggested that excessive mechanical loading on already compromised spinal structures can progressively affect disc degeneration and might result in chronic LBP.

Spine loads associated with work tasks may also increase the risk of LBP. Liles et al. [13] reported that injury costs increase dramatically as job difficulty increases. In addition, industry surveillance studies found that the mechanical measures of spine moment, spine compression and spine shear on the job were closely related to LBP reporting [14,15]. Therefore, it is important to understand the mechanical loading of an LBP patient's spine during work tasks (such as lifting exertions) because this may represent a mechanism that further compromises the back's musculoskeletal system.

If one could understand, quantitatively, the characteristics of spine loading in those with LBP, then situations that might further exacerbate a low back disorder could be avoided. However, the mechanisms by which a history of LBP increases risk are poorly understood.

Several biomechanical studies have attempted to determine whether a history of LBP results in greater spine loading and, potentially, an increase in LBP risk. Many studies have identified differences in muscle recruitment patterns between those with and those without LBP [16–19]. However, traditionally, it has been difficult to interpret these effects on spine loading [20]. Lavrieviere et al. [20] suggested that, given the variability in muscle response in LBP, the use of electromyography (EMG)-assisted models might be necessary to appreciate these differences. Until recently the use of EMG-assisted models with patients with LBP has been problematic because there were no means to properly calibrate the EMG signal in patients with LBP. Calibration of the EMG signal in patients with LBP has been difficult because patients with LBP are reluctant to exert the maximum exertions necessary to calibrate the EMG signal.

Recently, an EMG normalization technique not requiring maximum exertions has been developed and validated that could be used with patients with LBP [21,22]. These advancements have permitted the first interpretation of spine loading for those with LBP [23]. This study has demonstrated that after adjusting for differences in body mass (moment normalization), when patients with LBP perform the same exact (kinematically controlled) lifting exertions as asymptomatic individuals, spine loading of patients with LBP was 26% greater in compression and 70% greater in anterior-posterior (A/P) shear. Greater spine loading was primarily the result of increases in muscle antagonistic coactivation presumably resulting from increased guarding. The study also found that when subjects were permitted to adapt their own lifting exertion style (as opposed to kinematically controlled exertions), the patients with LBP changed their kinematic patterns in an attempt to minimize the external moments (and spine loads) to which they were exposed. These

findings suggest that subjects with LBP have developed proprioceptive tolerance limits above which they are unwilling to load the body and, thus, adapt alternative lifting strategies. However, the realistic lifting environment often yields situations that made it difficult to employ alternative lifting strategies. In addition, because those with LBP are typically heavier than asymptomatic individuals, they experience additional spine loading resulting from their greater body mass. This information suggests that lifting exertions performed by those with LBP represent a substantially different situation compared with asymptomatic individuals.

Our previous investigation [23] of spine loading associated with patients with LBP investigated sagittally symmetric lifts, exclusively, and employed a relatively small population of subjects. Hence, we do not have an understanding of how patients with LBP spine loadings would develop during more realistic lifting situations that would be encountered as patients return to the workplace.

The objective of this study was to determine how three-dimensional spine loading compared in subjects experiencing low back pain compared with asymptomatic individuals among the variety of lifting conditions and situations that would be expected of patients with LBP as they return to the workplace.

Methods

Approach

This study employed a well-developed EMG-assisted model to assess spine loading as LBP, and asymptomatic subjects lifted a variety of loads from various lift origin regions and asymmetric positions reflective of work conditions. The analyses examined the spine loading response of those with LBP compared with those without LBP as the horizontal, vertical and asymmetric location of the lift origin varied and as the weight of the object lifted changed.

Subjects

A total of 123 subjects participated in this study. Sixty-two of the subjects (32 men and 30 women) had LBP at the time of the testing and were recruited from several medical practices. This group had pain primarily of muscular origin (as diagnosed by their orthopedic surgeon) with median pain duration of 5.5 months. The LBP characteristics of the group are summarized in [Table 1](#). Patients were excluded from the study if physical examination showed signs of lower extremity deficit or hyperflexia. Within the LBP group, 35% reported local back pain only, 52% reported a distribution of 75% back pain and 25% leg pain, and 13% reported an equal distribution of pain between back and leg.

Sixty-one age-matched asymptomatic (during the previous year) individuals (31 men and 30 women) were recruited to perform in the study. Gross anthropometric characteristics

Table 1
Pain and SF-36 Health Survey results for low back pain patients

Impairment measure	Mean	Standard deviation
Pain level (0 to 10 scale)	5.0	1.9
Duration (months)	10.2	13.6
Million Visual Analog	68.4	26.6
SF 36 Physical Functioning	20.7	5.5
SF 36 Role—Physical	4.8	1.3
SF 36 Bodily Pain	6.1	2.2
SF 36 General Health	17.9	5.1
SF 36 Vitality	12.2	4.1
SF 36 Social Functioning	7.3	2.2
SF 36 Role—Emotional	4.5	1.3
SF 36 Mental Health	20.9	4.9
SF 36 Reported Health Transition	3.3	0.8

of the subject population are reported in Table 2 and indicate that the LBP and asymptomatic groups were nearly identical in average height but differed in weight and torso dimension with the LBP group being considerably heavier and larger.

Experimental design

The laboratory study was designed to evaluate the spine loading of subjects as they lifted under a variety of experimental conditions representing the array of manual materials handling conditions documented in industrial situations [24]. This phase employed a repeated-measures within-subject design. The independent variables in this study were subject group membership (LBP vs. asymptomatic), weight lifted, lift origin region and lift asymmetry position. Four weights were lifted (4.5, 6.8, 9.1 and 11.4 kg) under free-dynamic conditions starting from each of five lift origin regions varying in vertical height and horizontal distance from the spine (shoulder height at a moment arm distance of 30.5 cm from the spine, waist height at a moment arm distance of 30.5 cm from the spine, knee height at a moment arm distance of 30.5 cm from the spine, mid-shin height at a moment arm distance of 30.5 cm from the spine, far-waist

