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Postures and Movements of Upper Arms and Upper Back During Box Handling in Real Setting

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ABSTRACT

Considering the lack of studies assessing biomechanical exposure during manual material handling (MMH) in real work environment, the aims of this study are: (1) describing postures and movements of the upper back and upper arms during MMH performed in a regular workday in a real setting; (2) comparing postures and movements according to height level of the MMH; and (3) investigating the relationship between postures/movements and the workers' experience. Fourteen workers (28.14 ± 6.73 years) from the distribution sector of an automotive factory were evaluated during four hours of their regular work. Three workers who presented more than five years performing MMH tasks were considered as expert (6.33 ± 0.57 years of experience in MMH tasks). Eleven workers were classified as novices (1.24 ± 0.78 years). Postures and movements of upper back and upper arms were measured using inclinometers. APDF percentiles (10th, 50th, and 90th) were obtained for angles and angular velocities. All data were descriptively analyzed and a one-way ANOVA was performed in order to compare biomechanical exposure during MMH tasks performed in three different, and most adopted, heights (floor, chest and shoulder levels). Pearson correlation test was applied to investigate the association between experience and biomechanical exposure variables. Alfa level was set at 0.05. In general, the descriptive analyses showed no expressive difference between expert and novice workers. Significant statistical differences in upper back and upper arms posture and movement among the three most frequent handling heights were found. Moreover, there was a positive and significant correlation between workers' experience and humeral elevation. Despite the limited number of workers, we could evaluate what in fact happen in real settings. We believe that the evaluation of larger samples would demonstrate differences between expert and novice workers also in real settings, as we could observe a tendency of safer strategies among experienced workers. The challenge is finding larger groups of workers doing MMH tasks considering the lean production systems.

Keywords: Manual Material Handling, Movement Recording, Biomechanical Exposure, Real Work Environment

INTRODUCTION

Manual material handling (MMH) is harmful to the musculoskeletal system due to the physical strain generated during the work journey (Chaffin & Park, 1973; Ayoub, 1992; Straker, 1999; Yeung et al., 2002; Koehoorn et al., 2010). The literature shows several factors identified in MMH that are directly or indirectly involved in determining work-related musculoskeletal disorders (WRMDs), such as working procedures, force, awkward postures, organizational and psychological factors (Marras, 2000). Reviews on MMH in the construction and patient care sectors characterize MMH tasks as potentially harmful due to the association between high loads and the development of WRMD (van der Molen et al., 2005). The physical load arising from load handling is composed of many well-defined risk factors, such as upper limb elevation above the shoulder height, trunk flexion combined with rotation and spine inclination (Marras et al., 1993; Marras, 1999).

The relationship between biomechanical exposure and spine injuries due to MMH is well described in the literature (Gagnon, 2003; Gagnon, 2005; Marras et al., 2006; Plamodon et al., 2010; Plamodon et al., 2014). Moreover, there is a high incidence of low back disorders (Bureau of Labor Statistics, 2001), and high costs to rehabilitate the subjects (Leight et al., 1997; Murphy & Vollin, 1999). Thereat, many studies have focused on the evaluation of strategies that may reduce musculoskeletal load on the spine, including training programs destined to the workers. However, the literature is not as extensive when it comes to the musculoskeletal load imposed on other body segments than the spine during MMH, such as the upper limbs.

In order to control the development of WRMD, the first alternative for intervention is characterized as extrinsic (Mathiassen, 2006), and consists on work mechanization or alteration of the objects to be handled. However, despite the technological advance, MMH still exists in many workplaces requiring more selective and manual activities (Dempsey et al., 1998; Chung et al., 2005; Plamodon et al., 2006). Some individual characteristics may reduce the risk for developing disorders, and are related with the experience of each worker in MMH tasks (Granata et al., 1999; Gagnon, 2005). A few studies have described biomechanical strategies adopted by expert workers that are able to reduce the physical load imposed to the spine (Authier et al., 1996; Gagnon et al., 2002; Gagnon, 2003; Gagnon, 2005; Marras et al. 2006; Hodder et al., 2010; Plamodon et al., 2010; Dutta et al., 2011; Plamodon et al., 2014). These studies have mainly evaluated strategies involving the spine, feet and knees, as well as the position of the hands on the boxes. However, the impact of the experience on the upper back and upper limbs are still poorly addressed.

