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Variation in spinal load and trunk dynamics during repeated lifting exertions

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Abstract

Objectives. To quantify the variability in lifting motions, trunk moments, and spinal loads associated with repeated lifting exertions and to identify workplace factors that influence the biomechanical variability.

Design. Measurement of trunk dynamics, moments and muscle activities were used as inputs into EMG assisted model of spinal loading.

Background. Traditional biomechanical models assume repeated performance of a lifting task produces little variability in spinal load because the assessments overlook variability in lifting dynamics and muscle coactivity.

Methods. Five experienced and seven inexperienced manual materials handlers performed 10 repeated lifts at each combination of load weight, task asymmetry and lifting velocity.

Results. Box weight, task asymmetry and job experience influenced the magnitude and variability of spinal load during repeated lifting exertions. Surprisingly, experienced subjects demonstrated significantly greater spinal loads and within-subject variability in spinal load than inexperienced subjects. Trial-to-trial variability accounted for 14% of the total variation in compression overall and 32% in lateral shear load. Although the mean spinal load was safely below the NIOSH recommended limit; due to variability about the mean, more than 20% of the lifts exceeded the recommended limit.

Conclusion. Spinal load changed markedly from one exertion to the next despite identical task requirements. Trial-to-trial variability in kinematics, kinetics, and spinal load were influenced by workplace factors, and may play a role in the risk of low-back pain.

Relevance

Ergonomic assessments considering only the mean value of spinal load overlook the fact that a large fraction of the lifts may exceed recommended levels. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Spine loads; Biomechanical modeling; Low back disorders; Variability

1. Introduction

Ergonomic task analyses often assume a task is performed in a biomechanically repeatable manner. Most ergonomic tools and biomechanical models predict identical spinal load in repeated exertions given the same workplace parameters. However, evidence from motor control analyses and musculoskeletal measurements indicate the potential for significant variability during the repeated performance of a specific task. This variability may influence the interpretation of the results of ergonomic risk assessments.

Variability in biomechanical performance and spinal load during lifting tasks may influence the risk of low-back disorders (LBDs) associated with the task. Mirka and Marras [1] concluded that biomechanical variability influences the relative number of repeated exertions that might exceed the lifting guideline limits [2]. Fig. 1 illustrates the distributions of compressive load associated with two hypothetical tasks. One task may possess an average spinal load and a narrow distribution of loads resulting in a very low probability of any exertion exceeding spinal tolerance levels. A similar task may be associated with identical mean spinal load but a wide

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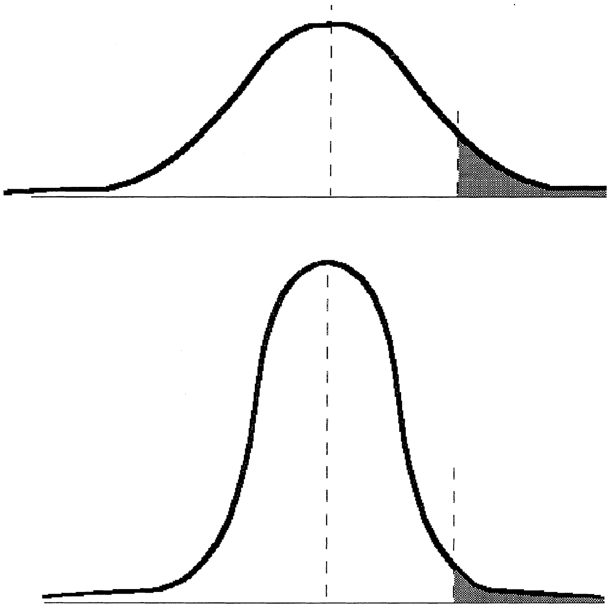

Fig. 1. As variability of biomechanical performance increases, the relative number of repeated exertions with spinal loads greater than recommended tolerance also increases, despite similar mean spinal load values.

distribution, resulting in a significant percentage of the repeated exertions that exceed spinal tolerance. However, because the mean values were similar, traditional ergonomic assessments may interpret the two tasks as equally safe.

