Journal of Electromyography and Kinesiology 20 (2010) 813–822

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Quantitative biomechanical workplace exposure measures: Distribution centers

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ARTICLE INFO

Article history:
Received 29 December 2009
Received in revised form 19 March 2010
Accepted 19 March 2010

Keywords:
Ergonomics
Occupational biomechanics
Physical exposures
Low back pain
Low back disorders
Workplace assessments

ABSTRACT

Physical work exposure characteristics assessed in most previous epidemiologic studies have been described mostly in gross categorical terms (e.g. heavy work, lifting and forceful movements, etc.) and have resulted in relatively moderate associations with low back pain risk. We hypothesized that it was necessary to characterize work demands in a much more quantitative fashion so that the precise biomechanically meaningful measures of exposure were available for risk analysis. In this study, we used sophisticated instrumentation to continuously document 390 physical exposures during lifting (in four types of distribution centers) throughout work. This study profiles these exposures and shows how these exposures vary as a function of the type of distribution center and compares the exposures to (previously documented) manufacturing exposures. Static load and load moment measures were found to greatly under-represent true (dynamic) load and load moment exposures to workers. Lift durations averaged 11–12% of the cycle time in distribution environments. This study indicates that distribution workers are commonly exposed to greater extreme loads and move much more rapidly than manufacturing employees. The information provided here can serve as a basis for low back pain risk assessments.

1. Introduction

Occupational low back pain (LBP) causality has been associated with a combination of personal factors (e.g. genetics), psychological/psychosocial factors, and physical exposures (NRC/IOM, 2001). It is currently difficult, if not impossible, to modify most individual or psychological factors. However, it is possible to mediate exposure to many of the physical exposures encountered in the workplace. Given the high cost of LBP and the rapidly accelerating cost of health care, it has been demonstrated that it is possible to significantly influence LBP rates and their associated health care costs by minimizing physical risk factor exposure through workplace design (NRC/IOM, 2001).

The precise role of physical factors in LBP causality has been difficult to assess in occupational settings. Physical risk factors such as lifting and forceful movements, heavy physical work, awkward postures, and static postures have been generally associated with LBP risk through epidemiology studies. While the strength of association between these factors and risk have been reported to be generally moderate it varies between studies (NIOSH, 1997). However, most epidemiology studies have defined these risk factors in gross categorical terms making it difficult to evaluate a worker's exposure to a risk factor and difficult to understand what would constitute as effective control measure. Most studies have simply reported the presence or absence of the gross risk factor category without reporting how much exposure was present. Thus, more quantitative measures could help specify the relationship between physical exposure and risk. In addition, the relationship between risk and physical exposure appears to be a non-linear function. Moderate exposures are considered protective, whereas, extremely low and high physical exposures appear to increase risk (Chaffin and Park, 1973; Chaffin, 1974; Videman et al., 1990). Thus, in order to delineate the dose–response relationship it is necessary to employ continuous exposure metrics.

Because of the difficulty in obtaining these precise exposure measures, these quantitative and continuous exposures are seldom considered in traditional epidemiologic assessments of risk. In order to assess the precise role of physical exposure and LBP risk it is necessary to quantify the exposure to the risk factors so one could assess "how much exposure is too much exposure" to risk factors. Previous reviews have shown that the better risk factors are quantified the better one is able to assess their relationship with risk (NRC/IOM, 2001).

The few studies that have attempted to quantify physical exposure at the workplace have suggested that increased risk of LBP was associated with multivariate exposures including load moment exposure, increases in dynamic trunk motion, frequency of exposure, and the maximum trunk angle required by the task (Marras et al., 1993, 1995, 2000). The strongest univariate association between physical risk factors and LBP risk was associated with peak load moment exposure (odds ratio = 5.17). However, even this variable was quantified in a very crude manner. Load moment was evaluated by estimating the distance of the object lifted from

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doi:10.1016/j.jelekin.2010.03.006

the spine (using a tape measure) and multiplying the weight of the object (using a bathroom scale). Such a crude measure ignores many of the factors that contribute to biomechanical loading of the spine such as dynamic characteristics of object handling, directions of load moment relative to the spine (e.g. asymmetry), torso movements and load height when lifted. Since the load moment variable holds promise, we hypothesized that a much more precise assessment of risk can be derived if load moment and the relevant biomechanical variables associated with exposure were better quantified.

In this study a moment monitor capable of quantifying numerous physical exposure variables over the course of a workday (Marras et al., 2009) was employed to assess exposure in distribution center environments. Distribution centers were chosen because significant back related lost time risk has been reported in these environments (BLS, 2009). In addition, these environments contain many of the previously discussed risk exposure factors and, given their dynamic nature, make the application of traditional assessment tools extremely challenging. The goal of this study was to quantify and describe distribution center exposures to physical factors with enough precision so that future studies could assess their relationship with risk.

2. Methods

2.1. Approach

This study monitored real-time exposures of distribution center workers performing manual materials handling tasks associated with 47 manual materials handling (order picking) jobs sampled in 19 distribution centers within the Midwestern United States. Since we were concerned with physical exposure characterization in this study, the *job* (as opposed to the worker) was considered the unit of analysis. For each of the jobs sampled, we collected a spectrum of static and dynamic measures of physical exposures including dynamic load moment exposures and torso kinematics. Workers were monitored continuously with a custom made measurement system for up to 4 h in up to seven workers performing each job. Exposure measurements were collected on 193 distribution center workers.

Independent variables in this study consisted of the "type" of distribution center (grocery, automotive parts, clothing, and general retail distribution). The characteristics of the physical exposures in these four types of distribution centers were described and statistically compared for significant differences.

2.2. Data collection sites

The data collection sites were comprised of distribution center organizations in which employees perform repetitive material handling tasks (i.e. order picking, truck loading/unloading, replenishment, sorting, etc.) continuously throughout the workday. Sites were also selected based upon location and willingness on the part of management to cooperate with the study group. Based upon these criteria we were able to target grocery, automotive parts, clothing, and general retail distribution center environments for participation in the study.