Despite the biomechanical differences identified among expert workers, two points deserve attention on these studies. First, the term “experience” has not been well defined in the literature. Expert workers may be made identified by colleagues and managers as competent handlers (Authier et al., 1996). Moreover, they can be considered according to the years of experience (Gagnon, 2003; Gagnon, 2005; Marras et al. 2006; Hodder et al., 2010; Plamodon et al., 2010; Plamodon et al., 2014). However, there is a large variability in the literature regarding the reference to identify expert workers by years of experience. A worker may be considered expert when working on the same activity for at least one year (Marras et al., 2006) or for at least 10 years (Gagnon, 2005). The second point is related to the local where the workers were evaluated. All studies were conducted in laboratories, ensuring the control of the analyzed variables, but impairing the realistic reproduction of the real working conditions.

Industrial workplaces include several tasks, including MMH. Therefore, it is difficult to acknowledge the representativeness of MMH on the biomechanical exposure of the workers. Consequently, the real effect of interventions focused on MMH tasks is not measurable. The evaluation of biomechanical exposure during an occupational task may be fundamental to understand the real need of interventions as well as the effect of these interventions. Furthermore, the recording of biomechanical exposure during the work journey makes possible to compare physical loads generated in specific tasks. To the present date only one study addresses MMH in real setting have used direct measurements (Silva et al., 2012). Silva et al. (2012) evaluated wrist and forearm postures during palletizing and depalletizing tasks performed with adapted boxes. They have focused the biomechanical assessment on the distal upper limb. Despite this unique study, the recording of physical exposure at real workplaces is applied to investigate repetitive work. The investigation of real biomechanical exposure has been performed through prolonged data acquisition in real occupational settings, in order to establish the duration of the tasks and do not neglect the many activities that compose the overall job (Mathiassen et al., 2003; Trask et al., 2008).

Therefore, the literature lacks evidence on the effect of the experience on the biomechanical load of upper limbs in MMH tasks recorded in real settings. With this in mind, the aims of this study were: (1) describing postures and movements of the upper back and upper arms during MMH performed in a regular workday in a real setting; (2) comparing postures and movements according to height level of the MMH; and (3) investigating the relationship between postures/movements and the workers’ experience.

METHODS

Subjects

All subjects working in the supplying sector of an automotive industry were invited to participate. Only workers with no history of musculoskeletal disorders in the past six months were included. The sample was composed by fourteen right-handed workers (28.14 ± 6.73 years). The ones with more than five years performing MMH tasks were considered as expert (3 workers, 6.33 ± 0.57 years of experience as handlers). The others were classified as novice (11 workers, 1.24 ± 0.78 years of experience). All workers completed the informed consent approved by the Ethics Committee of the Federal University of São Carlos.

Evaluation

Biomechanical exposure recordings were performed for each work during four hours of their regular work. Postures and movements of the upper back and upper arms were measured with inclinometers based on triaxial accelerometers (LoggerTeknologi HB, Åkarp, Sweden). The sensors were fixed with doubled-sided tape to the right of the spine at the level of the C7 vertebrae, and on the upper arms, at the level of the deltoid muscle insertion. Before being coupled on the workers each sensor was calibrated according to the procedures described by the manufacturer. After the fixation, a second calibration was performed in order to inform the system the neutral position, as well as the direction of each movement.

Data were acquired at 20 Hz. The 10th, 50th and 90th percentiles of the APDF (Amplitude Probability Distribution Function) were obtained from the angles and angular velocities of each segment. A researcher (HN) was responsible for recording recording the time of the tasks being performed during the data collection. Each MMH task was identified in the recording, and classified according to the height level of the handling: (1) floor level; (2) chest level; (3) and shoulder level. Data for non-handling tasks were discarded.

Statistical analysis

The statistical analysis was performed using the software SPSS 20.0. Normality and homoscedasticity were verified through the Kolmogorov-Smirnov and Levene test, respectively. The difference among the three MMH heights was tested using a one-way ANOVA. When significant difference was found, the Tukey post-hoc test was applied. The Pearson correlation test was applied to investigate the relationship between workers’ experience and the biomechanical exposure variables. The significance level was set at 5%.

