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Spine loading as a function of lift frequency, exposure duration, and work experience

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Abstract

Background. Physiological and psychophysical studies of the effects of lifting frequency have focused on whole-body measurements of fatigue or subjective acceptance of the task and have not considered how spine loads may change as a function of lift frequency or lift time exposure. Our understanding of biomechanical spine loading has been extrapolated from short lifting bouts to the entire work day and may have led us to incorrect assumptions. The objective of this project was to document how spine loading changes as a function of experience, lift frequency, and lift duration while repetitively lifting over the course of an 8-h workday.

Methods. Twelve novice and twelve experienced manual materials handlers performed repetitive, asymmetric lifts at different load and lift frequency levels throughout an 8-h exposure period. Compression, anterior–posterior shear, and lateral shear were evaluated over the lifting period using an EMG-assisted biomechanical model.

Results Spinal loads increased after the first 2 h of lifting exposure regardless of the lift frequency. Loading was also greater for the inexperienced subjects compared to experienced lifters. The greatest spine loads occurred at those lift frequencies and weights to which the workers were unaccustomed.

Interpretation. Increases in spine loading were tracked back to the changes in muscle recruitment patterns that typically involved increased muscle coactivation. The results emphasize the importance of previous motor programming in defining spine loads during repetitive lifting. These results indicate a very different influence of frequency and lift time exposure compared to physiologic and psychophysical assessments. This study has shown that it is not sufficient to extrapolate from short lift periods to extended exposure periods if the biomechanical loading implications of the task are of interest.

Keywords: Low back pain; Spine loads; Electromyography; Modeling; Ergonomics

1. Introduction

In many occupational circumstances low back disorders (LBDs) are believed to be related to cumulative trauma exposure and, therefore, also repetitive lifting exposure (Marras, 2003; Marras and Kim, 1993; Marras et al., 1995; Anderson, 1988; Kelsey et al., 1984; Magora, 1975). With the increased number of distribution centers in the US, an even greater exposure to repetitive lifting is expected in the years to come. Hence, extended periods of materials handling continues to be a concern for occupational health.

Previous studies exploring the relationship between lift frequency and LBD risk have based their recommendations upon whole-body physiological fatigue, whole-body psychophysical assessments, and short duration biomechanical assessments. Physiological and psychophysical studies have found that increases in lift frequency were monotonically related to increases in heart rate, oxygen consumption and energy expenditure (Ciriello et al., 1990; Garg, 1989; Karwowski and Yates,

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1986; Legg and Pateman, 1984; Mital, 1987a; Petrofsky and Lind, 1978; Welbergen et al., 1991; Wu and Hsu, 1993). Electromyography-based studies indicated that repetitive lifting may fatigue the back muscles and the muscular load on the low back would be expected to increase with higher lift frequencies (Dolan and Adams, 1998; Bonato et al., 2003; Nielsen et al., 1998). However, these studies only examined a limited number of muscles during the lifting task and did not evaluate the influence of muscle coactivation upon spine loading. Psychophysical studies have found that increases in lift frequency resulted in decreases in the maximum acceptable weight of lift (MAWL) (Ayoub et al., 1980; Ciriello et al., 1990; Garg, 1989; Garg and Saxena, 1979; Karwowski and Yates, 1986; Mital, 1987a,b; Snook, 1978; Snook and Ciriello, 1991; Wu and Hsu, 1993) accompanied by increases in the perception of fatigue and level of exertion (Garg, 1989; Genaidy and Al-Rayes, 1993; Karwowski and Yates, 1986; Legg and Pateman, 1984). Hence, subjects perceive that increased rates of lift are more costly to the body.

Physiological and psychophysical studies rely upon the assumption that whole-body measurements are directly related to a pain mechanism in the lower back (Leamon, 1994). While several studies have examined the effects lifting speed (Marras et al., 1993, 1995) biomechanical evaluations of lift frequency are limited (Garg, 1989; De Looze et al., 1996). The effect of lifting speed may not be strongly associated with lift frequency within the range of realistic lifting frequencies. In addition, interpretations of these frequency assessments were limited by the confounding of higher frequencies with lower weight exposure. In addition, neither study considered the effect of lift frequency on muscle coactivation patterns which would more accurately predict spinal loading. Thus, much of the research investigating the effect of changing lift frequency may not accurately or adequately represent risk of injury to the lower back.