Clearly, the risk associated with lifting exertions must be associated with the *variability* of the lifting biomechanics as well as the mean value. Therefore, workplace factors that influence the biomechanical variability associated with a lifting task subsequently influence the risk of exceeding injury tolerance and associated LBD risk. Although a specific workplace parameter may marginally reduce the spinal compression, if it also dramatically augments the variability, the benefits may be questionable.

To improve our understanding of the etiology of spinal loading and low-back pain risk, it is necessary to identify the biomechanical variability associated with lifting exertions as well as the workplace factors that influence that variability. A companion paper assesses the variability associated with performance of a model currently used to estimate spinal loads [3]. The objectives of this research were twofold. First, quantify the variability in lifting motions, trunk moment, trunk muscle activities, and spinal loads associated with repeated dynamic lifting exertions. Second, identify the workplace factors, including experience, that influence the variability associated with lifting tasks. We included work experience as a variable to evaluate whether more experienced workers were more consistent, i.e. reduced variability, in their lifting motions and spinal loads than inexperienced subjects.

2. Methods

Twelve healthy males with no prior history of LBD volunteered to participate in this study. The subject population included seven college students and five experienced manual materials handler (MMH) warehouse selectors from a local distribution center. The subjects' ages ranged from 22 to 34 years with an average age of 26.1 years. The average (SD) stature of the subject population was 179.2 (4.5) cm and the average weight was 74.7 (7.0) kg. Experienced and inexperienced subjects were similar in height – 180 and 179 cm, respectively, and in weight – 79.2 and 72.4 kg, respectively. Subjects were required to lift weighted boxes under various trunk velocity and asymmetry conditions from knee height to an upright posture. Lifting exertions were performed one at a time, with 1 min of rest between exertions to minimize the possibility of fatigue.

Independent variables consisted of two box weights (13.6 and 27.3 kg), two levels of task asymmetry (sagittally symmetric, 60° right), and two subjective lifting velocities (preferred lifting velocity, faster than preferred). Asymmetric tasks were achieved by requiring the subject to lift the weighted box from a knee-height platform located 60° to the subject's right. The weight and asymmetry conditions were chosen to represent the typical range of conditions observed among low and high risk (of LBD) industrial jobs [4,5]. The subjective velocity levels of "preferred" and "faster than preferred" lifting styles were chosen to permit examination of two lifting velocities without artificially influencing the natural motion variability. Each condition was repeated 10 times. The trials were randomized with respect to weight, asymmetry, lifting velocity and repetition number.

EMG data were collected from bipolar surface electrodes over the right and left erector spinae, rectus abdomini, latissimus dorsi, external abdominal obliques, and internal abdominal obliques as described in Ref. [6]. Myoelectric data were low-pass filtered at 1 kHz, high-pass filtered at 30 Hz, notch filtered at about 60 Hz, rectified, averaged using a 20 ms sliding window filter and then normalized relative to values collected during maximum voluntary contraction (MVC) exertions. Maximum EMG values were collected during static flexion, extension, right-twist, left-twist, right-lateral, and left-lateral MVC exertions performed against a reference frame in an upright posture.

Trunk motion data were recorded from an electrogoniometer designed to measure sagittal, lateral, and twisting motions of the lumbar region of trunk. Dynamic external loads were determined from a force plate (Bertec 4060A) at the subject's feet. An electro-mechanical vector monitor was employed to record the location of the lumbo-sacral junction relative to the center of the force plate [6]. External forces and moments applied to the lumbo-sacral junction of the spine were computed from the force plate data and the hip location and orientation kinematic data using the methods of Granata et al. [8] and Fathallah et al. [7].