RESULTS

In general, the descriptive analyses showed no expressive difference between expert and novice workers. Regarding the height of the tasks, floor and chest levels demanded the adoption of extreme postures when compared to MMH performed at the shoulder level ($p < 0.05$), as shown in Table 1. No statistical differences were observed for angular velocities when the height levels were compared.

Table 2 presents data for novice and expert workers. The qualitative analysis shows that the elevation of upper arms at the floor level is lower for the experts than for the novices. MMH performed at the chest level was associated with low biomechanical demand for the segments evaluated. Moreover, in this condition the experts presented higher movement velocities. The correlation analysis indicated a positive and moderate correlation between experience and left arm elevation ($r = 0.72$; $p = 0.027$) for MMH tasks performed at shoulder level.

Table 1. Upper back and upper arms posture and movements during manual material handling in three different heights.

Body segment	Distribution (APDF)	Heights		
		Floor level	Chest Level	Shoulder Level
Upper back flexion (+)/extension (-)				
Movement (deg)	10th	0.1 (6.1)	-2.9 (6.6)	-6.7 (10.1)
	50th	34.2 (18.1)[a]	17.3 (12.1)	12.9 (18)[a]
	90th	68 (15.2)[a]	60.5 (14.7)	48.1 (20.3)[a]
Velocity (deg/s)	10th	4.6 (1.3)	5.7 (1.5)	5.6 (1.5)
	50th	31 (6.1)	35.6 (8.7)	34 (6.3)
	90th	100.5 (16.2)	112 (21.4)	102.2 (20.7)
Right upper arm elevation				
Movement (deg)	10th	11.1 (3.2)	11.4 (3.3)	13.3 (3.3)
	50th	25.7 (4.3)[a]	27.1 (5.9)[b]	38.5 (20.3)[a,b]
	90th	50.5 (6.7)[a]	52.1 (11.4)[b]	69.6 (24.4)[a,b]
Velocity (deg/s)	10th	6.4 (1.8)	7.4 (1.9)	8.1 (2.2)
	50th	41 (8.3)	44.8 (10.4)	45.4 (10.6)
	90th	124.9 (20.7)	133.3 (29.3)	131.9 (23.4)
Left upper arm elevation				
Movement (deg)	10th	11.7 (4.3)	11 (2.9)	13.3 (3.4)
	50th	28 (7.7)[a]	27.1 (4.9)[b]	38.7 (18.5)[a,b]
	90th	51.8 (9.5)[a]	53.4 (9.6)[b]	75.9 (24.8)[a,b]
Velocity (deg/s)	10th	6.2 (1.8)	7 (1.6)	8 (1.9)
	50th	39.3 (8.2)	42.9 (9.3)	45.3 (10.1)
	90th	121.4 (20.1)	128.2 (25.6)	128.9 (23.3)

Statistically significant difference ($p < 0.05$; Tukey): [a]Floor level vs Shoulder Level; [b]Chest level vs Shoulder Level

Table 2. Upper back and upper arms posture and movements during manual material handling in three different heights between novice and experts workers