Biomechanical investigations of spine loading, to date, have been restricted to analyses of brief periods of lifting (Granata and Marras, 1993; Marras and Granata, 1997a,b; Snook and Ciriello, 1991). During these lifting bouts, subjects performed a limited number of exertions and spine load magnitudes were assumed to represent those experienced throughout the course of a workday. However, several studies exploring motor recruitment patterns resulting from fatigue (Marras and Granata, 1997a,b; Parnianpour et al., 1988; Sparto et al., 1997a; Sparto et al., 1997b) suggest that repetitive lifting over the course of an extended period may indeed influence the motor recruitment pattern and result in changes in the loading pattern on the spine. In addition, one would expect that exposure to given lifting frequencies due to extensive task experience might establish a preference for a specific motor recruitment patterns that could bias spine loading and, potentially, over-ride the effects of lift frequency requirements. Nonetheless, there exists a void in the literature in that these spine loading issues have been under explored during long duration lifting bouts.

Therefore, the primary objective of this study was to determine how spine loading changes in response to lift frequency exposure, weight lifted, and lift period duration over an 8-h work day. A secondary objective was to expose any differences in the spinal loading responses to lift frequency and lift duration between novice and experienced manual materials handlers.

2. Methods

2.1. Approach

The purpose of this study was to assess how spine loading changes in response to subject experience, load weight, lift frequency, and duration of lifting exposure. This study required both experienced and inexperienced subjects to lift under one of three weight conditions (moment exposure) over six different days where a different lift frequency was assigned on each day. Subjects were asked to lift for an entire 8-h period. An EMG-assisted biomechanical model was used to estimate spine loading throughout the 8-h lifting period.

2.2. Subjects

Twenty-four participants (3 females and 21 males) with no prior history of low back pain (LBP) volunteered for this study and received an hourly wage plus a bonus for finishing all test conditions. Twelve novice (no manual material handling experience) and twelve experienced manual material handlers (at least one year experience) served as subjects. Subjects' ages ranged from 19 to 33 years. The average (SD) stature and weight for novices was 177 cm (8 cm) and 75 kg (15 kg), respectively and for experienced subjects was 177 cm (4 cm) and 81 kg (16 kg), respectively.

2.3. Experimental design

The experimental design consisted of a repeated measures design with two between-subjects factors (load moment and experience) and one within-subjects factor (lift frequency). The *independent variables* included experience level, load moment, lift frequency, and time block. The initial load moment to which the subject was exposed was defined by three initial static load moment levels (8, 36, and 85 N m). In order to control this initial moment exposure, subjects were positioned on a force plate relative to the position origin of one of three loads (1.1, 4.9, or 11.7 kg). Subjects were exposed to only one of the load moment conditions but were tested under all frequency conditions. Hence, they lifted the safe load but under different lift frequency conditions on each test day. The lift frequency consisted of six levels: 2, 4, 6, 8, 10, and 12 lifts/min (lpm). Subjects were tested on six separate 8-h sessions, once under each frequency condition. Presentation order of the lift frequency condition was randomized. All test sessions were separated by at least one day of rest. The effect of time was evaluated by dividing the 8-h work day into four 2-h blocks of time. Two experience levels, novice (no manual material handling (MMH) experience) and experienced (at least 1 year of full-time MMH experience) were chosen so that results could be applicable to a wide range of MMH workers.

The *dependent measures* consisted of the three-dimensional spine loading predicted by an electromyography (EMG)-assisted biomechanical model (described below) during the experimental task lifts. Compression, Anterior–posterior (A/P) shear, and lateral shear were all predicted by the model. Spine loading information was collected for one lift cycle every 10 min throughout the 8-h session. Data were averaged over 2-h periods so that exposure time could be assessed. In order to allow for comparisons between subjects, spinal loading was normalized to the subject's body weight.

2.4. Apparatus and spine load estimates

EMG activities of the ten muscles (erector spinae, latissimus dorsi, external oblique, internal oblique, and rectus abdominus on both the right and left sides of the body) were required as input to the EMG-assisted biomechanical model. EMG data were collected using bipolar surface electrodes spaced approximately 3 cm apart over the ten trunk muscles' sampling locations (Mirka and Marras, 1993). The myoelectric data were low-pass filtered at 500 Hz, high-pass filtered at 30 Hz, rectified, and averaged using 20 ms sliding window filter. All EMG signals were normalized relative to the maximum voluntary contraction values collected prior to experimental testing.