An EMG-assisted biomechanical model employed the EMG, kinetic, and kinematic data as input to compute the dynamic loads on the spine. The model incorporated the normalized muscle activities, dynamic trunk motion, and external loads to determine the contractile forces of the ten co-contracting muscles. Spinal compression, lateral shear, and anterior–posterior (AP) shear forces were computed from the vector sum of the muscle forces. Thus, three-dimensional dynamic spinal loads were determined for each lifting exertion. The data collection methods, biomechanical model and validation have been published previously [6,9–16]

Intra-class correlations (ICCs) were performed to identify the independent parameters that influenced the variability of the biomechanical data [17]. Repeated analysis of variance (ANOVA) statistical analyses were performed to augment the ICC results and for comparison with previous research. ANOVA was also performed on within-subject variability measures to identify factors that influence distribution widths. For all significant independent variables, post-hoc analyses in the form of Tukey multiple pairwise comparisons were performed to determine the source of the significant effect(s). An alpha level of 0.05 for all statistical tests was selected.

3. Results

3.1. Analysis of means

Mean values of trunk motion dynamics and spinal loads demonstrate that the results agree with previously published values. This supports the validity of the analyses of motion and spinal load variability data which follow. Analyses of the mean data trends provides biomechanical insight into the associated variability.

Statistical ANOVA results indicate that the lifting task parameters influence the three-dimensional dynamic motion patterns of the trunk. Post-hoc analyses identified the significant kinematic trends (Table 1). Increasing the weight of the box significantly reduced the sagittal lifting velocity and acceleration of the trunk. This agrees with industrial measurements [4,5] demonstrating significant negative correlations between lifting velocities and accelerations as a function of box weight. As one might expect, task asymmetry increased lateral and twisting plane range of motion, velocity, and accelerations. A significant ANOVA interaction between experience and velocity condition (not shown in the post-hoc Table 1) demonstrated that the experienced warehouse selectors produced lower peak sagittal velocities in the "faster than preferred" condition than the inexperienced subjects. However, within each experience group, the "faster than preferred" lifting style failed to generate significantly faster peak sagittal velocities than the "preferred velocity" condition (Table 1). Subjects responded to the "faster than preferred" lifts by significantly increasing peak sagittal accelerations rather than the velocities.

Lateral and twisting range of motion and peak velocities were significantly influenced by task asymmetry. This was expected from a priori evaluations of the lifting tasks, i.e. the motion in the lateral and transverse planes were greater during asymmetric tasks than during sagittally symmetric tasks. Experienced manual material handlers generated significantly greater lateral trunk accelerations than the inexperienced subjects, particularly during the asymmetric exertions.

The trunk moments generated during the lifting exertions were influenced by box weight, task asymmetry, and experience level (Table 2). As expected, increased

Table 1
Post-hoc (Tukey) analyses of trunk motion means[a]

		Range of motion (deg)			Velocity (deg/s)			Acceleration (deg/s^2)		
		Sagittal	Lateral	Twisting	Sagittal	Lateral	Twisting	Sagittal	Lateral	Twisting
Experience	Inexperienced	**56.2**	9.8	3.0	**62.5**	10.8	4.4	126.9	**1.2**	16.9
	Experienced	**48.3**	9.9	2.0	**54.7**	11.2	6.7	118.8	19.2	12.4
Weight (kg)	13.6	51.7	9.7	2.6	**62.7**	11.0	4.9	**134.7**	9.4	16.1
	27.3	52.8	9.9	2.4	**54.4**	11.0	4.1	**111.1**	11.1	13.1
Velocity	Preferred	53.9	10.1	2.3	57.6	10.5	4.7	**112.5**	**5.7**	**14.0**
	Fast	50.7	9.6	2.7	59.5	11.5	4.3	**133.2**	**14.5**	**15.3**
Asymmetry (deg)	0	51.4	**4.6**	**1.6**	**61.7**	**3.5**	**2.6**	129.5	3.7	2.6
	60	53.1	**16.1**	**6.6**	**55.4**	**18.4**	**11.6**	117.3	16.8	26.6

[a] Bold numbers denote statistically significant differences between variable levels at $\alpha \leqslant 0.05$. Standard deviations of these data can be found in Table 5.