Body segment	Distribution (APDF)	Floor level		Chest Level		Shoulder Level	
		Novice	Expert	Novice	Expert	Novice	Expert
Upper back flexion (+)/extension (-)							
Movement (deg)	10th	1.1 (6.7)	-3 (1.4)	-2.7 (7.4)	-3.2 (4.6)	-6.4 (11.2)	-7.4 (9.8)
	50th	34.6 (18.1)	25.8 (20.2)	16.7 (13.2)	18.9 (10.1)	12.5 (18.5)	14.1 (23.8)
	90th	66.9 (17.6)	71.6 (3)	59.1 (16.7)	64.8 (6.6)	50.3 (18.1)	41.4 (33.7)
Velocity (deg/s)	10th	4.6 (0.9)	4.5 (2.4)	5.3 (1.4)	7.2 (0.8)	5.7 (1.7)	5.4 (5.4)
	50th	30.6 (4.4)	32.2 (11)	32.7 (7.8)	44.1 (4.8)	34.1 (6.9)	33.7 (6.7)
	90th	98.6 (12.8)	106.4 (26)	104.3 (16)	135.1 (19)	102 (19.2)	102.9 (33)
Right upper arm elevation							
Movement (deg)	10th	10.3 (2.9)	13.9 (2.8)	10.5 (3)	15 (3.1)	12 (2.5)	17.5 (14.5)
	50th	24.6 (4.2)	29.8 (1.9)	25.2 (10.8)	33.1 (4.8)	40.7 (25.4)	33.7 (0.8)
	90th	49.8 (7.3)	53.1 (3.4)	49.9 (13.3)	54.5 (3.2)	71.2 (29.2)	61.5 (18.5)
Velocity (deg/s)	10th	6.6 (1.4)	5.6 (3.2)	6.6 (1.9)	8.8 (0.8)	8 (2.3)	7.1 (0.9)
	50th	41.4 (7.3)	39.7 (13.2)	40.4 (10)	51.7 (4.9)	45.7 (10.7)	37.6 (6.4)
	90th	124.4 (18)	126.7 (33)	119.7 (20)	152 (21.7)	131.8 (25)	119.5 (8.2)
Left upper arm elevation							
Movement (deg)	10th	11 (2.7)	14.4 (8.4)	11.2 (3.5)	10.7 (0.7)	13.9 (3.7)	12.3 (4.5)
	50th	26.4 (4)	33.9 (15.6)	26.7 (5.7)	28.1 (2.6)	40 (23)	38.2 (6)
	90th	50.7 (7.6)	55.9 (16.3)	51.8 (8.7)	53.4 (8.7)	77 (30.6)	74.2 (14.7)
Velocity (deg/s)	10th	6.5 (1.3)	5.1 (3.3)	6.5 (1.6)	8.2 (1.2)	7.8 (2.2)	7.3 (0.8)
	50th	40.1 (6.3)	36.4 (14.8)	39 (8.5)	49.1 (8.6)	45.2 (10.4)	39.3 (6.4)
	90th	121.2 (15)	121.9 (37)	115.6 (17)	146.9 (26)	128.7 (24)	117.2 (23)

DISCUSSION

The results reported here have added information of the proximal part of the upper limbs and upper back to the available literature. Significant statistical differences in upper back and upper arms posture and movement among the three most frequent handling heights were found. Moreover, there is a positive and significant correlation between workers' experience and humeral elevation. These results are a new piece of evidence since they are based in evaluations performed with both experts and novice workers in a real work environment. Furthermore, all workers were evaluated when performing the same working task.

Difference in postural demand according to handling height has been previously reported. According to Oliveira et al. (2011), greater postural demand to the shoulders was observed in extreme handling heights (bellow waist and at the shoulder level). The results reported here agreed that larger humeral elevation occurs when the boxes are delivered to the shoulder height. However, when the handling was performed at the floor level, larger upper back flexion has occurred. Besides handling heights, in their laboratorial study, Oliveira et al. (2011) have also investigated the effect of weight in upper limb postures and muscular activation (EMG). The results showed a minor effect of box weight on postures, but a clear effect on EMG. The weight of the boxes handled by the workers evaluated in the present study varied from 10 up to 23 kilograms. However, according to the literature, this weight variation may not have any effect on the posture data reported here. Therefore, it may have changed movement velocity and also muscular load. Thus, further studies should consider the weight handled. Moreover, the weight of the handled object is associated with the risk to develop musculoskeletal disorders in several body segments (Chaffin & Parker, 1973; Dempsey et al., 1998; Chung et al., 2005; Ciriello et al., 2008)

Unfortunately, the reduced number of workers has impaired the comparison between expert and novice subjects. The number of expert workers was particularly low. However, it was possible to identify a positive and significant correlation between experience and humeral elevation of the left arm during handling at the shoulder level. The longer the experience, the larger the humeral elevation. Considering the high postural demand observed when MMH tasks were performed at the shoulder level, experts may have used their left (and non-dominant arm) to tilt the box and decrease spine extension. Given that all workers were right-handed, the use of the left arm to tilt the box was expected. This can justify the humeral elevation occurrence on the left side.