Table 2
Anthropometric measures for the asymptomatic and patient groups

Anthropometric measures	Asymptomatic, N=61		Patients, N=62		p Value
	Mean	SD	Mean	SD	
Age	36.85	10.07	38.37	9.88	.4002
Weight	169.69	38.30	200.4	46.39	.0001*
Standing height	173.03	10.17	172.89	9.25	.9361
Spine length	52.67	6.63	50.72	5.43	.0758
Trunk depth	22.41	5.95	26.83	5.96	.0001*
Trunk breadth	30.01	3.51	33.17	4.88	.0001*
Trunk depth xiphoid	22.02	3.45	25.05	4.47	.0001*
Trunk breadth xiphoid	29.95	3.55	31.43	4.41	.0430*
Trunk circumference	86.62	13.53	101.05	16.62	.0001*

*Indicates significant differences at $p < .05$ adjusting for the number of comparisons.

height at a moment arm distance of 61 cm from the spine and far-knee height at a moment arm distance of 61 cm from the spine (Fig. 1). The lifts ended with the body in an upright position with the weight located at elbow height (elbow angle about 90 degrees). In addition, subjects performed each lift from five different symmetric and asymmetric (lift asymmetry) positions (Fig. 2). The combination of weight lifted, lift origin region and lift asymmetry were intended to represent the range of lift exertion variable combinations expected of a worker returning to the workplace [24,25].

The dependent variables consisted of the EMG activity of 10 trunk muscles, trunk and hip kinetic as well as kinematic information, and the resulting spinal loads.

Apparatus

EMG activity was collected through the use of bipolar silver-silver chloride electrodes that have a 4 mm diameter and were spaced approximately 3 cm apart. Electrodes recorded activity at the 10 major trunk muscle sites consisting of right and left muscle pairs of erector spinae, latissimus dorsi, rectus abdominus, external oblique and internal oblique muscles. EMG preparations and electrode placements were previously described [26]. The raw EMG signals were preamplified, high-passed filtered at 30 Hz, low-passed filtered at 1,000 Hz, rectified and smoothed with a 20-ms sliding window filter. Skin impedances were maintained below 100 K Ω .

EMG calibration normalization was performed using an asymmetric reference frame [27] that isolated the exertions and postures of the torso. Pelvic and leg positions were also controlled using a pelvic support structure [28]. The asymmetric reference frame provided static resistance against the upper body and monitored torque production about L5–S1. The pelvic support structure was mounted to a force plate (Bertec 4060A; Worthington, Ohio). The forces and moments measured at the center of the force plate were mathematically translated and rotated to L5–S1 [28]. A computer displayed real-time moment about L5–S1 to the subject and allowed them to control the exertion magnitude.

Trunk kinematics were monitored with a triaxial goniometer (lumbar motion monitor). The device acts as an instrumented exoskeleton of the spine that measured instantaneous three-dimensional position, velocity and acceleration of the trunk. The device design, accuracy and application have been reported previously [29]. During the spine loading study, ground reaction forces were monitored by means of a force plate and trunk muscle EMG activities recorded as described above. A set of electrogoniometers in conjunction with a force plate were used to document the moments and forces exerted about L5–S1 [30] during these free dynamic lifts (Fig. 1). The set of goniometers measured the position of L5–S1 as well as the pelvic orientation of the subject relative to the center of the force plate. Based on these relative positions, the three-dimensional forces and moments measured at

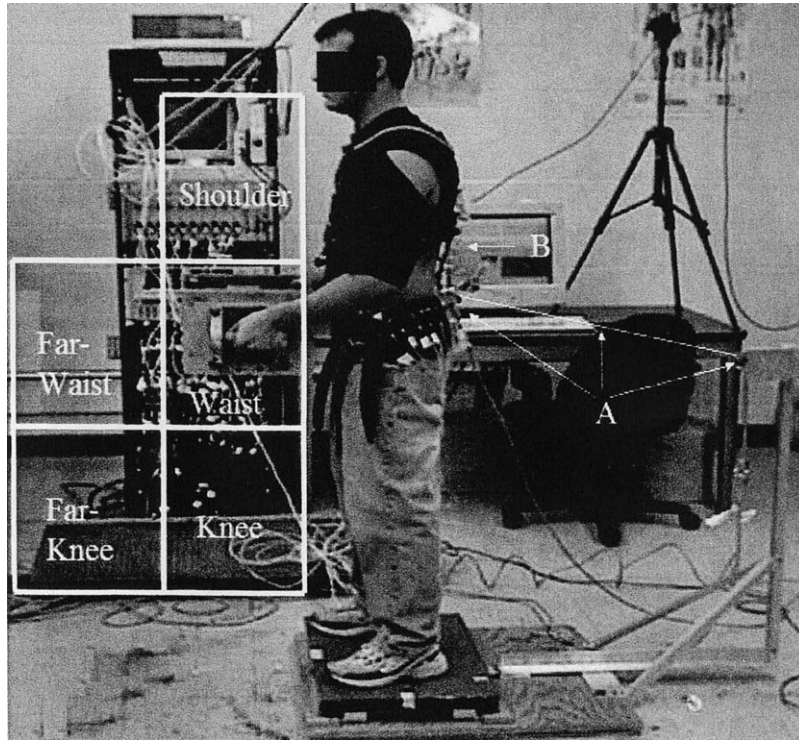


Fig. 1. Definitions of the five lift origin regions. Subject instrumentation A) goniometric system for monitoring position of L5/S1 relative to the force plate, and B) the lumbar motion monitor or LMM.

the force plate were mathematically translated and rotated up to L5–S1.

All signals were collected simultaneously through customized Windows-based software developed in the Biodynamics Laboratory. The processed signals were collected at 100 Hz and recorded on a computer by means of an analog-to-digital converter.

EMG calibration

An EMG calibration (normalization) procedure was recently reported that does not require a maximum exertion in

order to calibrate the EMG signal [21]. Typically, EMGs are normalized relative to a maximum voluntary contraction (MVC). However, MVCs are often subjective and potentially limited by the sensation of pain in injured individuals [31,32]. This new technique estimates the slope of the EMG-force relationship and predicts an expected maximum contraction in order to “anchor” the maximum value. The EMG-force relationship was established through a series of low-level exertions performed in flexion, extension and axial twisting. These test conditions produced a series of EMG-force relationship points from which a relationship slope was derived.