Table 2
Post-hoc (Tukey) analyses of trunk motion and spinal load means[a]

		Trunk moment (Nm)			Spinal load (N)		
		Sagittal	Lateral	Twisting	Lat shear	AP shear	Compress
Experience	Inexperience	**201**	**70**	**20**	**279**	**1110**	**5536**
	Experience	**266**	**51**	**26**	**416**	**1448**	**6662**
Weight (kg)	13.6	**201**	**54**	**19**	**297**	**1083**	**5268**
	27.3	**266**	**67**	**28**	**398**	**1476**	**6930**
Velocity	Preferred	240	64	22	366	1344	6198
	Fast	227	57	24	329	1214	6000
Asymmetry (deg)	0	**222**	**37**	**12**	**294**	**1101**	**5716**
	60	**245**	**84**	**36**	**401**	**1457**	**6481**

[a] Bold numbers denote statistically significant differences between variable levels at $\alpha \leqslant 0.05$. Standard deviations of these data can be found in Table 6.

box weight resulted in significantly greater lifting moments in all the three dimensions. Similarly, task asymmetry statistically increased the measured lifting moments in all the three dimensions. Significant interactions indicated that although the "faster than preferred" condition was associated with increased sagittal acceleration, it failed to statistically increase trunk moments. Experienced warehouse selectors generated significantly greater peak trunk moments than the inexperienced subjects despite the fact that the box weights were identical for both groups. This suggests that greater shoulder strength allowed the experienced subjects to comfortably hold the box at a greater distance from their trunk.

Spinal compression, AP shear, and lateral shear loads were all influenced by box weight, task asymmetry, and subject experience level (Table 2). Spinal loads increased significantly with box weight and task asymmetry, agreeing with previous research documenting similar trends. Experienced warehouse selectors demonstrated significantly greater spinal compression, AP shear, and lateral shear forces on the lumbo-sacral region of the spine than the inexperienced subjects. This was related to the greater lifting moments and muscle co-contraction generated by the experienced subjects.

3.2. ICC of kinematics, moments, spinal loads

ICCs were examined to describe the relative amount of variability associated with each independent variable. Not unexpectedly, subject-to-subject differences typically accounted for the greatest source of variability in trunk motion, lifting moments, and spinal load. The weight of the box accounted for a significant amount of the variability associated with dynamic sagittal trunk moment and spinal compression, whereas task asymmetry strongly influenced the lateral and twisting moments (Table 3). However, trial-to-trial variations describe 12–24% of the trunk moment variability. Trial-to-trial variability in spinal load ranged from almost 14% in compression to more than 32% in lateral shear load. Thus, spinal load changed markedly from one exertion to the next despite identical task requirements. Experience also contributed significantly to the variability in sagittal plane trunk moment, lateral shear and compressive loads on the spine.

Much of the intra-class variability of lifting moments and spinal loads could be explained from the motion variables describing the task performance (Table 4). The nature of the lift under asymmetric conditions requires that the lateral and twisting range of motion variance be

Table 3
ICC results of trunk moments and spinal loads[a]

	Trunk moments			Spinal loads		
	Sagittal (% var)	Lateral (% var)	Twisting (% var)	Lateral shear (% var)	AP shear (% var)	Compress (% var)
Subject	44.91	32.87	24.81	37.32	54.32	28.32
Experience	11.69	6.96	3.77	14.75	3.83	10.93
Weight	31.47	4.28	9.00	10.98	19.93	46.42
Velocity	0.00	0.00	0.00	0.00	0.00	0.00
Asymmetry	0.00	32.18	43.04	4.20	3.38	0.00
Trial	11.90	23.70	19.35	32.74	18.51	14.32

[a] Values represent the percent of total variance within a column.