Given the similarity of order picking jobs within certain "types" of distribution activities, jobs were differentiated based upon the department (or section) of work exposure (where workers did not move from one department to another). For example, a grocery distribution center may consist of four different job types, depending upon how order picking tasks are distributed. Usually employees select or "pick" products in one of several departments each with different physical layouts. In grocery distribution centers order selectors typically work in dry groceries, produce, frozen foods, or boxed meats departments. Hence, a grocery facility with these four types of lifting activities (areas) would contribute four jobs (with multiple workers in each job) to the database. By contrast, in general merchandise distribution centers, there may be only one picking or selecting job defined for the entire facility (albeit with many employees).

Overall, a total of 19 different distribution centers were included in this study. Four types of products were handled by the employees within these distribution centers and a total of 47 jobs were identified within these facilities. Table 1 summarizes the types of products handled and the number of jobs sampled from each type of distribution center.

2.3. Subjects

One hundred and ninety-three (193) workers from 47 distribution center jobs participated in the exposure data collection. The average age (SD) of the participants was 36.3 (10.9) and 83% of the sample was male. Average (SD) height and weight of the subjects was 175.8 (9.3) cm and 82.8 (17.9) kg, respectively. The average (SD) worker experience of these subjects was 4.66 (4.88) years. No participation restrictions relative to current or past worker back pain experiences were employed in the inclusion criteria as we were interested in typical exposures. The only requirement was that the employee had experience performing the sampled job and was currently able to perform the job at the normal pace.

2.4. Exposure sampling

Variance component analysis was used to determine the number of employees needed to collect a statistically valid sample from a subset of key dependent variables. The variance component analysis was used to assess the effects of testing additional employees for a given job. This indicated a large reduction in variance when adding a second employee to the job sampling and an additional benefit to variance reduction when adding a third employee to the sample set. Adding a fourth employee had little change in variance for the dependent measures of interest. In addition, previous studies have also demonstrated that three subjects are needed to minimize variance between workers when quantitative measures of activity are of interest (Marras et al., 2000). Therefore, within each job at least three and up to 7 volunteers were recruited for the exposure measurements. These participants signed informed consent documentation and were compensated for their participation with gift cards from area merchants. Each employee was monitored for up to four hours and, given normal productivity requirements, included several hundred lifts per participant.

2.5. Apparatus

Exposure data were obtained using the custom instrumentation we have developed and described previously (Marras et al., 2009). The instrumentation is essentially an automated data collection system that continuously monitors and records, 3-D hand locations

Table 1
The number of jobs sampled by distributed product type.

Product type	Number of sites	Number of jobs
Grocery	6	14
Auto parts	4	8
General merchandise	4	13
Clothing	5	12
Total	19	47

relative to the L5/S1 spine (including vertical height and horizontal distances), the instantaneous load weight (static and dynamic), the orientation of the torso, and the timing of lifting events. This information allows the measurement of both static and dynamic 3-D analyses of exposures. A picture of a subject wearing the measurement system is shown in Fig. 1. This device automatically measured 390 exposure variables for each lift. An analysis of measurement accuracy has been reported previously (Marras et al., 2009). Excellent field accuracy can be obtained from this device with resultant moment arm distance average absolute error (AAE) of 1.2 inches (3.05 cm) and negligible error for weight measurement.

Data were continuously collected using the built-in microprocessor and stored on memory flash cards for later analysis. The data processing programs used load measurement data from the handles to identify lift initiation and termination. Therefore, the data analysis software was able to delineate the lift characteristics listed above as well as identify the intervals of time during which lifting is occurring and the inter-lift (rest) periods.

The global origin of the coordinate system used to define the exposure metric variables considers its center at the L5/S1 disc of the lumbar spine. Positive *X* axis is rightward to the human body. Positive *Y* direction is forward. Positive *Z* axis is pointing upward (Fig. 2).

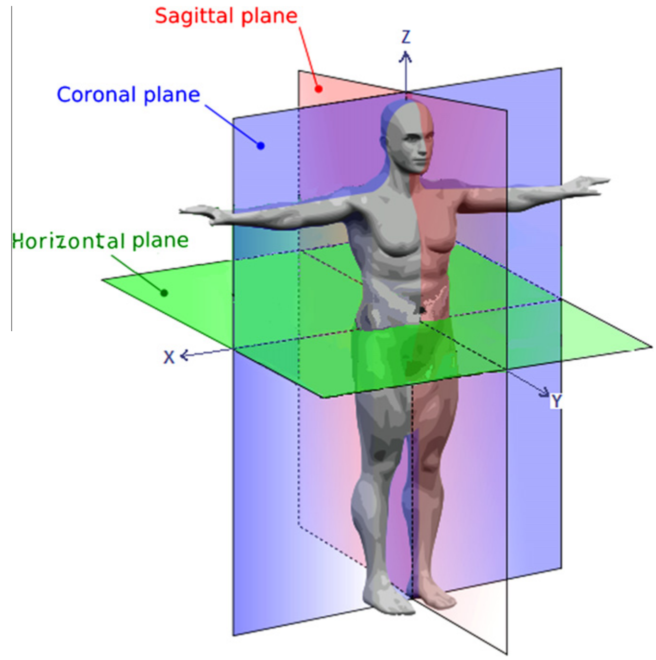

Fig. 2. The coordinate system used by the moment exposure tracking.

2.6. Procedure

Each volunteer was asked to review and sign informed consent documents and then was instrumented with the data collection system. Once a participant was instrumented and ready to return to the workplace they were followed by a member of the research team who would primarily be observing unit integrity and keep track of the type of work performed. Using multiple instrumentation backpacks we were able to monitor up to five workers at a time.

Employees were instructed to work at a normal pace and lift as they normally would. For example, if the employee normally worked on a productivity standard we asked for that pace to be maintained. This was necessary to obtain accurate temporal data regarding the periods of time between moment exposures and accurate measures of cumulative moment exposure.

Fig. 1. Instrumentation worn by subject.