Trunk kinematics were monitored using a tri-axial goniometer (Lumbar Motion Monitor or LMM) (Biodynamics Solutions, Columbus, Ohio USA), designed to measure the instantaneous three-dimensional motion of the lumbar trunk (Marras et al., 1992). The device design specifications and accuracy have been reported previously (Marras et al., 1992). Trunk moment exposure was monitored as the subjects stood on a force plate (Bertec 4060A; Bertec, Worthington, Ohio, USA). The position of the spine relative to the force plate and the pelvic orientation was evaluated using a goniometric system described by Fathallah et al. (1997).

The EMG-assisted biomechanical model used to evaluate spine loads was developed in the Biodynamics Laboratory at the Ohio State University over the past 20 years. This model has been validated for robustness in sagittal bending (Granata and Marras, 1993) and lateral bending (Marras and Granata, 1997a,b), axial twisting (Marras and Granata, 1995), as well as lowering exertions (Davis et al., 1998), and repetitive lifting (Marras et al., 1999). The model also takes into account gender-based anatomical differences in the muscle size as well as origin and insertion points (Marras et al., 2001; Jorgenson et al., 2001).

2.5. Experimental task

Subjects performed whole body free-dynamic lifts, representative of a common repetitive industrial lifting operation (Marras et al., 1993). The task involved a vertical origin height of 88 cm, vertical destination height of 121 cm, origin moment arm distance of 74 cm, as well as an asymmetry of 90°. Two subjects performed the experimental task simultaneously. One subject lifted the load from a conveyer origin and placed it on another destination conveyer where it was delivered to the other subject. The second subject performed the identical task at the other end of the conveyor system (Fig. 1). The subject lift frequency was governed by a metronome that produced a tone when a lift was to take place. The pace of the lift (between tones) was left to the discretion of the subject. The task was repeated at the session's specified frequency for 8-h with typical industrial break schedules (two 15 min breaks and a half hour lunch break). The experiment was approved by the University Institutional Review Board.

2.6. Data normalization and analyses

Statistical significance was assessed using a repeated measures analysis of covariance structure. In this analysis, fixed effects consisted of lift frequency and time block. Subject experience and load moment conditions were considered between-subject variables. Because

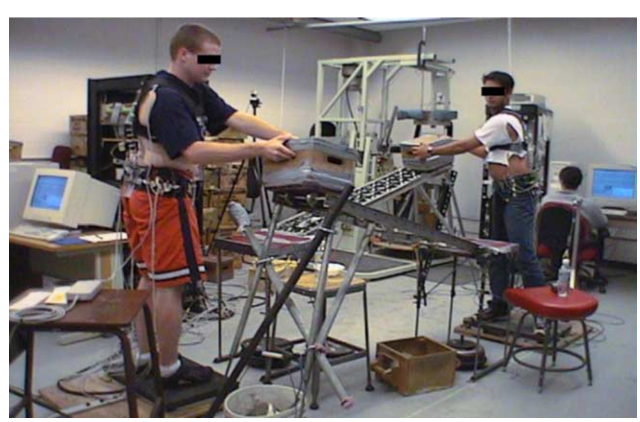

Fig. 1. Experimental set-up.

both random and fixed effects were present, the mixed procedures analysis of SAS was employed to identify significant effects and significant contrasts for their main and interactive effects on the three-dimensional spine loading. In this study, statistical significance was defined as an alpha level of 0.05 (SAS, 2001).

3. Results

Table 1 summarizes the statistically significant findings of this study. The analyses indicated that the three-dimensions of spinal loading were each affected by different factors. As expected, the normalized compression increased monotonically as moment exposure increased. The 85 N m moment resulted in an average increase of 12% greater compression than the 36 N m moment and the 36 N m level moment yielded 14% greater relative spine compression compared to 8 N m moment.

On average, experienced subjects exhibited 13% less compressive load on their spines compared to inexperienced subjects. However, this trend was dependent upon the magnitude of the moment exposure. As shown in Fig. 2, post hoc analyses indicated that only the 8 N m condition resulted in statistically significant differences between the experience groups ($P = 0.0008$). It is also interesting to note that regardless of moment exposure condition, novice subjects experienced similar compressive loads on the spine, whereas, experienced subjects responded as expected by increasing spinal compression when the moment increased. Even though average novice spine compression increased with moment exposure, the effect was statistically non-significant.