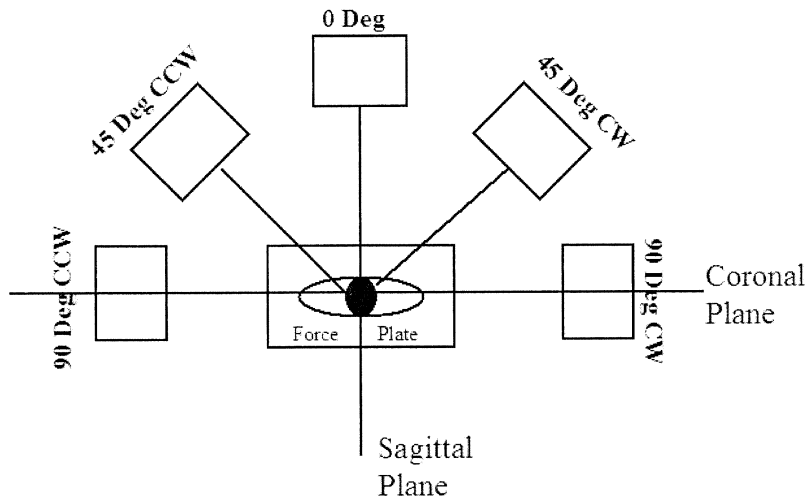


Fig. 2. Asymmetric lift positions.

A recent study [22] reported minor differences in EMG-assisted model results when comparing this normalization method versus maximum exertions to calibrate the EMG signal.

Procedure

Upon arriving at the laboratory, the subjects were, first, informed about study procedures, their ability to refuse to complete a particular lift and their need to inform experimenters about any further discomfort. Consent to participate was acquired by means of a document approved by the University institutional review board.

Next, subjects were prepared for the spine loading assessment testing. Anthropometric measurements were collected and surface electrodes then were applied using standard placement procedures described earlier for muscles of interest. The subject was positioned in the experimental apparatus, and EMG calibration procedures were completed as described previously.

After a rest period, the lifting exertions began. In order to ensure patient safety, all lift origin region conditions (Fig. 1) were completed at each weight level before increasing to the next weight. Hence, lifts were performed in the least taxing positions (eg, lowest expected lift moment) first and then progressed to more demanding lifts (eg, higher expected lift moment) at each weight level. Asymmetry order presentation was counterbalanced between subjects. Subjects were required to keep the feet stationary on the force plate (for force monitoring purposes) but were free to move the rest of the body as they wished.

Spine load assessment

Over the past 20 years, our laboratory has developed a three-dimensional dynamic biomechanical model that can determine how the vertebral joint at L5–S1 is loaded during a dynamic motion [33–45]. The model yields subject- and task-specific spine loading information. Our model assumes that we can pass one imaginary transverse plane through the thorax and another imaginary transverse plane through the pelvis. According to the laws of physics, only muscles that pass through both of these planes are capable of imposing loads on the lumbar spine. EMG is used to monitor every major muscle group that passes through both of these two planes. The lumbar motion monitor tracks the positions of the two planes relative to one another and permits adjustment of muscle activity for muscle length and velocity. This information is used to assess the muscle force associated with each muscle. These forces are represented as vectors acting between these two imaginary planes. Magnetic resonance imaging data have been collected to ensure that origin and insertions of muscle vectors are anatomically realistic and adjusted for gender differences and muscle fiber orientation [46]. Summation of muscle forces in each cardinal plane is used to compute spinal forces. Comparison of model-predicted external moment with measured external moment

is used as a validation measure. The model has been validated for forward bending [36,40], lateral bending [42] and twisting [41] exertions. Adjustments to muscle location and size were also made relative to each subject's body mass index [47] because the LBP group was considerably heavier than the asymptomatic group yet similar in stature.

Statistical analyses

Analysis of kinematic status was performed using analysis of variance procedures to determine significant differences between the asymptomatic and patient groups for each of the dependent kinematic motion parameters. Multiple comparisons were made using Bonferoni adjustments.

Before statistical testing, log transformations were performed on spine loading data to ensure normality and variance equality between subject groups [48]. Statistically significant differences in spine loading assessments were identified by means of a repeated measures analysis of covariance structure analysis implementing mixed modeling procedures using SAS software [49]. The procedure allowed for fixed effects as well as random effects. Fixed effects were lift origin region, weight, asymmetric position and subject group. Random effects were the result of the subjects. Mixed modeling procedures were used to identify significant differences resulting from the main effect of subject group, lift origin region, weight, asymmetry position and all two- and three-way interactions as a function of spine loading measures, moments, trunk kinematics and pelvic kinematics. Post hoc contrasts were employed to identify the significant differences between asymptomatic and patient groups within each asymmetric condition, weight level, lift origin region and their interactions at the 0.05 level of significance.

Results

Spine loads were significantly ($p < .01$) greater in the LBP group compared with the asymptomatic group. Over all conditions, compression was about 11% greater and A/P shear about 18% greater in the patients with LBP. Statistically significant increases in spine loading were noted as a function of lift origin region, lift asymmetry position and the magnitude of the weight lifted for the LBP group compared with the asymptomatic group among most of the dimensions of spine loading. Compression and A/P shear values were of greater magnitude and greater relative difference than the lateral shear values. Table 3 summarizes the statistically significant effects and interactions as a function of the subject group (LBP vs. asymptomatic).

Figs. 3 and 4 show the difference in compression and A/P shear, respectively, between the asymptomatic and LBP groups as a function of lift origin region. Under all lift origin conditions LBP subjects exhibited greater compression and A/P shear. However, the relative difference varied as a function of the region. Under the most biomechanically taxing

Table 3
Statistical analysis p values for differences between experimental group and the interaction of experimental conditions and group

Effect	Spinal loading		
	Compression	Lateral shear	Anteroposterior shear
Subject group	0.0001 [†]	0.6577	0.0003 [†]
Subject group*region	0.0005 [†]	0.0001 [†]	0.0002 [†]
Subject group*weight	0.3157	0.0571	0.9611
Subject group*region*weight	0.9853	0.9904	0.9638
Subject group*asymmetry	0.0001 [†]	0.0001 [†]	0.5137
Subject group*region*asymmetry	0.0720	0.0013 [†]	0.0042 [†]
Subject group*weight*asymmetry	0.5905	0.8904	0.9309

[†]Indicates significant differences at $p < .05$ adjusting for the number of comparisons.

lift origin region conditions, both compression and A/P shear differences between the subject groups were the smallest observed (10% to 13% difference in compression for the far-knee, far-waist and knee regions, and 11% to 19% differences in A/P shear for the same lift origin regions), whereas the largest relative differences between the subject groups occurred at the least taxing lift origin regions (25% to 30% difference in compression for shoulder and waist regions and 24% to 35% difference in A/P shear for the same regions).