2.7. Database development

A total of 58,796 exertions were recorded, including over 42,000 lifts and nearly 17,000 lowers (cases are often dropped and not lowered in distribution centers). Custom software was developed to analyze each of the exertions. A database that contains the load moment exposures, hand position data, torso kinematics, and duty cycle parameters was built based on the results of the analyses.

Three hundred and ninety (390) variables were included in the physical exposure database. In general exposures can be categorized as: (1) load related variables (weights, moments, push, pulls, etc.), (2) position related variables (load origins and destinations as well as load velocity and acceleration characteristics, spine positions, velocities, accelerations, etc.), and (3) timing related variables (lift durations, time of peak loadings, lifting frequencies, time between lifts, etc.). Given the large number of variables, only a subset of the exposure metrics will be described as a function of these exposure categories.

2.8. Data analysis

Descriptive statistics were computed for the aggregate of all variables combined over all jobs. Distribution plots were generated for all exposure variables. In addition, these measures were described as a function of the type of distribution exposure (as defined in Table 1). In the interest of space a summary of what are considered to be key biomechanical measures were compiled for this effort. Analysis of variance (ANOVA) was used to identify statistically significant differences between types of distribution centers using SAS version 9.1.3. Post hoc evaluations were performed using the Ryan–Einot–Gabrial–Welsch (REGWF) multiple range test.

Table 2
Descriptive statistics for (a) load variables, (b) position variables, (c) timing variables.

Variable	Technical	Units	Mean	Standard deviation	Mean of minimum	Mean of maximum	Mean of 5th percentile	Mean of 95th percentile
Load variables								
Load weight	sFz	N	65.99	20.45	18.61	177.65	26.68	125.51
Max dynamic lift force	Max dFz	N	99.13	38.70	11.31	506.93	26.23	226.66
Abs. max dynamic slide force	Max |dFy|	N	42.84	19.30	4.90	159.84	11.79	95.61
Abs. max dynamic lift/slide force	Max |dFyz|	N	107.48	41.86	19.35	515.90	34.82	237.53
Abs. max static transverse plane load moment	Max |sMxyFz|	Nm	34.61	12.39	6.14	106.15	11.68	70.75
Abs. average static transverse plane load moment	Average |sMxyFz|	Nm	23.31	8.51	3.81	72.07	7.90	47.55
Abs. max static forward-bend load moment	Max |sMxFz|	Nm	33.80	12.17	5.79	104.20	11.25	69.29
Abs. max static side-bend load moment	Max |sMyFz|	Nm	11.50	4.36	1.25	47.03	3.06	25.82
Max static right side-bend load moment	|Max sMyFz|	Nm	9.11	3.71	0.21	41.49	1.37	22.25
Max static left side-bend load moment	|Min sMyFz|	Nm	8.59	3.85	0.14	41.32	1.19	21.69
Abs. max dynamic forward-bend load moment	Max |dMxFz|	Nm	41.96	17.63	3.85	225.34	9.53	102.04
Abs. max dynamic side-bend load moment	Max |dMyFz|	Nm	12.19	5.29	0.78	70.59	2.32	30.19
Max dynamic right side-bend load moment	|Max dMyFz|	Nm	9.23	4.25	0.15	60.04	0.97	24.75
Max dynamic left side-bend load moment	|Min dMyFz|	Nm	8.66	4.42	0.11	59.17	0.80	24.10
Abs. max dynamic transverse plane load moment	Max |dMxyFz|	Nm	43.13	18.08	4.10	229.75	9.93	104.68
Abs. average dynamic transverse plane load moment	Average |dMxyFz|	Nm	20.89	7.57	2.50	68.11	5.56	44.17
Abs. max dynamic forward-bending resultant (sagittal) moment	Max |dMxFyz|	Nm	42.85	17.85	4.79	224.61	11.26	102.01
Abs. max dynamic resultant moment	Max |dMr|	Nm	44.16	18.35	5.18	229.29	11.93	104.79
Abs. average dynamic resultant moment	Average |dMr|	Nm	22.75	8.02	3.16	69.67	6.83	45.85
Abs. max dynamic twisting slide moment	Max |dMzFy|	Nm	5.22	2.81	0.34	28.74	0.98	13.47
Abs. max dynamic forward-bend slide moment	Max |dMxFz|	Nm	10.89	5.13	0.57	53.83	1.82	27.44
Abs. max dynamic lateral plane slide moment	Max |dMxzFy|	Nm	11.80	5.54	0.79	55.98	2.29	28.95
Position variables								
Max transverse plane moment arm	Max MAxy	m	0.52	0.06	0.24	0.87	0.36	0.70
Start transverse plane moment arm	Start MAxy	m	0.44	0.06	0.14	0.80	0.26	0.63
End transverse plane moment arm	End MAxy	m	0.42	0.06	0.14	0.76	0.24	0.60
Max resultant moment arm	Max MAr	m	0.60	0.07	0.29	0.95	0.41	0.79
Start height	Start Ht.	m	0.91	0.12	0.36	1.61	0.51	1.35
End height	End Ht.	m	1.03	0.15	0.47	1.64	0.67	1.43
Start asymmetry (0° is far right)	Start Asym	°	89.39	5.10	40.15	137.52	64.60	113.94
End asymmetry (0° is far right)	End Asym	°	88.95	5.46	40.23	136.59	64.61	113.19
Abs. max forward moment arm	Max |MAy|	m	0.50	0.06	0.22	0.85	0.34	0.68
Abs. max side moment arm	Max |MAx|	m	0.17	0.03	0.04	0.44	0.08	0.29
Abs. max up moment arm	Max |MAz|	m	0.36	0.06	0.06	0.77	0.13	0.62
Abs. max lateral plane moment arm	Max |MAxz|	m	0.52	0.06	0.24	0.87	0.36	0.70
Abs. max sagittal plane moment arm	Max |MAyz|	m	0.59	0.07	0.28	0.93	0.40	0.78
Abs. max sagittal trunk angle	Max |Sag Ang|	°	51.88 (37.00)	13.52	6.51 (9.57)	107.08 (70.39)	16.4 (15.55)	91.12 (60.74)
Abs. max lateral trunk angle	Max |Lat Ang|	°	17.28 (13.81)	2.67	3.17 (4.87)	37.93 (26.88)	7.76 (7.78)	27.64 (20.37)
Max right lateral trunk angle	Max R Lat Ang	°	14.15 (11.83)	3.38	0.61 (3.25)	35.46 (25.32)	4.04 (5.42)	25.04 (18.72)
Max left lateral trunk angle	Max L Lat Ang	°	13.25 (5.52)	3.03	0.58 (-2.50)	33.34 (18.24)	3.47 (-0.67)	23.95 (12.30)
Max sagittal trunk flexion velocity	Max Sag Flex Vel	°/s	72.86 (44.09)	19.02	2.81 (-3.00)	282.77(185.22)	14.90 (5.13)	132.53 (84.21)
Max sagittal trunk extension vel[a]	Max Sag Ext Vel	°/s	84.08 (61.42)	19.62	5.50 (8.59)	306.70 (211.09)	25.00 (21.70)	158.55 (111.48)
Max sagittal trunk acceleration	Max Sag Acc	°/s^2	703.21	171.16	56.39	3195.12	211.09	1262.72
Max sagittal trunk deceleration	Max Sag Dec	°/s^2	668.31	174.12	68.81	2976.06	209.36	1235.07
Abs. max lateral trunk velocity[a]	Max |Lat Vel|	°/s	105.28(43.74)	21.23	15.83 (1.51)	254.74 (119.35)	39.64 (10.53)	179.89 (81.48)
Max rightward lateral trunk velocity[a]	Max R Lat Vel	°/s	89.84 (35.93)	20.08	6.29 (-6.34)	237.79 (110.78)	27.17 (4.22)	164.49 (73.69)
Max leftward lateral trunk velocity[a]	Max L Lat Vel	°/s	90.12 (55.11)	19.07	6.43 (12.77)	243.42 (132.67)	27.85 (23.61)	164.7 (92.84)
Max lateral trunk acceleration	Max Lat Acc	°/s^2	855.83	192.72	91.88	2457.03	278.52	1578.99
Max lateral trunk deceleration	Max Lat Dec	°/s^2	856.26	189.72	92.65	2437.89	283.15	1559.57
Max box up acceleration	Max Box Z Acc	m/s^2	11.49	7.73	0.39	112.79	1.44	41.97
Max box up deceleration	Max Box Z Decel	m/s^2	6.26	3.32	0.23	64.69	0.98	17.10
Timing variables								
Duration	Dur Ex	s	2.75	0.97	0.54	10.45	0.82	5.79