It is interesting to note that lift frequency, alone, did not significantly influence spine compression. However, frequency and moment, in combination, did influence spine compression in a complex manner. This trend is shown in Fig. 3. Under the 8 N m condition, the 8 lifts

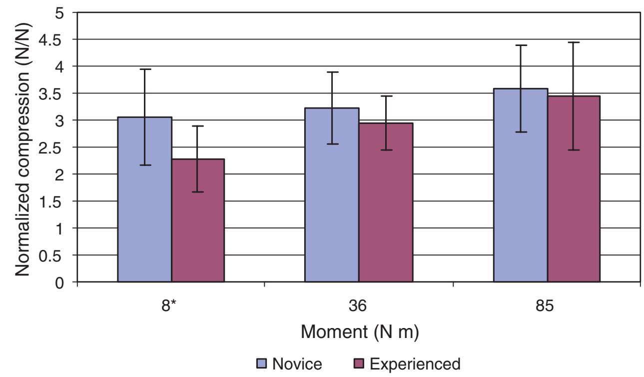

Fig. 2. Interactive effect of moment and experience on compressive loading (* indicates significant difference between novice and experienced subjects).

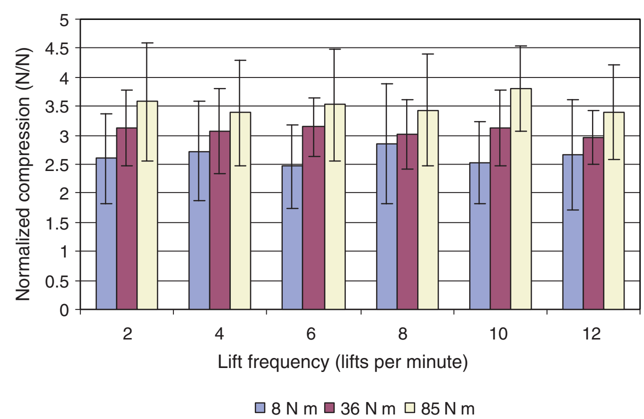

Fig. 3. Interactive effect of moment and frequency on compressive loading (N/N represents normalized to body weight).

per minute (lpm) condition yielded the highest compression. Under the 36 N m condition, average spine compression remained relatively constant at nearly all lift frequencies. However, the 85 N m moment exposure resulted in the greatest mean compression at 10 lpm followed by the 2 lpm conditions.

Frequency also influenced lateral shear force with the 8 lpm conditions yielding the greatest spine compression under all three moment exposure conditions. Fig. 4 indicates that this increase in lateral shear at the 8 lpm condition was dominated by the novice subjects response where their normalized shear was nearly twice that of the experienced subject. Novice subjects also exhibited significantly greater lateral shear loads under the 10 lpm condition compared to experienced subjects. However, at the highest lift frequency, 12 lpm, both novice and experienced subjects exhibited relatively low normalized lateral shear.

The duration of the lifting exposure (time) also had an unexpected significant influence on spine compression. As shown in Fig. 5, compression increased over

Table 1
Summary of statistically significant effects (* indicates significant p value)

Effect	Compression	A/P shear	Lateral shear
Moment	0.0002*	0.4802	0.4331
Experience	0.0043*	0.4962	0.0663
Frequency	0.8448	0.2426	<0.0001*
Time	0.0042*	0.7190	0.9517
Moment * experience	0.0432*	0.2108	0.0971
Moment * frequency	0.0024*	0.9258	0.1798
Moment * time	0.4255	0.0263*	0.6527
Experience * frequency	0.2621	0.9260	<0.0001*
Moment * experience * frequency	—	0.2009	0.0015*

—Term removed for reduced mixed model.