Table 4
ICC results of trunk motion variables[a]

	Range of motion			Velocity			Acceleration		
	Sagittal (% var)	Lateral (% var)	Twisting (% var)	Sagittal (% var)	Lateral (% var)	Twisting (% var)	Sagittal (% var)	Lateral (% var)	Twisting (% var)
Subject	66.90	10.42	32.13	72.66	14.91	11.78	58.79	19.36	26.10
Experience	23.33	0.00	0.11	3.67	0.19	0.00	0.00	9.96	0.00
Weight	0.39	0.00	0.00	4.93	0.00	0.27	0.24	0.00	1.30
Velocity	0.00	0.00	0.00	1.43	0.00	0.59	20.45	0.00	0.00
Asymmetry	1.17	84.28	53.90	0.81	71.32	63.03	0.00	2.81	13.42
Trial	8.20	5.28	13.85	16.48	13.56	24.33	20.50	67.86	59.18

[a] Values represent the percent of total variance within a column.

largely explained by asymmetry. Similarly, lateral and twisting velocity variabilities were accounted for by task asymmetry. Recognizing that trunk dynamics significantly influenced trunk moments and spinal loads, it should not be surprising that the kinematic and kinetic intra-class correlation distributions look similar. However, it is important to note that trial-to-trial variability explained 20–67% of the task acceleration variability. Hence, performance of identical lifting tasks does *not* necessarily produce similar lifting kinetics or kinematics. This indicates that multiple trials are necessary to observe the full spectrum of trunk performance associated with a task.

3.3. Kinematic standard deviations

Post-hoc analyses of significant ANOVA results demonstrate how workplace factors influence biomechanical variability (Table 5). Thus, ANOVA of variability suggests how the experimental variables affect the width of the distribution. Increased box weight significantly reduced the variability (standard deviation) associated with the sagittal extension velocities and accelerations. Increased task asymmetry generated greater variability associated with twisting velocities, lateral accelerations, and twisting accelerations. Conversely, increased task asymmetry was associated with reduced variability of lateral velocities. Sagittal range of motion had very little variability because the subjects lifted the box from the same height in every trial.

The biomechanical variability associated with lifting moments in the sagittal and lateral planes were not statistically influenced by box weight (Table 6). Conversely, twisting moment variability increased with box weight. Task asymmetry did not significantly influence sagittal or lateral trunk moment variabilities but statistically increased the variability in transverse plane moments. Contrary to expectations, experienced warehouse selectors demonstrated greater sagittal and twisting moment variability than inexperienced subjects. However, the increased variability in trunk moment was in proportion to the moment magnitudes generated by the experienced versus inexperienced subjects. Significant experience by asymmetry interactions demonstrated that the inexperienced workers generated more lateral moment variability during the sagittally symmetric exertions than during the asymmetric tasks.

Box weight and subject experience increased not only the spinal load magnitude, but also significantly the variability of the spinal loads (Table 6). The variability in the AP shear and compressive loads applied to the lumbo-sacral spine increased by 43% and 20%, respec-

Table 5
Post-hoc (Tukey) analyses of trunk motion variability (Standard deviations)[a]

		Range of motion (deg)			Velocity (deg/s)			Acceleration (deg/s^2)		
		Sagittal	Lateral	Twisting	Sagittal	Lateral	Twisting	Sagittal	Lateral	Twisting
Experience	Inexperienced	2.7	2.1	2.0	7.2	**4.5**	5.1	22.1	**41.4**	29.6
	Experienced	2.3	1.8	1.8	6.5	**3.6**	4.5	21.8	**32.6**	28.7
Weight (kg)	13.6	2.7	2.1	2.0	**7.5**	4.1	4.8	**25.1**	36.9	29.8
	27.3	2.3	1.8	1.8	**6.2**	4.0	4.9	**18.7**	37.2	28.5
Velocity	Preferred	2.8	2.2	2.0	6.8	3.7	**4.1**	20.9	36.2	29.2
	Fast	2.2	1.8	1.8	7.0	4.3	**5.5**	23.0	37.8	29.2
Asymmetry (deg)	0	2.7	1.8	1.6	7.2	**4.5**	**4.1**	22.6	**29.9**	**22.0**
	60	2.3	2.1	2.2	6.5	**3.6**	**5.5**	21.3	**44.2**	**36.3**

[a] Bold numbers denote statistically significant differences between variable levels at $\alpha \leqslant 0.05$.