Similarly, subjects with LBP always exhibited greater compression and A/P shear loading under all symmetric/asymmetric conditions compared with the asymptomatic subjects. Figs. 5 and 6 indicate that compression and A/P shear differences were greater between subject groups when lifting clockwise (CW) compared with lifting from counterclockwise (CCW) asymmetries (over twice as much compression difference between LBP and asymptomatic groups when lifting in CW positions compared with CCW positions). The same trend held for lateral shear, but the dif-

ferences were not as great in magnitude with greater differences between subject groups seen in CW lifts compared with CCW lifts (about 3% difference in increase between directions).

A significant difference between LBP and asymptomatic individuals also was present for the unique combinations (interaction) of lift origin region and asymmetry. Consistent with the previous patterns, patients with LBP exhibited greater A/P shear loads under many of the condition combinations. As shown in Figs. 7, A and B, many of the lift origin/asymmetry combinations were significantly greater (20% to 30%) in A/P load for the LBP group. Of particular interest were the differences in loads between subject groups at the far-knee origin region in combination with the CW and CCW asymmetries. Little difference existed in the symmetric A/P loads between subject groups. However, far greater A/P loads (15% to 30%) occurred at the asymmetric lifting positions under the far-knee lift origin regions. This condition was of particular concern because the loads approached or exceeded 1,000 N in shear, which is often considered the tolerance limit for A/P shear [42].

Significant differences in compression and lateral shear occurred as a function of the weight handled between the LBP and the asymptomatic group. In all cases the LBP group exhibited more loading compared with the asymptomatic group. However, the differences in loading between subject groups were greatest at the lower weights of lift. Compression differences were approximately 3% different, and lateral shear differences were about 5.3% different under the 4.5-Kg lifting condition. As the weight increased, this difference in spine loading decreased to the point where at 11.4 Kg the loading differences between subject groups were minimal as a result of weight lifted.

Significant muscle usage differences were observed between subjects groups. As shown in Fig. 8, statistically greater activity was observed in the LBP group for all muscle groups except for the erector spinae muscle group. Average increases in muscle activities in the LBP group

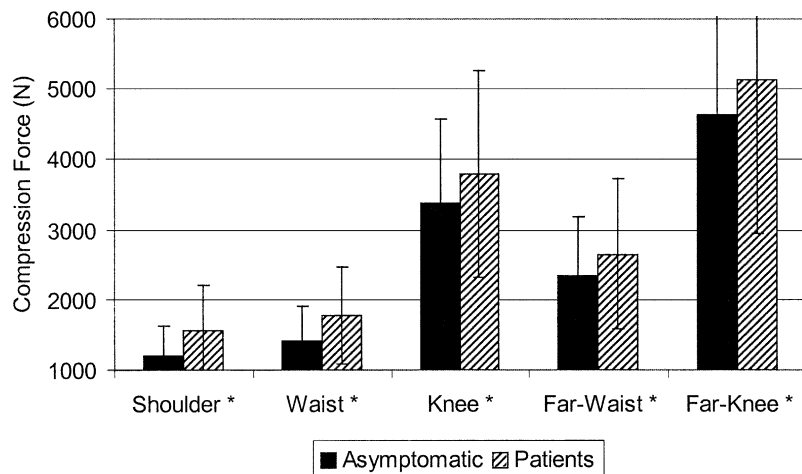


Fig. 3. Compressive force as a function of lift origin and subject group (* indicates significant differences between groups, $p < 0.05$).

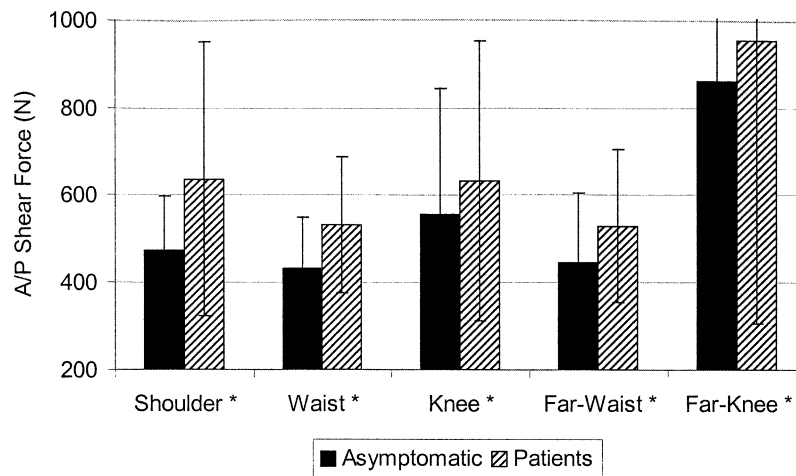


Fig. 4. A/P shear force as a function of lift origin and subject group (* indicates significant differences between groups, $p < 0.05$).

compared with the asymptomatic group were on the order of 32%.

Many trunk kinematic measures were significantly different between the LBP and asymptomatic groups as a function of the various experimental conditions. Table 4 summarizes the statistically significant ($p < .01$) differences in kinematic measures between the two groups during the lifting exertions. In most cases the LBP group exhibited significantly lower values in kinematics compared with the asymptomatic participants. This table indicates that, in particular, the asymmetry conditions resulted in a multitude of differences in lateral motion, twisting motion and pelvic rotation. In all cases the end result of these changes was to minimize the moment for participants with LBP.

Discussion

This effort represents a first step toward quantitatively matching a patient's specific abilities to an acceptable level of spine loading experienced during a lifting exertion. The load magnitudes selected for this study were purposely

designed to represent the load magnitudes commonly recommended in return-to-work programs. The results demonstrate that in those with LBP, spine loading is increased relative to asymptomatic counterparts over a series of lifting exertions representative of those expected in a work environment.

Some of the most surprising findings of this study involved the nature of the relationship between the LBP patients' spine loadings and specific workplace conditions. The general pattern of spine loadings in asymptomatic individuals behaved as expected [50,51], varying as a function of lift origin region, lift asymmetry position and weight lifted. However, the nature of the differences in spine loading patterns between the patients with LBP and asymptomatic subjects among the experimental conditions were not expected. These findings provide several significant insights into the functioning of the trunk's musculoskeletal system in response to the experience of LBP. Several unique findings are worthy of discussion.