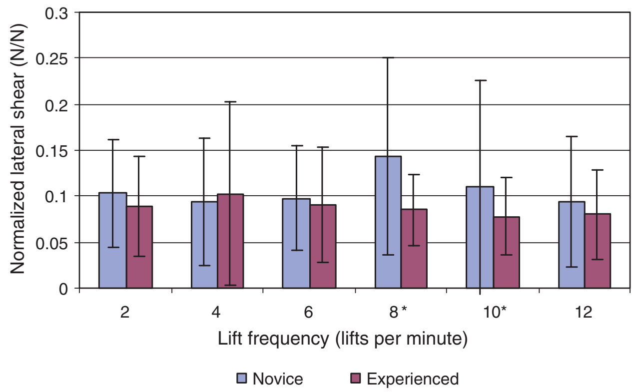

Fig. 4. Interactive effect of experience and lift frequency on lateral shear (* indicates significant difference between novice and experienced subjects) (N/N represents normalized to body weight).

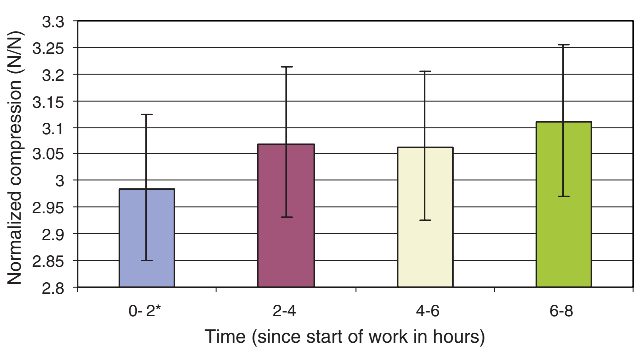

Fig. 5. Main effect of time of day on compressive loading. (* indicates significantly different from other time blocks) (N/N represents normalized to body weight).

the first 2 h of lifting exposure and then remained rather consistent throughout the duration of the lifting period. Fig. 5 indicates an increase in average normalized compression over last 2 h of lifting exposure, however, this increase was not statistically significant.

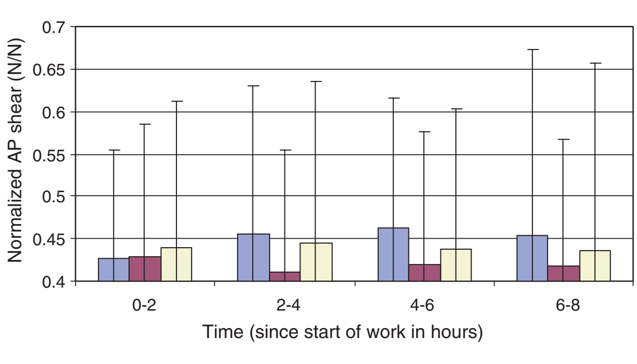

Fig. 6. Interactive effect of moment and time on A/P shear (N/N represents normalized to body weight).

The moment by time of exposure interaction significantly influenced A/P shear (Fig. 6). The trend appears to be dominated by the response of subjects under the 8 N m moment exposure condition. Under this condition, the first 2 h were significantly lower in A/P shear from the remainder of the day.

Fig. 7 shows the influence of the three-way interaction between experience, frequency, and moment upon lateral shear force in the spine. Of particular interest are the relatively high lateral shear forces experienced by the novice subjects in response to lift frequencies at or above 8 lpm. It was also interesting to note that at each lift frequency (except for the 8 lpm condition) the highest and lowest moment exposures produced the greatest lateral shear with the moderate moment exposure producing the lowest shear. A very different pattern was exhibited by the experienced subjects. The peak lateral shear value for the experienced group was 28% less than the peak value for the novice group. The lift frequencies at 6 lpm and below yielded the greatest lateral shear forces on the spine. In addition, at the 4 and 6 lpm frequencies the 36 N m condition yielded the greatest lateral shears. However, for frequencies of 8 lpm and greater, the lateral shear increased monotonically with moment exposure as would be expected.