Table 6
Post-hoc (Tukey) analyses of spinal load variability (Standard deviations)[a]

		Trunk moment (Nm)			Spinal load (N)		
		Sagittal	Lateral	Twisting	Lateral shear	AP shear	Compress
Experience	Inexperienced	**21**	22	**6**	**86**	**174**	**503**
	Experienced	**32**	21	**10**	**155**	**292**	**692**
Weight (kg)	13.6	25	21	**7**	114	**192**	**543**
	27.3	28	22	**9**	128	**273**	**651**
Velocity	Preferred	28	21	8	116	249	617
	Fast	25	21	9	126	216	578
Asymmetry (deg)	0	25	21	**6**	120	**176**	556
	60	28	22	**10**	121	**289**	638

[a] Bold numbers denote statistically significant differences between variable levels at $\alpha \leqslant 0.05$.

tively, as the box weight increased from 13.6 to 27.3 kg. Variability in the AP shear load during asymmetric tasks was 64% greater than during sagittally symmetric tasks. A significant weight by velocity interaction for lateral shear variability (not shown in post-hoc Table 6) demonstrated that variability was greater during the "faster than preferred" condition, but only for the 13.6-kg box. Experienced selectors generated spinal load variabilities 80%, 66%, and 38% greater than inexperienced subjects in the lateral, AP, and compressive directions, respectively. Spinal load variability was more than can be attributed to a proportional increase in the mean values associated with the experienced and inexperienced groups. The increased coefficient of variation, i.e. standard deviation divided by mean, increased significantly for lateral shear and AP shear loads, but not for compression. Although the variability associated with transverse plane trunk moments and AP shear loads on the spine increased with task asymmetry, the increase was less than proportional to the increased mean values.

4. Discussion

The analysis of the lifting tasks performed in this study demonstrated that workplace factors influence both spinal load magnitudes and the variability in spinal loads. Dynamic spinal compression values for the tested conditions averaged 5790 N, with a standard deviation of 1480 N. Task analyses might observe that the mean compressive load on the spine was below the NIOSH MPL limit of 6400 N [2]. Such conclusions would overlook the fact that over 20% of the lifts exceeded the recommended MPL compression. Identical lifting tasks in terms of weight, origin, and destination will generate a wide range of spinal loads. Therefore, it is necessary to recognize the biomechanical variability associated with a lifting task as well as the workplace factors that influence variability.

Our results regarding the magnitude of spinal loads agree with trends cited in the literature. Results illustrating spinal loads increased with box weight and task asymmetry agree with prior biomechanical assessments [18–20] and indicate potential mechanisms of injury associated with occupationally related LBDs [4,5,21,22]. Table 2 illustrates that spinal loads were not statistically influenced by the lifting velocity condition; contrary to previous research demonstrating a significant increase in spinal load with trunk extension velocity [9,10,16]. This disparity can be explained by the fact that the subjective nature of the lifting velocity conditions failed to generate statistically different trunk velocities. During the "faster than preferred" condition, subjects may have keyed on the velocity of the box, moving the load faster using arm and shoulder motion, while maintaining the trunk motion at a velocity similar to the "preferred" lifting velocity. Thus, the spinal loads in all velocity conditions were similar because the measured trunk velocities were similar. One might be tempted to point out that the subjective velocity condition significantly influenced extension acceleration or inertial force of the load, and thereby argue that spinal load might increase due to inertial factors. However, the magnitude difference was not sufficient enough to significantly increase the dynamic lifting moment or associated spinal loads. Hence, the magnitudes of spinal compression and shear forces, as well as the measurable trends associated with lifting parameters agree with previous research, supporting the validity of our efforts.

It has been argued that increasing the variability of spinal load is detrimental because it increases the relative number of exertions performed at levels exceeding recommended tolerances. Although many studies have examined the influence of workplace factors upon the magnitude of spinal loads, few have investigated the influence of workplace factors upon the variability of spinal load. Mirka and Marras [1] found significant myoelectric variability associated with exertion level and trunk motions during controlled lifting exertions.