Table 2 (*continued*)

Variable	Technical	Units	Mean	Standard deviation	Mean of minimum	Mean of maximum	Mean of 5th percentile	Mean of 95th percentile
Duration of non load exposure	Dur non-Ex	s	21.25	14.37	0.87	317.78	1.73	80.77
Duration of get	Dur Get	s	0.66	0.21	0.03	4.85	0.10	1.99
Duration of carry	Dur Carry	s	1.77	0.81	0.16	8.17	0.36	4.25
Duration of place	Dur Place	s	0.50	0.19	0.03	4.52	0.08	1.63
Percent time of max dynamic lift force	% Time Max |dFz|	%	53.32	8.98	1.81	99.51	7.80	96.75
Percent time of abs. max dynamic slide force	% Time Max |dFy|	%	48.69	7.53	0.58	99.14	4.82	93.67
Percent time of abs. max dynamic lift/slide force	% Time Max |dFyz|	%	52.81	8.83	1.79	99.51	7.89	96.39
Percent time of abs. max static transverse plane load moment	% Time Max |sMxyFz|	%	49.05	9.24	0.09	100.00	0.34	99.84
Percent time of abs. max static forward-bending load moment	% Time Max |sMxFz|	%	49.23	9.39	0.09	100.00	0.35	99.85
Percent time of abs. max static side-bending load moment	% Time Max |sMyFz|	%	50.93	5.07	0.12	99.98	1.86	99.26
Percent time of abs. dynamic forward-bending load moment	% Time Max |dMxFz|	%	51.66	9.92	1.02	99.78	5.97	97.56
Percent time of abs. max side-bending dynamic load moment	% Time Max |dMyFz|	%	53.10	6.21	1.04	99.82	6.97	97.06
Percent time of abs. max dynamic transverse plane load moment	% Time Max |dMxyFz|	%	51.61	10.03	1.04	99.79	5.95	97.51
Percent time of absolute forward-bending resultant (sagittal) moment	% Time Max |dMxFyz|	%	54.99	8.21	1.35	99.77	7.06	97.60
Percent time of abs. max dynamic resultant moment	% Time Max |dMr|	%	54.62	8.44	1.33	99.79	6.98	97.60
Percent time of abs. max dynamic twisting slide moment	% Time Max |dMzFy|	%	48.85	5.84	0.39	99.67	3.60	95.67
Percent time of abs. max dynamic forward-bending slide moment	% Time Max |dMxFy|	%	48.10	9.87	0.51	99.53	3.96	95.48
Percent time of abs. max dynamic lateral plane slide moment	% sTime Max |dMxzFy|	%	47.20	9.59	0.39	99.48	3.66	95.26
Frequency	Freq.	Lifts/min	2.28	1.53	0.17	7.71	0.49	5.39

[a] Values in parentheses show equivalent LMM values.

3. Results

Descriptive exposure metrics for the load, position, and temporal exposure categories are reported in Table 2. This table reports the mean, standard deviation, minimum values, maximum values, 5th percentile, and 95th percentile exposures for 70 exposure variables that summarize the database. Examination of the variable standard deviations, minimum and maximum values relative to the variable mean indicate significant variation in worker exposure for most of these key variables.

Table 3 reports the descriptive statistics for the key physical exposure measurement variables as a function of the "type" of distribution center observed. In this table, the information was categorized as a function of the type of product distributed in the distribution center (grocery, auto parts, apparel, and general merchandise). This table also reports *p*-values (and post hoc test results) indicating which biomechanical exposure variables are statistically different between distribution center environments.