First, when the percent change in spine loading was considered as a function of lift origin region, larger differences between LBP and asymptomatic subject groups were observed in lift origin regions that would be expected to be

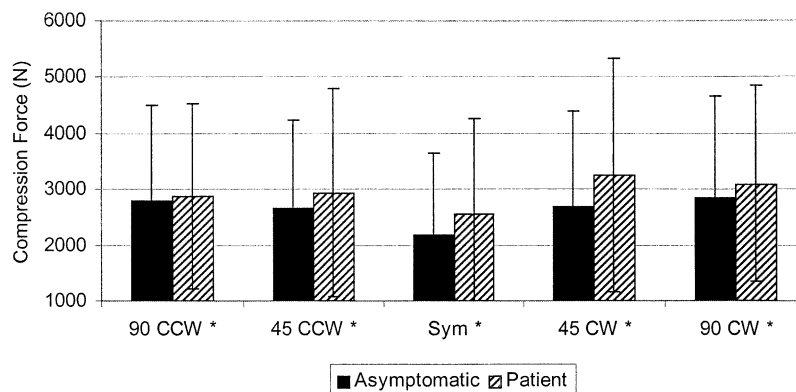


Fig. 5. Compression force as a function of lift asymmetry position and subject group (* indicates significant difference between group, $p < 0.05$).

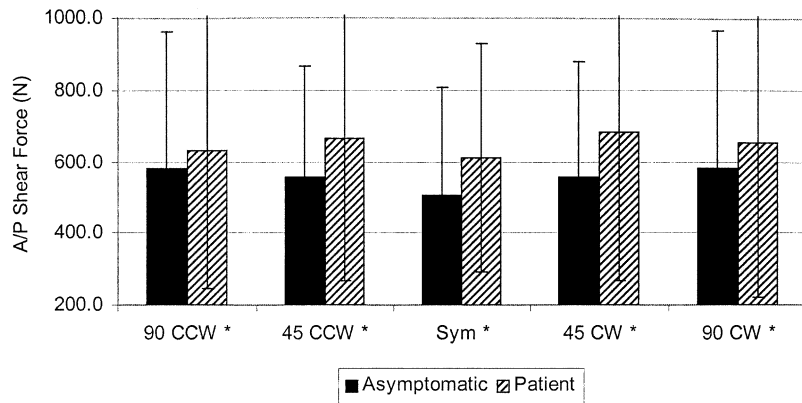


Fig. 6. A/P shear force as a function of lift asymmetry position and subject group (* indicates significant difference between group, $p < 0.05$).

the least stressful, biomechanically. In the cases of both compression and A/P shear, Figs. 3 and 4 indicated that the largest difference in loading between patients with LBP and asymptomatic individuals occurred in the shoulder lift origin region followed by the waist lift origin region. In absolute terms, these lift origin regions are the least taxing on the biomechanical system. However, the relative increase in loading among the subjects with LBP compared with the asymptomatic group is large (25% to 35%) in these two regions. Thus, patients with LBP pay a greater relative biomechanical cost for lifting in these regions. Most notably, the increased A/P shear observed in the shoulder lift origin region in the LBP group resulted in a mean shear value that exceeded that in the knee lift origin region for both the LBP and asymptomatic subjects, whereas A/P shear in the shoulder region was lower than that in the knee region for the asymptomatic subjects.

Examination of the kinematic profiles recorded during lifting exertions revealed that the LBP patients' mean sagittal plane angular hip velocities and accelerations were equal to or even greater than those of the asymptomatic group under

these presumably less taxing conditions. Hence, there appears to be a musculoskeletal trade-off occurring where LBP subjects employ greater hip movement in lieu of torso motion. Examination of the EMG data recorded during the lifting exertions revealed significantly increased activities (up to 60%) for the LBP subjects compared with the asymptomatic group in all muscles except the erector spinae group in the shoulder and waist lift origin regions. These findings indicate that the musculoskeletal system increases antagonistic coactivation as a means to control or "guard" against this increased kinematic task demand. It is interesting that less erector spinae activity is displayed compared with the asymptomatic group. This indicates a very different coactivation strategy in the LBP group compared with the asymptomatic group. It is this "different" coactivation pattern that results in increases in spine loading in the LBP group.

Second, perhaps the most unexpected pattern involving differences in loading between the LBP group and the asymptomatic group involved the asymmetric lift position variable. Fig. 5 indicated that the differences in compression between the LBP group and the asymptomatic groups

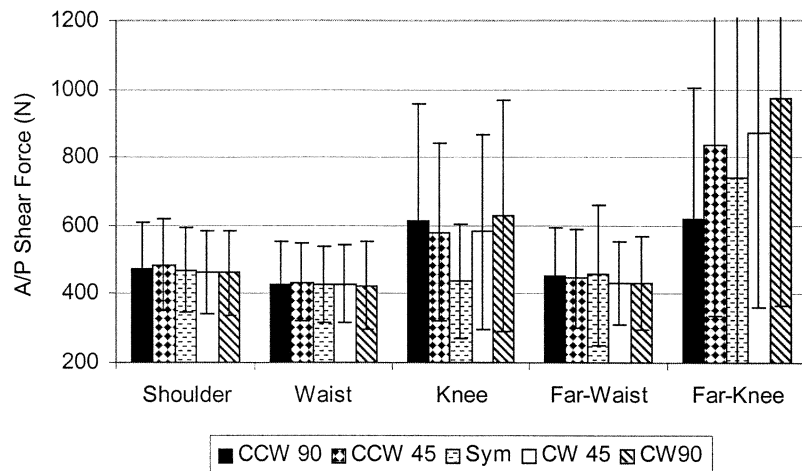


Fig. 7a. A/P shear lift origin by asymmetry position interaction for the asymptomatic group.