Besides the association between experience and upper arm elevation, a few tendencies were observed among expert workers. Thus, it seems that these workers develop some biomechanical strategies. High range of upper back motion was seen in the 10th. When they handled at floor level, larger postures occurred in the 90th percentile for all body segments. Moreover, high angular velocities were detected in the 90th in MMH tasks at chest level. This motor behavior allows greater adaptation capacity to diverse work conditions and is considered as a protective factor to the development of WRMDs (Kilbom & Persson, 1987; Granata et al., 1999; Gagnon, 2005; Madeleine et al., 2009). The higher range of motion observed among expert workers, in special when handling at both floor and chest levels, reflects the intrinsic variability pattern acquired over time (Mathiassen et al., 2003). The high angular velocities among experts can be explained by their short work cycles. However, short work cycles have been reported for novice workers due to their high potential to develop fatigue (Madeleine et al., 2009). However, this result has been reported for butchers, who have a more manual and repetitive work (Madeleine et al., 2003). We believe that the postural strategies and the overtime-acquired work conditioning are responsible for faster cycles.

Studies that compared experienced butchers with a reference student group (Madeleine et al., 2003; Madeleine et al., 2008) and slaughterhouse workers (Madeleine et al., 2009) with different experience levels have shown distinct results when the activity was realized in simulated or real environment. When the subjects were evaluated in the simulated setting, experienced subjects had higher range of motion and work cycles than the reference group (Madeleine et al., 2003; Madeleine et al., 2008). Therefore, the experience has provided more variability in motor pattern. Mathiassen (2006) points that creating more variation in biomechanical exposure is an alternative to decrease the existing similarity between activities/tasks and, thus, create prevention strategies. Thus, Madeleine and co-workers suggest that strategies seem among experienced butchers may be related to a lower incidence of musculoskeletal disorders (Madeleine et al., 2003; Madeleine et al., 2008). It is worth mentioning that two of the three reported studies have evaluated students as non-experienced subjects instead of workers with less experience. Less experienced workers were evaluated in the real work environment (Madeleine et al., 2009), and had higher work cycle than the more experienced. Srinivasan & Mathiassen (2009) state that more varied motor strategies are presented in more experienced workers. However, the implementation of variability in a work environment where the quality control and production demand dictate the way the worker perform the tasks may be difficult. These findings corroborate with the tendencies observed in our results: in general, experienced workers had higher range of motion and angular velocities than novice ones.

When investigating worker's experience, the reference adopted to identify experts is quite important. We have considered that workers presenting more than five years of professional experience with MMH tasks are experts (Plamodon et al., 2010). This reference can be considered as an average across the studies reported in the literature (Gagnon, 2003; Gagnon, 2005; Marras et al. 2006; Hodder et al., 2010; Plamodon et al., 2010; Plamodon et al., 2014). We believe that five years are enough to see strategies among the workers, as reported in the studies developed by Plamodon et al. (2010; 2014). However, the important contribution produced by Gagnon and co-workers on expert handlers' strategies reports that the time necessary for motor acquisition due to the working time is ten years (Gagnon, 2005). Nevertheless, they have evaluated the workers in controlled conditions, performing simulated tasks. It may restrict the subjects' motor variability. Madeleine et al. (2009) considered one year as enough to produce slaughterhouse expert workers because the tasks are very stereotyped and repetitive. As they could not find a variability pattern between the subjects, the experience time was considered as limiting.

Studies developed in real work environment have a potential advantage to investigate biomechanical exposure as the work place has an important influence on the generation of physical variability (Granata et al., 1999). However, the variation in the working tasks due to the daily production demand may be considered as a limitation. Thus, even when presenting the same position, workers may have presented different biomechanical exposure. Despite the limitations of this study, such as the reduced sample, this kind of investigation is valuable. A piece of knowledge on motor strategies developed by expert handlers and applied in their real environment could be reported. Several studies performed in laboratories show biomechanical strategies developed by experienced workers, especially those related to feet, knees and spine positioning (Authier et al., 1996; Gagnon et al., 2002; Gagnon, 2003; Gagnon, 2005; Plamodon et al., 2010; Plamodon et al., 2014). Those strategies are reported as efficient on reducing spinal strain. However, no study describing such findings in the industrial environment has been found. The knowledge of strategies resulting from working experience is important on the elaboration of adequate training programs. Moreover, the design of objects to be handled can be improved. Further studies should consider the assessment of the workers in different working days in order to minimize the effect of the daily production demand on the biomechanical exposure.