4. Discussion

This paper has, for the first time, quantitatively described biomechanically relevant physical exposures in distribution center environments throughout the course of a work day. The goal of this paper was simply to describe the spectrum of exposures so that future analyses could determine their association with risk.

These data provide the opportunity to make several observations comparing force exposures among exposure metrics. First, the mean load weight underestimates dynamic lift force by 50%. When the 95 percentile values are compared this underestimation jumps to over 80%. Thus, simply considering object weight in a biomechanical analysis can significantly underestimate the loading occurring in the body. This data also reveal the added force required by the combination of sliding and lifting an object as it typical is in these environment. Comparison of the mean lift/slide force to the load weight indicates that the weight underestimates the force by over 60%.

Second, a variable of considerable interest from a biomechanical perspective as well as for its previously reported association with risk is the load moment (force × distance) variable. In this study we were able to measure both static as well as dynamic load moment exposures as well as partition these exposures into the cardinal plane exposures. The mean dynamic load moment exposure was generally 25% greater than the mean static load moment when lifting. This difference grew to nearly a 50% difference when the 95 percentile exposures were considered. Thus, static load moments significantly underestimated the dynamic load moment exposure. Hence, static moment exposures should be used with caution as a measure of biomechanical exposure since they would underestimate the forces acting upon the spine.

Third, significantly large spine velocity and acceleration values were observed in these environments in both the sagittal and lateral planes of the body. Thus, simple posture assessments would not adequately describe the exposures in these environments. Furthermore, examination of Table 3 indicates that absolute maximum sagittal trunk angle was not significantly different between the four distribution centers, whereas, sagittal plane velocity did differ significantly between centers, thus, emphasizing the importance of dynamic motion measures.

Finally, these data provide insight into the temporal aspect of these lifting environments. Table 2 indicates that the average lift

Table 3
Differences among distribution center types for (a) load variables, (b) position variables, (c) timing variables, (d) individual anthropometric variables (see Table 2 for units).