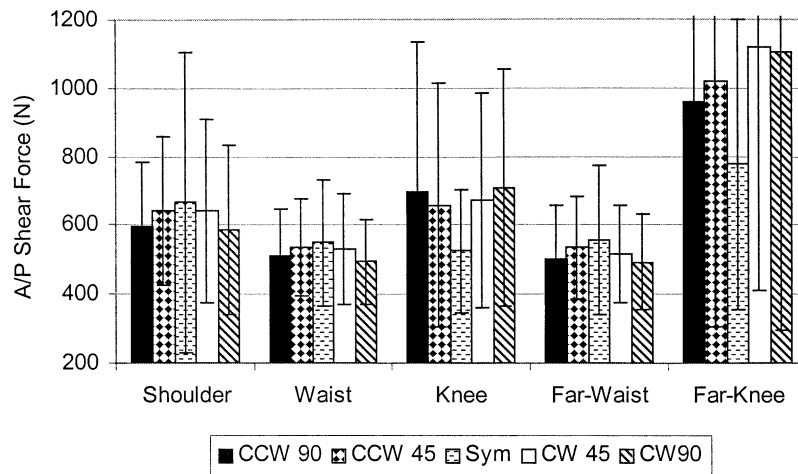


Fig. 7b. A/P shear lift origin by asymmetry position interaction for the patient group.

were over twice as large in the CW asymmetries compared to the CCW asymmetries. Such differences had not been reported earlier. However, no previous spine loading studies involving patients with LBP have explored the effects of asymmetric lifting. Our results indicate little difference between CW and CCW compression values within the asymptomatic group, yet increases in compression in CW compared with CCW movements within the patients with LBP. Table 4 revealed that spine lateral kinematics as well as pelvic rotation kinematics changed significantly between subject groups as a function of asymmetry position, thus indicating the adoption of alternative lifting strategies in the LBP group. However, these adaptations occurred only as a function of CCW asymmetry. Kinematic measures were essentially the same during lifting in the CW direction for both groups of subjects. Yet, as was the case for differences observed as a function of lift origin region, the musculoskeletal system was taxed to a greater degree in the CW direction compared with the CCW direction. It is unclear why the LBP group

did not choose to adopt alternative lifting strategies in the CW direction as they did in the CCW direction.

Interesting differences in antagonistic coactivation also occurred as a function of the asymmetric lifting positions. Under most conditions the LBP group coactivated the trunk muscles to a much greater extent than the asymptomatic group. Examination of the CW-CCW differences in EMG patterns indicated that subjects with LBP coactivated 8 of the 10 trunk muscles to a greater degree in the CW direction compared with the CCW direction. This greater muscle activation in the CW direction was responsible for the greater loading. It was also interesting to note that when the subject pain diagrams were reviewed, twice as many subjects reported right-side pain compared with left-side pain. Thus, the majority of subjects might have increase guarding when rotating CW.

Third, to a lesser extent than expected, load weight magnitude also played a role in spine loading differences between

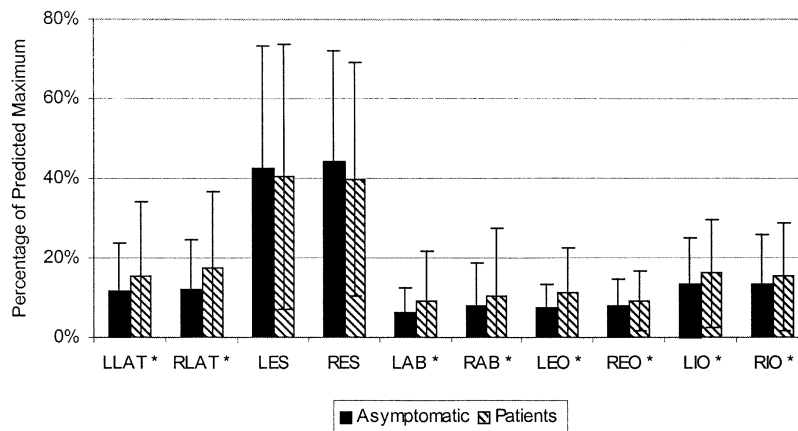


Fig. 8. Percentage of predicted maximum muscle activity shown as a function of subject group (* indicates significant difference between group $\alpha=0.05$; LLAT=left latissimus dorsi; RLAT=right latissimus dorsi; LES=left erector spinae; RES=right erector spinae; LAB=left rectus abdominus; RAB=right rectus abdominus; LEO=left external oblique; REO=right external oblique; LIO=left internal oblique; RIO=right internal oblique).

Table 4
Significant differences for trunk and pelvic kinematic measures during lifting tasks

Effect	Minimum position	Maximum position	Maximum velocity	Maximum deceleration	Maximum acceleration
Subject group		P		S, L	S, L
Subject group*region	S, L, P	S, P	S, P	S, L, P	S, P
Subject group*weight		P		S	
Subject group*region*weight					
Subject group*asymmetry	L, T, R	L, T, P, R	L, P, R	L, T,	L, T, P, R
Subject group*region*asymmetry	L				S
Subject group*weight*asymmetry					

L=significant differences for side-to-side trunk motion; P=significant difference for pelvic tilt; R=significant differences for pelvic rotation; T=significant differences for transverse trunk motion; S=significance for sagittal trunk motion. $p < .05$ adjusted for multiple comparisons.

LBP and asymptomatic subjects. In general, larger differences between the LBP and asymptomatic subjects groups were observed at the lower weight levels, but these differences were rather minor compared with the asymmetry and lift origin differences. As with the other significant spine loading differences, differences in loading could also be explained by differences in muscle coactivations. These findings again suggest that the largest differences in spine loading between asymptomatic subjects and patients with LBP are found in the least taxing conditions.

One might question why the relative differences in loading were greater in the least taxing biomechanical conditions. It would appear that these less biomechanically taxing positions provide the opportunity for patients with LBP to increase spine coactivity in an attempt to increase spine stability [52–54]. There is no need for an intact (asymptomatic) individual to co-contract to the same degree as patients with LBP in these postures. However, under the more taxing external loading conditions, both groups of subjects sense the need to control trunk motion and stability to a greater degree and, therefore, coactivate the trunk muscles. In addition, under greater external loading conditions system stability is inherent with greater magnitude loads. Thus, the difference between the groups is diminished. Hence, compared with asymptomatic workers, it appears that the least taxing activities would contribute relatively more to a cumulative trauma index compared with the more taxing tasks [55–57].

Thus, exertion conditions that would be considered relatively low stress, and would be considered good candidates for return to work tasks, may be more costly from a biomechanical perspective than expected. These findings are consistent with epidemiologic observations by Infante-Rivard and Lortie [58] who found that “pain associated with carrying out simple daily movements” were the best indicators of LBP relapse. Hence, their findings may indicate that the patients were experiencing greater spine loading in these simple tasks than would be expected.