However, the application of constant extension moments during externally controlled, isokinetic exertions employed in that study did not realistically represent industrial lifting exertions. Furthermore, it has been shown that constant extension moment exertions may influence the muscular behavior of the system [23], questioning the application of those results to industrial lifting tasks. Nonetheless, our results agree with the conclusions of Mirka and Marras [1], and demonstrate that workplace factors influence the variability of trunk muscle activity during realistic lifting exertions. Our analyses have documented that the kinematic trajectory, including the three-dimensional velocity and acceleration components of trunk motion, demonstrate significant variability. This variability is influenced by workplace factors. The combination of kinematic and myoelectric variability generate significant spinal load variability. Thus, identical lifting tasks generated distributions of peak spinal loads with standard deviations of 10–40% of the mean values.

Box weight, job experience and, to a small extent, task asymmetry influence the variability of spinal load during repeated lifting exertions. Compression variability increased with box weight and worker experience. Increased variability of the spinal loads with box weight was related to a statistically significant 52% increase in sagittal trunk moment variability. During the heavy lifting conditions, the variability in antagonistic muscle activity of the rectus abdomini and external obliques was over 38% greater than during the lower weight conditions. Just as antagonistic activity dramatically increases the magnitude of spinal loads [24], the variability in that myoelectric activity will also significantly influence the variability in spinal loads. Hence, the relation between workplace factors and spinal load variability may be explained through the influences upon muscle co-contraction and lifting dynamics.

Contrary to our expectations, the experienced manual materials handlers (MMH) produced greater spinal loads and spinal load variability than inexperienced subjects. Peak compression values generated by experienced warehouse selectors were more than 20% greater than the similar biomechanical loads generated by the inexperienced subjects, i.e. 6662 N versus 5536 N. Similar trends were described in an analysis of worker experience upon spinal loads during warehouse selection tasks [25]. Given the identical nature of the task, the difference in compression values between the two groups must be attributed to external trunk moment and trunk muscle coactivity. The experienced group generated dynamic sagittal lifting moments 32% greater than the inexperienced subjects. Experienced subjects also generated antagonistic muscle activity approaching twice (178%) the level demonstrated by the inexperienced group (Fig. 2). Normalized activity in rectus abdominis were 5.7% and 11.1% for experienced and inexperienced groups, respectively. Both external trunk moments and muscle co-contraction are known to significantly affect spinal load [18,24,26,27]. Increased antagonistic muscle contraction and increased lifting moments require greater effort from the trunk extensor muscles. Thus, when experienced MMH lifted heavy boxes, peak erector spinae myoelectric activities were approximately 95% of the maximum during the period of peak extension moment. Results by Keyserling et al. [28,29] indicate this may be a potential hazard under these circumstances because the job strength requirements may exceed subject strength capacity.

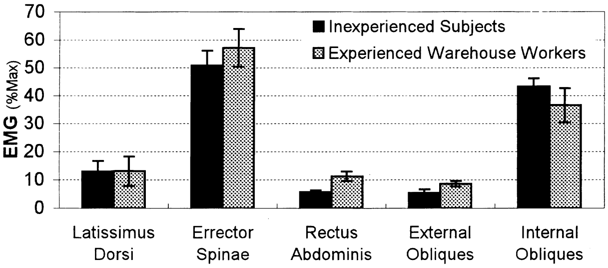

Fig. 2. Experienced subjects generated greater muscle activity in the erector spinae, rectus abdomini and external obliques as demostrated by the values representing the EMG at the instant of peak moments during sagitally symmetric, 13.6-kg lifting exertion.

Compressive load variability associated with experienced subjects was 38% greater than the inexperienced subjects. Because of their greater lifting strength, it was understandable that the experienced warehouse workers were capable of holding the load further from their body, thereby generating greater trunk moments and associated spinal loads (Table 2). However, considering both groups lifted boxes of identical weight, the increased spinal load was not related to weight, but rather to technique. Why the experienced group chose to generate greater trunk moments is unclear. We expected that warehouse selection experience would lead to techniques resulting in reduced spinal loading and more repeatable performance of the lifting tasks in experienced MMH workers than in inexperienced subjects. The contrary was observed. The variability demonstrated by the experienced subjects was related to the variability in sagittal lifting moments, 52% greater with the experienced MMH than the inexperienced subjects.