Variable	Distribution center type								
	Grocery		Auto		Clothing		General merchandise		*p*-Value
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	
Load variable									
Load weight	69.07	19.22	67.51	19.20	61.46	14.47	61.11	18.49	0.0641
Max dynamic lift force	105.77	39.81	103.07	38.36	91.84	27.33	87.36	31.98	0.0282*
Abs. max dynamic slide force	41.67	17.11	41.69	19.94	43.37	16.81	41.04	20.78	0.9486
Abs. max dynamic lift/slide force	112.74	41.32	111.25	41.19	100.10	30.35	96.17	36.56	0.0845
Abs. max static transverse plane load moment	36.22^{AB}	11.57	37.42^{A}	11.36	29.66^{C}	7.78	32.05^{BC}	10.49	0.0026*
Abs. average static transverse plane load moment	22.97^{AB}	7.07	25.65^{A}	8.24	21.11^{B}	6.01	22.24^{AB}	7.39	0.0452*
Abs. max static forward-bend load moment	35.37^{A}	11.27	36.48^{A}	11.09	28.91^{B}	7.66	31.37^{AB}	10.34	0.0028*
Abs. max static side-bend load moment	12.09^{A}	4.78	12.98^{A}	4.49	10.03^{B}	2.89	10.17^{B}	3.26	0.0011*
Max static right side-bend load moment	9.54^{AB}	3.96	10.34^{A}	3.73	7.84^{B}	2.95	8.29^{B}	2.96	0.0047*
Max static left side-bend load moment	9.17^{A}	4.42	10.01^{A}	4.16	7.10^{B}	2.41	7.36^{B}	2.45	0.0003*
Abs. max dynamic forward-bend load moment	44.26^{AB}	17.02	47.11^{A}	18.19	35.68^{C}	11.73	37.07^{BC}	13.82	0.0014*
Abs. max dynamic side-bend load moment	12.99^{AB}	6.15	13.85^{A}	5.54	10.71^{BC}	3.45	10.43^{C}	3.73	0.0021*
Max dynamic right side-bend load moment	9.80^{AB}	4.82	10.43^{A}	4.11	8.05^{B}	3.57	8.14^{B}	3.27	0.0124*
Max dynamic left side-bend load moment	9.29^{A}	5.19	10.29^{A}	4.95	7.17^{B}	2.30	7.11^{B}	2.59	0.0003*
Abs. max dynamic transverse plane load moment	45.50^{AB}	17.65	48.45^{A}	18.65	36.77^{C}	12.08	38.02^{BC}	14.08	0.0014*
Abs. average dynamic transverse plane load moment	20.77	7.33	22.47	6.88	19.61	5.49	19.89	6.83	0.2385
Abs. max dynamic forward-bend resultant (sagittal) moment	45.07^{A}	17.36	48.03^{A}	17.77	36.83^{B}	11.87	37.53^{B}	14.40	0.0015*
Abs. max dynamic resultant moment	46.42^{A}	18.00	49.56^{A}	18.30	38.04^{B}	12.25	38.64^{B}	14.78	0.0015*
Abs. average dynamic resultant moment	22.74	8.13	24.36	7.40	21.49	5.83	21.25	6.90	0.1915
Abs. max dynamic twisting slide moment	5.11	2.79	5.55	3.28	4.87	2.04	4.91	2.83	0.6935
Abs. max dynamic forward-bend slide moment	10.89	5.22	10.80	5.52	10.30	3.93	10.72	5.55	0.9548
Abs. max dynamic lateral plane slide moment	11.74	5.57	11.75	5.94	11.14	4.23	11.60	5.98	0.9547
Position variables									
Max transverse plane moment arm	0.52^{B}	0.06	0.55^{A}	0.06	0.48^{C}	0.05	0.52^{B}	0.07	0.0001*
Start transverse plane moment arm	0.43^{B}	0.06	0.46^{A}	0.06	0.41^{B}	0.06	0.44^{AB}	0.06	0.0020*
End transverse plane moment arm	0.42^{B}	0.05	0.45^{A}	0.05	0.38^{C}	0.05	0.42^{B}	0.07	0.0001*
Max resultant moment arm	0.61^{A}	0.07	0.63^{A}	0.07	0.56^{B}	0.06	0.60^{A}	0.07	0.0004*
Start height	0.93	0.12	0.92	0.13	0.88	0.11	0.89	0.12	0.1329
End height	1.05^{A}	0.14	0.94^{B}	0.18	1.11^{A}	0.10	1.04^{A}	0.15	0.0001*
Start asymmetry (0° is far right)	89.34	5.48	89.76	4.02	88.35	5.47	89.19	4.81	0.6578
End asymmetry (0° is far right)	88.83	5.82	89.92	4.25	88.07	5.93	88.32	5.57	0.4590
Abs. max forward moment arm	0.50^{B}	0.06	0.54^{A}	0.06	0.47^{C}	0.05	0.50^{B}	0.07	0.0001*
Abs. max side moment arm	0.17^{B}	0.03	0.19^{A}	0.04	0.16^{B}	0.03	0.16^{B}	0.02	0.0001*
Abs. max up moment arm	0.37	0.06	0.36	0.07	0.34	0.05	0.35	0.07	0.1600
Abs. max lateral plane moment arm	0.52^{B}	0.06	0.55^{A}	0.06	0.48^{C}	0.05	0.52^{B}	0.07	0.0001*
Abs. max sagittal plane moment arm	0.60^{A}	0.07	0.61^{A}	0.07	0.55^{B}	0.06	0.59^{A}	0.07	0.0006*
Abs. max sagittal trunk angle	52.56	9.64	54.04	20.33	47.67	10.27	51.82	13.63	0.1967
Abs. max lateral trunk angle	18.59^{A}	2.26	16.44^{B}	3.24	16.98^{B}	2.32	16.64^{B}	2.53	0.0001*
Max right lateral trunk angle	15.82^{A}	2.98	12.86^{B}	3.60	14.11^{B}	3.49	13.39^{B}	3.05	0.0001*
Max left lateral trunk angle	14.01^{A}	2.72	13.48^{AB}	3.72	12.18^{B}	2.31	12.71^{AB}	3.15	0.0177*
Max sagittal trunk flexion velocity	83.04^{A}	15.44	74.58^{B}	18.59	65.48^{C}	21.50	65.10^{C}	15.85	0.0001*
Max sagittal trunk extension velocity	88.69^{AB}	16.42	73.99^{B}	21.13	91.55^{A}	20.49	81.97^{BC}	16.83	0.0001*
Max sagittal trunk acceleration	779.44^{A}	169.13	678.74^{B}	186.27	691.24^{B}	158.93	639.53^{B}	129.27	0.0001*
Max sagittal trunk deceleration	741.77^{A}	171.42	643.22^{B}	185.09	663.45^{B}	169.10	601.05^{B}	133.97	0.0002*
Abs. max lateral trunk velocity	116.03^{A}	19.00	97.87^{B}	25.37	103.17^{B}	16.22	100.05^{B}	20.79	0.0001*
Max rightward lateral trunk velocity	100.65^{A}	17.87	85.27^{B}	22.44	85.60^{B}	17.30	84.15^{B}	19.27	0.0001*
Max leftward lateral trunk velocity	99.17^{A}	17.43	83.56^{B}	22.64	88.67^{B}	13.79	85.24^{B}	19.36	0.0001*
Max lateral trunk acceleration	946.88^{A}	180.85	806.86^{B}	217.37	833.91^{B}	161.01	803.65^{B}	190.70	0.0002*
Max lateral trunk deceleration	941.29^{A}	182.85	805.80^{B}	219.34	843.40^{B}	152.59	800.08^{B}	180.88	0.0003*
Max box up acceleration	12.24	6.75	13.43	10.30	10.00	6.51	9.36	6.65	0.0433*
Max box up deceleration	6.72	2.79	6.56	3.15	5.38	2.68	5.72	4.20	0.1589
Timing variables									
Duration	2.97^{A}	0.74	3.37^{A}	1.08	2.21^{B}	0.86	2.33^{B}	0.85	0.0001*
Duration of non load exposure	16.44^{B}	7.55	29.39^{A}	13.67	14.94^{B}	9.53	23.88^{A}	17.75	0.0001*
Duration of get	0.69	0.22	0.69	0.18	0.58	0.22	0.62	0.18	0.0325*
Duration of carry	1.97^{B}	0.60	2.36^{A}	1.01	1.31^{C}	0.64	1.41^{C}	0.64	0.0001*
Duration of place	0.47	0.14	0.54	0.20	0.46	0.18	0.50	0.24	0.2229
Percent time of max dynamic lift force	52.31^{B}	8.91	57.06^{A}	7.89	52.37^{B}	9.16	50.98^{B}	8.97	0.0129*
Percent time of abs. max dynamic slide force	47.61^{B}	7.35	47.62^{B}	7.01	52.04^{A}	9.52	47.17^{B}	5.63	0.0091*
Percent time of abs. max dynamic lift/slide force	51.38^{B}	9.09	56.08^{A}	7.22	52.47^{AB}	9.62	50.69^{B}	8.25	0.0261*
Percent time of abs. max static transverse plane load moment	50.75	7.25	50.13	7.22	46.88	11.00	46.62	10.08	0.0448*
Percent time of abs. max static forward-bending load moment	50.94	7.34	50.19	7.57	47.22	11.23	46.88	10.39	0.0688
Percent time of abs. max static side-bending load moment	51.28	4.54	49.57	4.79	51.40	5.60	51.76	5.36	0.2223
Percent time of abs. dynamic forward-bending load	51.02^{B}	9.70	56.56^{A}	7.60	50.30^{B}	8.84	47.72^{B}	10.33	0.0003*

Table 3 (*continued*)