Finally, these findings should be considered in perspective by recognizing potential study limitations. First, this study considered only the mechanical spine loading contribution to low back disorders. The literature recognizes that back

pain is multidimensional and involves many factors [7,9]. Second, not all the patients with LBP elected to perform all the exertions. Specifically, few subjects elected to perform the 90 CW or 90 CCW exertions when lifting the 9.1- and 11.4-Kg loads. Hence, the relationships observed in these extreme conditions might reflect only the less impaired subjects with LBP. Third, we elected not to normalize spine loading as a function of body weight in this study. A previous study [23] indicated that body mass normalization produces similar findings. However, the inclusion of such normalization would limit the applicability of the results. Hence, we elected to report the absolute spine loads because they would better reflect the loads expected during actual lifting exertions. Finally, the relationships described in this study involve subjects with LBP of muscular origin. It is unknown whether the relationship between kinematic status and LBP would be similar for LBP of structural origin.

Conclusions

1. Spine loading is greater in patients with LBP compared with asymptomatic individuals when performing similar lifting exertions. The difference in loading between LBP and asymptomatic individuals depends primarily on the lift origin location and to a lesser extent the weight of the object lifted.
2. Lift origin locations located at the least biomechanically taxing positions resulted in the greatest difference in loading between LBP and asymptomatic individuals. Clockwise asymmetric lifts yielded much greater spine loading in subjects with LBP compared with counterclockwise lifts.
3. The differences in spine loadings between the LBP and asymptomatic groups appear to be linked to differences in trunk muscle coactivation and possibly perceived needs for system stability.

Acknowledgments

This study was funded by the Ohio Bureau of Workers' Compensation. The assistance of Ms. Swetha Sivakumar,

Mr. Erich Theado, Ms. Lynn Michell and Mr. Christopher Hamrick in the execution of this study is gratefully acknowledged. In addition, we are grateful for the efforts of Dr. Robert Crowell and Dr. Daryl Sybert in subject recruitment.

References

- [1] Smedley J, Egger P, Cooper C, Coggon D. Prospective cohort study of predictors of incident low back pain in nurses. *Br Med J* 1997; 314:1225–8.
- [2] van Poppel MN, Koes BW, Deville W, Smid T, Bouter LM. Risk factors for back pain incidence in industry: a prospective study. *Pain* 1998;77:81–6.
- [3] Ferguson SA, Marras WS. A literature review of low back disorder surveillance measures and risk factors. *Clin Biomech* 1997;12:211–26.
- [4] Papageorgiou AC, Croft PR, Thomas E, Ferry S, Jayson MI, Silman AJ. Influence of previous pain experience on the episode incidence of low back pain: results from the South Manchester Back Pain Study. *Pain* 1996;66:181–5.
- [5] van Poppel MN, Koes BW, Deville W, Smid T, Bouter LM. Risk factors for back pain incidence in industry: a prospective study. *Pain* 1998;77:81–6.
- [6] MacDonald MJ, Sorock GS, Volinn E, Hashemi L, Clancy EA, Webster B. A descriptive study of recurrent low back pain claims. *J Occup Environ Med* 1997;39:35–43.
- [7] NRC. Musculoskeletal disorders and the workplace: low back and upper extremity. Washington, DC: National Academy Press, 2001.
- [8] Hamrick C. CTDs and ergonomics in Ohio. Paper presented at: International Ergonomics Association 2000/Human Factors and Ergonomics Society 2000 Congress; July 29–Aug 4, 2000; San Diego, CA.
- [9] NRC. Work-related musculoskeletal disorders: report, workshop summary, and workshop papers. Washington, DC: National Academy Press, 1999:229.
- [10] Adams MA, Freeman BJ, Morrison HP, Nelson IW, Dolan P. Mechanical initiation of intervertebral disc degeneration. *Spine* 2000;25: 1625–36.
- [11] Adams MA, McNally DS, Dolan P. “Stress” distributions inside intervertebral discs. The effects of age and degeneration. *J Bone Joint Surg Br* 1996;78:965–72.
- [12] Adams MA, McMillan DW, Green TP, Dolan P. Sustained loading generates stress concentrations in lumbar intervertebral discs. *Spine* 1996;21:434–8.
- [13] Liles DH, Deivanayagam S, Ayoub MM, Mahajan P. A job severity index for the evaluation and control of lifting injury. *Hum Factors* 1984;26:683–93.
- [14] Neumann WP, Wells RP, Norman RW, et al. Comparison of four peak spinal loading exposure measurement methods and their association with low-back pain. *Scand J Work Environ Health* 1999;25:404–9.
- [15] Norman R, Wells R, Neumann P, Frank J, Shannon H, Kerr M. A comparison of peak vs cumulative physical work exposure risk factors for the reporting of low back pain in the automotive industry. *Clin Biomech* (Bristol, Avon) 1998;13:561–73.
- [16] Danneels LA, Coorevits PL, Cools AM, et al. Differences in electromyographic activity in the multifidus muscle and the iliocostalis lumborum between healthy subjects and patients with sub-acute and chronic low back pain. *Eur Spine J* 2002;11:13–9.
- [17] Hubley-Kozey CL, Vezina MJ. Differentiating temporal electromyographic waveforms between those with chronic low back pain and healthy controls. *Clin Biomech* (Bristol, Avon) 2002;17:621–9.
- [18] Lu WW, Luk KD, Cheung KM, Wong YW, Leong JC. Back muscle contraction patterns of patients with low back pain before and after rehabilitation treatment: an electromyographic evaluation. *J Spinal Disord* 2001;14:277–82.
- [19] Ng JK, Richardson CA, Parnianpour M, Kippers V. EMG activity of trunk muscles and torque output during isometric axial rotation exertion: a comparison between back pain patients and matched controls. *J Orthop Res* 2002;20:112–21.
- [20] Larivie`re C, Gagnon D, Loisel P. A biomechanical comparison of lifting techniques between subjects with and without chronic low back pain during freestyle lifting and lowering tasks. *Clin Biomech* (Bristol, Avon) 2002;17:89–98.
- [21] Marras WS, Davis KG. A non-MVC EMG normalization technique for the trunk musculature: Part 1. Method development. *J Electromyogr Kinesiol* 2001;11:1–9.
- [22] Marras WS, Davis KG, Maronitis AB. A non-MVC EMG normalization technique for the trunk musculature: Part 2. Validation and use to predict spinal loads. *J Electromyogr Kinesiol* 2001;11:11–8.
- [23] Marras WS, Davis KG, Ferguson SA, Lucas BR, Gupta P. Spine loading characteristics of patients with low back pain compared with asymptomatic individuals. *Spine* 2001;26:2566–74.
- [24] Marras WS, Lavender SA, Leurgans SE, et al. The role of dynamic three-dimensional trunk motion in occupationally-related low back disorders. The effects of workplace factors, trunk position, and trunk motion characteristics on risk of injury. *Spine* 1993;18:617–28.
- [25] Marras WS, Lavender SA, Leurgans SE, et al. Biomechanical risk factors for occupationally related low back disorders. *Ergonomics* 1995;38:377–410.
- [26] Marras WS, Mirka GA. Electromyographic studies of the lumbar trunk musculature during the generation of low-level trunk acceleration. *J Orthop Res* 1993;11:811–7.
- [27] Marras WS, Mirka GA. A comprehensive evaluation of trunk response to asymmetric trunk motion. *Spine* 1992;17:318–26.
- [28] Granata KP, Marras WS, Fathallah FA. A method for measuring external loads during dynamic lifting exertions. *J Biomech* 1996;29: 1219–22.
- [29] Marras W, Fathallah F, Miller R, Davis S, Mirka G. Accuracy of a three dimensional lumbar motion monitor for recording dynamic trunk motion characteristics. *Int J Industr Ergonom* 1992;9:75–87.
- [30] Fathallah FA, Marras WS, Parnianpour M, Granata KP. A method for measuring external spinal loads during unconstrained free-dynamic lifting. *J Biomech* 1997;30:975–8.
- [31] Mayer TG, Smith SS, Kondraske G, Gatchel RJ, Carmichael TW, Mooney V. Quantification of lumbar function. Part 3: Preliminary data on isokinetic torso rotation testing with myoelectric spectral analysis in normal and low-back pain subjects. *Spine* 1985;10:912–20.
- [32] Kishino ND, Mayer TG, Gatchel RJ, et al. Quantification of lumbar function. Part 4: Isometric and isokinetic lifting simulation in normal subjects and low-back dysfunction patients. *Spine* 1985;10:921–7.
- [33] Davis KG, Marras WS, Waters TR. The evaluation of spinal loads during lowering and lifting. *Clin Biomech* (Bristol, Avon) 1998;13: 141–52.
- [34] Granata KP, Marras WS. An EMG-assisted model of loads on the lumbar spine during asymmetric trunk extensions. *J Biomech* 1993;26:1429–38.
- [35] Granata KP, Marras WS. The influence of trunk muscle coactivity on dynamic spinal loads. *Spine* 1995;20:913–9.
- [36] Granata KP, Marras WS. An EMG-assisted model of trunk loading during free-dynamic lifting. *J Biomech* 1995;28:1309–17.
- [37] Granata KP, Marras WS, Davis KG. Variation in spinal load and trunk dynamics during repeated lifting exertions. *Clin Biomech* (Bristol, Avon) 1999;14:367–75.
- [38] Marras WS, Reilly CH. Networks of internal trunk-loading activities under controlled trunk-motion conditions. *Spine* 1988;13:661–7.
- [39] Marras WS, Sommerich CM. A three-dimensional motion model of loads on the lumbar spine: I. Model structure. *Hum Factors* 1991; 33:123–37.
- [40] Marras WS, Sommerich CM. A three-dimensional motion model of loads on the lumbar spine: II. Model validation. *Hum Factors* 1991; 33:139–49.