It is curious that experienced subjects generated significantly greater spinal loads and spinal load variability despite the fact that research has indicated experience reduces the probability of low-back injury [30,31]. We were surprised to discover that the experienced subjects recruited significantly greater extensor muscle activities than the inexperienced subjects, particularly considering the MMH were likely stronger as a group than the inexperienced subjects (college students). However, it must be noted that the experienced subjects also generated greater flexor muscle activities, i.e. rectus abdomini, requiring increased contraction effort from the extensor muscles of the trunk [24]. Previous research [32,33] has suggested that antagonistic muscle activity is associated with trunk stability, indicating that experienced workers may have maintained a higher level of trunk stability than the inexperienced subjects. It is hypothesized that generating improved trunk stability may result in reduced risk of LBD [34]. Thus, experience may teach warehouse selectors to avoid potential injury associated with task performance variability by increasing trunk stability resulting in a concurrent increase in spinal load [35,36].

The relation between spinal load and tissue tolerance is dynamic and complex. It has been assumed that increased spinal load variability is harmful because the tail of a broad distribution has a greater probability of exceeding tissue tolerance. However, tissue tolerance can be influenced by loading history [37,38], cyclic loading [39,40], and the interaction between cyclic loading and load magnitude [41]. Thus, the dynamics of spinal tolerance must be considered when evaluating the results of repeated loading exertions. However, there is no evidence that increased spinal load by means of variability protects the spine. Hence, our results suggest that lifting task variability must be considered in ergonomic assessment, and the relation between variability and injury risk warrants further investigation.

The risk of occupationally related LBD has been linked to asymmetric postures in the workplace [4,5,22]. Our results demonstrate that both spinal load and spinal load variability increase significantly with task asymmetry. Previous research has attributed LBD risk during asymmetric exertions with increased spinal loads [9,16]. Increased spinal load variability with task asymmetry will increase the relative number of exertions that exceed biomechanical tolerances, resulting in greater LBD risk from asymmetric tasks. The ability to resist trunk moments in the lateral and transverse planes is significantly less than in the sagittal plane [11,12,42,43]. This suggests that the capacity to control increased lateral and twisting moment variability may be challenged during asymmetric exertions, resulting in greater potential for injury. This hypothesis is supported by the fact that increased muscle co-contraction is recruited during asymmetric and torsional exertions in order to control and stabilize the trunk [6,11,14,44,34]. Variability in spinal loading patterns associated with asymmetric lifting tasks may help explain the relation between LBD and asymmetric lifting tasks in industry.

When interpreting these results, one must consider the limitations associated with the study design. Subjective lifting velocities were chosen to permit examination of two lifting velocities without artificially influencing the natural motion variability. However, the resulting motions failed to generate significantly different trunk velocities between the two conditions. Research has found that spinal loads are influenced by lifting velocity [6,11,14,44,34]; therefore, it is likely that work factors associated with lifting velocity influence the width of repeated spinal load distributions. Unfortunately, because the lifting velocities were statistically similar, it was not possible to examine the influence of velocity upon the variability of spinal loading. Future research may attempt to examine the repeatable lifting variability as a function of trunk velocity. During the exertions, subjects were required to remain standing on a force plate with their feet in a fixed position. This measurement constraint may have influenced the variability of spinal loads, reducing the biomechanical variability related to stance and leg positioning. Finally, the length of time to complete all of the repeated exertions and experimental conditions was less than 2 h. To represent the variability associated with occupational settings, future research might examine the repeated exertions performed over a simulated 8-h work day.

5. Conclusions

Lifting kinetics, kinematics, and spinal load demonstrate significant variability under identical and repeated lifting conditions. Workplace factors such as the magnitude of the load, task asymmetry, and worker experience can influence variability. Ergonomic assessments considering only the mean value of spinal load overlook the fact that a large fraction of the lifts may exceed recommended levels despite mean levels safely below tolerance limits.

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