Variable	Distribution center type								
	Grocery		Auto		Clothing		General merchandise		p-Value
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	
moment									
Percent time of abs. max side-bending dynamic load moment	52.44	5.59	53.98	6.31	53.80	6.46	51.92	6.70	0.3273
Percent time of abs. max dynamic transverse plane load moment	50.92^{B}	9.87	56.56^{A}	7.93	50.27^{B}	8.78	47.64^{B}	10.37	0.0003^{*}
Percent time of abs. max dynamic forward-bending resultant (sagittal) moment	53.70^{B}	8.86	58.17^{A}	5.94	55.62^{AB}	8.28	52.06^{B}	7.49	0.0032^{*}
Percent time of abs. max dynamic resultant moment	53.14^{B}	9.03	58.06^{A}	6.30	55.23^{AB}	8.28	51.62^{B}	7.74	0.0020^{*}
Percent time of abs. max dynamic twisting slide moment	48.04^{B}	5.34	47.73^{B}	5.34	51.09^{A}	7.61	48.61^{AB}	5.09	0.0446^{*}
Percent time of abs. max dynamic forward-bending slide moment	46.26^{B}	8.01	51.69^{A}	7.16	48.87^{AB}	12.18	46.21^{B}	11.15	0.0320^{*}
Percent time of abs max dynamic lateral plane slide moment	45.48	7.94	50.34	6.85	48.31	11.98	45.30	10.73	0.0432^{*}
Frequency	2.59^{A}	1.33	1.19^{B}	0.67	2.97^{A}	1.39	2.35^{A}	1.90	0.0001^{*}
Individual anthropometric variables									
Age	33.61	11.08	36.32	11.12	39.85	9.85	36.82	11.18	0.0550
Body mass index	25.95^{AB}	4.33	24.73^{B}	5.17	27.88^{A}	3.97	28.04^{A}	6.32	0.0073^{*}
Weight	81.94^{AB}	16.11	75.65^{B}	17.56	84.36^{AB}	14.55	87.65^{A}	21.63	0.0196^{*}
Height	177.46	9.03	173.71	8.91	173.79	8.75	176.47	9.23	0.1126

Means with different letters (A, B, or C) are significantly different at $p < 0.05$.
**Indicates significance at $p < 0.05$.

duration was between 11% and 12% of the cycle time. In addition, these data indicate that, on average, the lifting frequency across all the DC jobs sampled was 2.28 lifts per minute. However, this did vary with distribution center type. Grocery, apparel, and general merchandise distribution centers exhibited significantly higher lift frequencies than automotive parts distribution.

While this paper reports the most comprehensive description of physical exposure in the work place that we are aware of, it is possible to make partial comparisons between this database and other types of occupational environments. Prior to this study, the most quantitative analysis of work environments involved exposures in manufacturing environments (Marras et al., 1993, 1995; Norman et al., 1998). It should be acknowledged that measurements made in these previous papers were much cruder than those reported in this study. However, with this caveat in mind we can observe the magnitude of exposure differences between the manufacturing and distribution center environments.

Several key variable comparisons are worthy of discussion. First, the mean load weight measured in this study was comparable to the average weight handled in manufacturing environments (65.99 N in distribution vs. 64.25 in manufacturing). However, the average *maximum* load handled in distribution centers was far greater (177.65 N) compared to the average maximum observed in high risk manufacturing environments (104.36 N). Thus, the load weight distribution appears to be skewed towards heavier loads in distribution center environments.

Second, the maximum moment arms (distance between the load and the spine) exposures in manufacturing environments (0.75 m) appear to be larger than the maximum moment arm observed in distribution environments (0.60 m). However, one must consider the crude nature and accuracy of previous studies documenting moment exposure in the manufacturing environment compared to the fairly accurate measures obtained in this study. The potential measurement error might also be indicated by the large variability this measure (standard deviation of 0.20) within the manufacturing environment compared to the rather small standard deviation in moment arm observed in this study (0.07).

Third, in depth analyses of the moment information revealed that the vast majority of the moment exposure occurred in moments about the *x*-axis (forward-bending moment). In both the static and dynamic moment measures, the vast majority of the exposure was about the *x*-axis. Thus, the lifts in the current sample tended to be less asymmetric than the observations from manufacturing environments. This may be a function of the fact that more walking is common in distribution environments that allows worker to "square up" with the destination point better.

Comparisons of these distribution center maximum moment exposures to manufacturing exposures indicated that maximum static forward-bending load moment exposures were greater in distribution centers (104.2 Nm which is the mean of each subject's maximum static transverse plane moments) than in manufacturing environments (57.9 Nm) (Marras et al., 1995). However, the mean static load moment in the sampled distribution center jobs was 33.8 Nm as compared to 41.8 Nm measured in our sample (Marras et al., 1995) of manufacturing jobs. One should note that this difference is much more than would be accounted for by the 20% shorter moment arms described above. In sum, these data indicate that there is much more variability in the load moment exposures in distribution environments as compared with that experienced in manufacturing.

Fourth, another important measure of risk has traditionally been frequency of lift. Our previous studies observed lift rates averaging 2.8 lifts per minute in manufacturing environments. The distribution center lift rate observed here was 2.28 lifts per minute. However, when comparing these exposures one must recognize that the energy expenditure associated with distribution center environments would be expected to be much greater since far more walking is required relative to that observed compared to manufacturing environments.

Next, we were also able to compare trunk motions using our instrumentation for the sagittal and lateral motions of the workers in this distribution center study and compare the exposures to our earlier studies in manufacturing environments. In general, distribution center workers moved much more rapidly than did manufacturing workers. We observed sagittal plane average maximum trunk extension velocities of 84°/s in this study, whereas average maximum sagittal extension velocities were 49.53°/s in the manufacturing environment (Marras et al., 1995). Comparisons of lateral plane motions indicated similar magnitude differences between the two environments.

Collectively, these comparisons of work types indicate that distribution workers are commonly exposed to more extreme loads and move much more rapidly than manufacturing employees. In addition, on average, distribution center workers are exposed to slightly shorter moment arms (relative to the spine). However, it should be noted that these comparisons have been made across different types of distribution center environments. None the less, these findings should provide valuable information for assessments of multivariate measures of risk.