CONCLUSION

Postures and movements changed according to handling heights and workers' experience. Extreme heights showed high postural demand. Despite the limited number of subjects evaluated, expert workers demonstrated a tendency to adopt safer handling strategies. To our knowledge no study investigating biomechanical upper limbs among expert and novice handlers was performed in real work environment. Therefore, results reported here have a valuable contribution to the full understanding of biomechanical exposure during MMH in real environment. It can improve efficient prevention and training programs aiming the reduction of WRMS. Further studies should consider the assessment of the larger groups of workers, in different working days and also during other tasks not related to MMH also performed throughout the workday.

REFERENCES

Authier, M., Lortie, M., Gagnon, M. (1996). Manual handling techniques: Comparing novices and experts. *International Journal of Industrial Ergonomics*. 17, 419-429.

Ayoub, M.M. (1992). Problems and solutions in manual materials handling: the state of art. *Ergonomics*. 35: 713-728.

Bureau of Labor Statistics. (2001). Lost-work time injuries and illnesses: Characteristics and resulting time away from work, 1999 (Washington DC: US Department of Labor).

Chaffin, D.B., Park, K.S. (1973). A longitudinal study of low-back pain as associated with occupational weight lifting factors. *American Industrial Hygiene Association Journal*. 34, 513-525.

Chung, M.K., Lee, I., Kee, D. (2005). Quantitative postural load assessment for whole body manual tasks based on perceived discomfort. *Ergonomics*. 48, 492-505.

Ciriello, V.M., Dempsey, P.G., Maikala, R.V., O'Brien, N.V. (2008). Secular changes in psychophysically determined maximum acceptable weights and forces over 20 years for male industrial workers. *Ergonomics*. 51, 593-601.

Dempsey, P.G., Ayoub, M.M., Westfall, P.H. (1998). Evaluation of the ability of power to predict low frequency lifting capacity. *Ergonomics*. 41, 1222-1241.

Dutta, T., Holliday, P.J. Gorski, S.M., Baharvandy, M.S., Fernie, G.R. (2011). The effects of caregiver experience on low back loads during floor and overhead lift maneuvering activities. *International Journal of Industrial Ergonomics*. 41, 653-660.

Frank, J.W., Kerr, M.S., Brooker, A.S., DeMaio, S.E., Maetzel, A., Shannon, H.S., et al. (1996). Disability resulting from occupational low back pain, part I: what do we know about primary prevention?: A review of the scientific evidence on prevention before disability begins. *Spine*. 21(24), 2908-2917.

Gagnon, M., Delisle, A., Desjardins, P. (2002). Biomechanical differences between best and worst performances in repeated free asymmetrical lifts. *International Journal of Industrial Ergonomics*. 29, 73-83.

Gagnon, M. (2003). The efficacy of training for three manual handling strategies based on the observation of expert and novice workers. *Clinical Biomechanics*. 18, 601-611.

Gagnon M. (2005). Ergonomic identification and biomechanical evaluation of workers' strategies and their validation in a training situation: Summary of research. *Clinical Biomechanics*. 20, 569-580.

Granata, K.P., Marras, W.S., Davis, K.G. (1999). Variation in spinal load and trunk dynamics during repeated lifting exertions. *Clinical Biomechanics.* 14, 367-375.

Hodder, J.N., MacKinnon, S.N., Ralhan, A., Keir, P.J. (2010). Effects of training and experience on patient transfer biomechanics. *International Journal of Industrial Ergonomics*. 40, 282-288.

Kilbom, A., Persson, J. (1987). Work technique and its consequences for musculoskeletal disorders. *Ergonomics*. 30, 273-279.

Koehoorn, M., Xu, F., Village, J., Trask, C., Teschke, K. (2010). Back injury trajectories in heavy industries: defining outcomes for epidemiological research. *Journal Occuppacional Environment Medicine.* 52, 908-912.