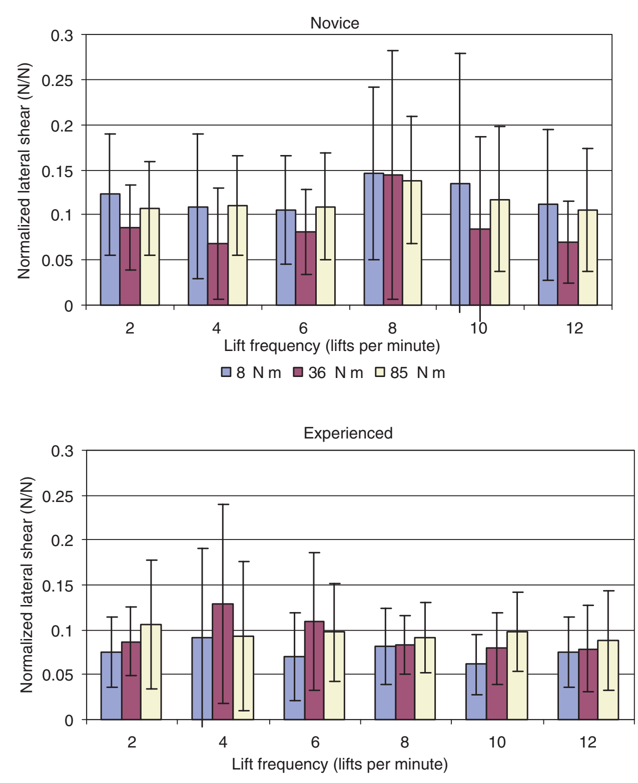

Fig. 7. Interactive effect of frequency and moment on novice and experienced subjects' lateral shears (N/N represents normalized to body weight).

4. Discussion

This study represents the first effort to consider biomechanical loading as a function of lift frequency and duration of lift under realistic three-dimensional lifting conditions over the course of an 8-h workday. The results demonstrated that spine loading is governed by a complex mixture of work related factors that affect the spine in multiple dimensions of loading. It is also obvious from these results that spine loading reflects the worker's experience in that motor programs are selected based upon MMH experience with duration of lifting, frequency of lifting, and load weight also influencing muscle recruitment profiles.

These findings suggest that the factors that influence biomechanical spine loading are not as intuitive as originally thought. It was expected that lift frequency would dominate the spinal loading patterns with greater spine loading occurring with greater lift frequencies and greater moment exposure. However, spine loading did not increase in such an orderly pattern. While compression did increase with increasing moment exposure, frequency affected complex spine loading in an unexpected manner. Furthermore, work experience played a large role in spine load determination. In-depth analyses of muscle coactivity (agonist compared to antagonist muscle activity) confirmed that many of the observed trends in spine loading were a result of statistically significant changes in the muscle coactivity (Parakkat et al., submitted for publication). It appears that frequency increases spine loading, through an increase in muscle coactivity, when subjects are exposed to conditions to which they are not accustomed. Experienced workers increased spine loading when they were forced to work at slower rates of lifts, whereas inexperienced workers increased their spine loads when they were forced to lift at faster paces. When load magnitude was considered, load magnitude interacted in an unexpected manner with frequency and experience. Experienced workers responded as expected with increasing spine load at greater load moment exposures only at greater lifting rates (which become more taxing and less common for them), whereas inexperienced subjects behaved in a very unpredictable manner with the lowest load moment often imposing greater than expected spinal load (again when exposed to repetitive conditions to which they were unaccustomed).

The non-monotonic spinal loading response to lift frequency suggest that motor programs are selected based upon the subject's perception of the task and from past experiences (Parakkat et al., submitted for publication). It is hypothesized that the subjects may have been more apt to utilize motor programs that correspond with those lift frequencies they commonly encountered. Parakkat et al. (2005) found that as experience is gained in an MMH task, spinal loading decreases because the pattern of muscle activation shifts from simultaneous to sequential contraction. It was found that novices had lower loading while lifting at the low frequencies (2, 4, 6 lpm) and that experienced subjects had lower loading while lifting at the high frequencies (8, 10, 12 lpm), thus giving an indication of the lift rates to which both populations were typically exposed. Novices may have responded with lower spinal loads to the low lift rates simply because these frequencies are associated with the daily activities of lifting. Similarly, experienced subjects may be exposed to higher lift rates at work and may therefore be able to adapt to these levels by selecting appropriate motor programs to minimize coactivity and, therefore, spinal loading levels (Parakkat, 2005). On the other hand, if the subject uses a previously developed motor program for another lift frequency, the neuromuscular response of muscle coactivity may be affected. These motor programs are not always suited for the lift frequency and the muscles are recruited to levels that are either too high or that are activated at inappropriate times, yielding high levels of coactivity and, in turn, results in unnecessarily high spinal loads.

Collectively, these trends point to a trend where spine loads increased when subjects were faced with lifting situations that they were not compatible with their preferred or "ingrained" motor recruitment patterns. For example, experienced workers are most likely used to lifting at greater frequency rates and have most likely optimized their muscle recruitment patterns so that they minimize cocontraction and the subsequent loading. Exposing these workers to slower lift rates could require them to recruit their muscles in a manner that is unnatural for them.