A couple of additional observations from the distribution database are also worthy of mention. We have been unable to find any previously published studies that have quantitatively described the subtasks associated with materials handling in distribution centers. Thus, some interesting observations can be derived from our database. First, we can see that the greatest duration of time exposure during materials handling activities (in distribution centers) is spent carrying the object (as opposed to getting it or placing it onto a pallet). In addition, workers appear to be exposed to significant load moments when carrying objects. While we have always assumed that the "get" phase of the lift would yield the greatest biomechanical exposures, the data indicates that significant loading can occur during the "carry" phase of the lift and these may even exceed those experienced during the get phase of the lift. Yet the literature is rather sparse relative to the biomechanical effects and health consequences of carrying objects compared to lifting them. Hence, much more research is needed to help understand the consequences of carrying.

Second, Table 2 also indicates that some underexplored materials handling characteristics (e.g. pushing moment during lifting defined as the product of the push/pull force and the vertical distance between L5/S1 and the midpoint of the hands) in distribution environments represent nontrivial exposures. Sliding a box in a distribution environment can expose workers to load moments that are close to the magnitude of the dynamic lift moment. This is most likely due to the effects of friction needed to break a box free from a pallet. In addition, significant asymmetric push moments are evident from Table 2 and these appear to be occurring at both high and low heights. Current studies are beginning to understand the influence of pushing and pulling (Knapik and Marras, 2009) and asymmetric exertions on spine loads (Kingma et al., 1998; Marras and Davis, 1998; Marras et al., 1998, 2003; Marras, 2008). Thus, an understanding of the biomechanical consequences these exposures may help us better understand how risk develops in distribution center environments.

Next, this data has provided some much needed exposure information relative to the height of materials handling activities. While the mean starting and ending heights appear acceptable (0.91 m and 1.03 m, respectively), one must realize that these values most likely represent the mid-height of most pallets. Most work occurs either below or above these points, thus the data points of concern would be the 5th and 95th percentiles measures of these variables.

It is interesting to compare exposures between types of distribution centers. Table 3 indicates that there are numerous statistically significant differences in load, position, and timing exposure characteristics between the various types of distribution centers. In addition, Table 3 indicates that there are some significant anthropometric differences between the workers employed in these different types of distribution centers. The distribution of load exposures can be appreciated via Fig. 3. This figure shows that clothing distribution centers had the overall lowest load exposure distribution. The automotive parts distributors showed a bi-modal distribution of box weights, with the higher mode approximately the same as that found in grocery distribution. There was more variability in the general merchandise category which resulted in more exposure to heavier weights. However, this figure indicates that the exposure to the heaviest loads, approximately 9% of the total observations, occurred in grocery distribution. These grocery observations were typically meat products.

In addition many of the position variables (moment arms, torso bends, etc.) were of lower magnitudes in clothing distribution centers. By contrast, many of the highest load moment and position exposures occurred in either grocery or auto parts distribution centers. In general, grocery and auto parts distribution appear to be fairly similar with respect to most variables except for the very large difference in frequency of lifting.

Finally, study limitations should be discussed. These results are specific to the manner in which the data were collected in these

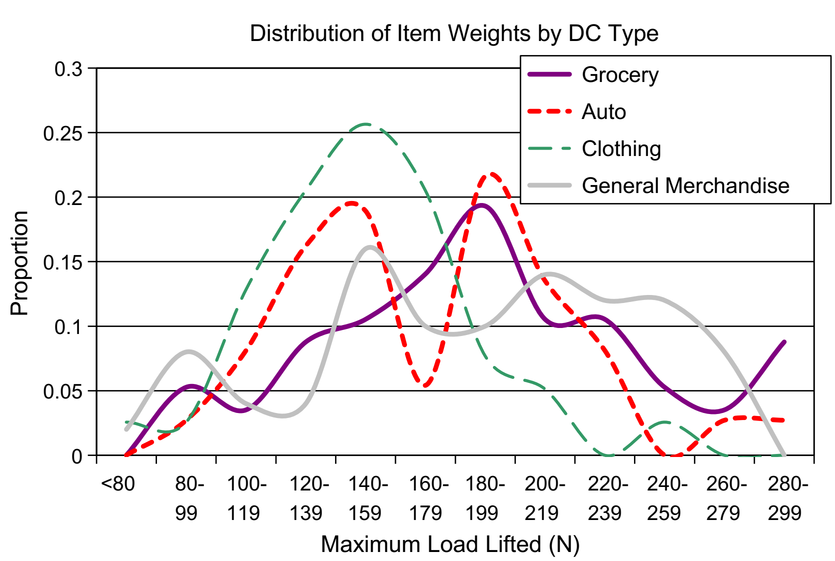

Fig. 3. Distribution of Item weights as a function of the type of distribution center.

distribution environments and, thus, they are a function of the instrumentation employed (Marras et al., 2000). A couple of instrumentation characteristics should be considered in this regard. First, the instrumentation required workers to use measurement handles to grab and lift the loads. It was observed that these handles slowed down the productivity of the worker. Thus, some of our temporal measures of exposure, especially, lift frequency might be under estimated. In addition, the handles allowed the worker to grab the box just about anywhere they chose. While it was possible to reduce the moment arm by grabbing the box close to the body, it was more typical for the worker to grab the box near the center of gravity so that excessive torque would not be generated about the wrist. Hence, we feel this worker behavior influence on moment measurement was probably minor. However, the handles also permitted the worker to lift near the top of the box as opposed to placing the hands under the box. Thus, our measures related to lift height might be over estimated. In addition, the measurement system required the worker to wear a back pack. This back pack was lightweight (<3 kg) but may have slightly restricted worker movement. Never the less, these equipment limitations should not detract appreciably from the value of this quantitative data. We feel that the benefits of precisely quantifying physical exposures should far out weight and limitations introduced by the equipment necessary to collect such precise and accurate data.

In conclusion, we have been able to quantitatively describe the biomechanically relevant exposures to workers in distribution center environments. These descriptions should provide a platform for further studies interpreting variable association with health risk as well as information that could be used to better understand the biomechanical system of the body.

Acknowledgements

Partial Support for this study was provided by the National Institute for Occupational Safety and Health (NIOSH) grant No. U01 OH07313. The authors wish to thank Mr. Pete Schabo for his role in the collection of data for this study.

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