- [41] Marras WS, Granata KP. A biomechanical assessment and model of axial twisting in the thoracolumbar spine. *Spine* 1995;20:1440–51.
- [42] Marras WS, Granata KP. Spine loading during trunk lateral bending motions. *J Biomech* 1997;30:697–703.
- [43] Marras WS, Granata KP. The development of an EMG-assisted model to assess spine loading during whole-body free-dynamic lifting. *J Electromyogr Kinesiol* 1997;7:259–68.
- [44] Mirka GA, Marras WS. A stochastic model of trunk muscle coactivation during trunk bending. *Spine* 1993;18:1396–409.
- [45] Reilly CH, Marras WS. Simulift: a simulation model of human trunk motion. *Spine* 1989;14:5–11.
- [46] Marras WS, Jorgensen MJ, Granata KP, Wiand B. Female and male trunk geometry: size and prediction of the spine loading trunk muscles derived from MRI. *Clin Biomech (Bristol, Avon)* 2001;16:38–46.
- [47] Wood S, Pearsall DJ, Ross R, Reid JG. Trunk muscle parameters determined from MRI for lean to obese males. *Clin Biomech (Bristol, Avon)* 1996;11:139–44.
- [48] Neter J, Wasserman W, Kutner M. *Applied linear regression models*. Boston, MA: Irwin, 1989:145.
- [49] SAS. *SAS Language*. Raleigh, NC: SAS Institute, Inc., 2001.
- [50] Marras WS, Granata KP, Davis KG, Allread WG, Jorgensen MJ. Effects of box features on spine loading during warehouse order selecting. *Ergonomics* 1999;42:980–96.
- [51] Marras WS, Davis KG. Spine loading during asymmetric lifting using one versus two hands. *Ergonomics* 1998;41:817–34.
- [52] Cholewicki J, McGill S. Mechanical stability of the in vivo lumbar spine: implications of injury and chronic low back pain. *Clin Biomech (Bristol, Avon)* 1996;11:1–15.
- [53] Cholewicki J, VanVliet IJ. Relative contribution of trunk muscles to the stability of the lumbar spine during isometric exertions. *Clin Biomech (Bristol, Avon)* 2002;17:99–105.
- [54] Panjabi MM. The stabilizing system of the spine. Part I. Function, dysfunction, adaptation, and enhancement. *J Spinal Disord* 1992;5:383–9,397.
- [55] Callaghan JP, Salewytch AJ, Andrews DM. An evaluation of predictive methods for estimating cumulative spinal loading. *Ergonomics* 2001;44:825–37.
- [56] Kumar S. Cumulative load as a risk factor for back pain. *Spine* 1990;15:1311–6.
- [57] Seidler A, Bolm-Audorff U, Heiskel H, et al. The role of cumulative physical work load in lumbar spine disease: risk factors for lumbar osteochondrosis and spondylosis associated with chronic complaints. *Occup Environ Med* 2001;58:735–46.
- [58] Infante-Rivard C, Lortie M. Ralapse and short sickness absence for back pain in the six months after return to work. *Occup Environ Med* 1997;54:328–34.