Inexperienced workers, on the other hand, have not developed a very sophisticated muscle recruitment model for themselves. Therefore, they co-contract under circumstances where one would expect minimal loading (i.e. low moment exposures). These observations might help explain the "survivor" effect that has been noted in the epidemiologic literature and might help explain the high injury and turnover rate often observed in new workers.

These findings suggest that the most important factor in determining muscle recruitment and subsequent spinal loading might be matching the motor program that the worker has developed for himself. This concept is consistent with the expectations of Erlandson and Fleming (1974) who suggested that motor control is driven by a satisfaction principle, where the match or mismatch between one's expectations of how one should recruit the muscles and what is actually required to perform a task determines the degree of cocontraction developed during a task.

Practically, these concepts point to a need to establish motor patterns through planned experiential activities.

Many of the martial arts use this concept as the basis for training.

Another unexpected finding of this study involved the influence of lift exposure duration (time). The largest spine compression increase in spine loading occurred during the first 2 h of lifting. The compressive force increased by 4% by the end of the 8-h session. A similar increase was notable under the 8 N m load moment conditions for A/P shear increases. The A/P shear load increased by 8% under the 8 N m exposure conditions. A review of the EMG data indicated that higher spinal loads occurred later in the day due to increased muscle coactivity.

Further analyses showed that the sagittal moment correspondingly increased significantly after the first 2 h of the day. This increase in sagittal moment may be due to a change in the coactivity patterns. If the subjects were experiencing increased muscular fatigue in the power producing muscles as the day progressed, they may be prompted to change their lifting technique. It is not known why subjects changed their lifting strategy during the course of the work day. One hypothesis may be related to the potential for muscle fatigue. Changes in coactivation patterns and lifting styles due to muscle fatigue have been noted previously in the literature (Trafimow et al., 1993).

Low back disorders are cumulative trauma disorders and are closely related with repetition. Prolonged exposure to repetitive lifting has been identified as a major risk factor for occupationally-related musculoskeletal disorders (Silverstein et al., 1986). The cumulative nature of LBD suggests that spinal loading increases throughout the day, as was shown in this study, while tolerance limits decrease. From this load–tolerance perspective, spinal loading may very well be well below the tolerance limits at the start of the workday, but will gradually increase up to or exceed the maximum permissible limits by the end of the shift. Although the spinal loading values in this study remained below the tolerance limits, the implications of the gradual spinal loading increase for MMH tasks that are more strenuous and variable than that in this study could be extremely detrimental and should be further investigated. Thus, these findings suggest that studies that extrapolate spine loading patterns observed during brief periods of lifting for an entire work day may not accurately represent the cumulative nature of LBP. In fact, studies that do extrapolate spine loading patterns may significantly underestimate spine loading for the end of the day.

There were several potential limitations of this study. First, the subjects were instrumented during the entire work day which may have introduced some discomfort affecting the results. However, this was necessary to obtain accurate measurements. Second, the experimental conditions represented in this analysis are only representative of a limited number of lifting situations. Third, in industry, most workers experience a mix of conditions that causes varied biomechanical responses. Given the vast variety of possible work conditions, it would be impossible to comprehensively evaluate the spectrum of potential repetitive lifting situations. However, the experimental situation evaluated here is based upon common high risk situations observed in industry (Marras et al., 1993). Future studies could use similar analyses to investigate spine loading associated with other forms of MMH work including pushing-pulling, carrying, lifting while the feet are moving, or seated work tasks.

5. Conclusions

The findings from this study indicate that spinal loading is a reflection of the motor program response which, in turn, is influenced by work experience and muscle activity redistribution that occurs throughout the day. The increased spinal loading levels exhibited by the novice workers due to under-developed motor control programs suggest that biomechanical risk is greatly reduced with experience. Thus, training that focuses on the proper sequencing of the muscle recruitment patterns, such as training provided to many who study some of the marshal arts might provide a means to minimize spine loading. Further research must be done to understand the effect that such programs would have on the development of MMH motor skills. The results also showed that biomechanical testing over short periods of time negates the effect of muscle fatigue and coactivation and can underestimate the cumulative effect of spinal loading.

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