Kuiper, J.I., Burdorf, A., Verbeek, J.H.A.M., Frings-Dresen, M.H.W., Van der Beek, A.J., Viikari-Juntura, E.RA. (1999). Epidemiologic evidence on manual materials handling as a risk factor for back disorders: a systematic review. *International Journal of Industrial Ergonomics*. 24, 389-404.

Leigh, J.P., Markowitz, S., Fahs, M., Bernstein, J., Mishel, L., Shin, C., Landrigan, P. (1997). 1992 cost of occupational low back pain in the US. *Archives of Internal Medicine*. 157, 1557-1568.

Madeleine, P., Lundager, B., Voigt, M., Arendt-Nielsen, L. (2003). Standardized low-load repetitive work: evidence of different motor control strategies between experienced workers and a reference group. *Applied Ergonomics*. 34, 533-542.

Madeleine, Voigt, M., Mathiassen, S.E. (2008). The size of cycle-to-cycle variability in biomechanical exposure among butchers performing a standardised cutting task. *Ergonomics*. 51, 1078-1095.

Madeleine, P., Madsen, T.M.T. (2009). Changes in the amount and structure of motor variability during a deboning process are associated with work experience and neck–shoulder discomfort. *Applied Ergonomics*. 40, 887-894.

Marras, W.S., Lavender, S.A., Leurgans, S.E., Rajulu, S.L., Allread, W.G., Fathallah, F.A., Ferguson, S.A. (1993). The role of dynamic three-dimensional trunk motion in occupationally-related low back disorders. The effects of workplace factors, trunk position, and trunk motion characteristics on risk of injury. *Spine.* 18, 617-628.

Marras, W.S. (1999). Effects of box features on spine loading during warehouse order selecting. *Ergonomics*. 42, 980-996.

Marras, W.S., Parakkat, J., Chany, A.M., Yang, G., Burr, D., Lavender, S.A. (2006). Spine loading as a function of lift frequency, exposure duration, and work experience. Clinical Biomechanics. 21, 345-352.

Mathiassen, S.E., Moller, T., Forsman, M. (2003). Variability in mechanical exposure within and between individuals performing a highly constrained industrial work task. *Ergonomics.* 46, 800-824

Mathiassen, S.E. (2006). Diversity and variation in biomechanical exposure: What is it, and why would we like to know? *Applied Ergonomics*. 37, 419-427.

Murphy, P.L. & Volinn, E. (1999). Is occupational low back pain on the rise? *Spine*. 24, 691-697.

Oliveira, A.B., Silva, L.C.C.B., Coury, H.J.C.G. (2011). How do low/high height and weight variation affect upper limb movements during manual material handling of industrial boxes? *Brasilian Journal of Physioterapy*. 15, 494-502.

Plamondon, A., Denis, D., Delisle, A., Larivière, C., Salazar, E., IRSST MMH Research Group. (2010). Biomechanical differences between expert and novice workers in a manual material handling task. *Ergonomics*. 53, 1239-1253.

Plamondon, A., Delisle, A., Bellefeuille, S., Denis, D., Gagnon, D., Larivière, C., IRSST MMH Research Group. (2014). Lifting strategies of expert and novice workers during a repetitive palletizing task. *Applied Ergonomics*. 45, 471-481.

Silva, L.C.C.B., Oliveira, A.B., Alem, M.E.R., Paschoarelli, L.C., Coury, H.J.C.G. (2012). Are cutout handles used when available in real occupational settings? Description of grips and upper extremities movements during industrial box handling. *Work*. 41, 4808-4812.

Srinivasan, D., Mathiassen, S.E. (2009). Motor variability in occupational health and performance. *Clinical Biomechanics*. 27, 979-993.

Straker, L.M. (1999). An overview of manual handling injury statistics in Western Australia. *International Journal of Industrial Ergonomics*. 24, 357-64.

Trask, C.M., Teschke, K., Morrison, J., Johnson, P.W., Village, J., Koehoorn, M. (2008). How Long Is Long Enough? Evaluating Sampling Durations for Low Back EMG Assessment. *Journal of Occupational and Environmental Hygiene*. 5, 664-670.

van der Molen, H.F., Sluiter, J.K., Hulshof, C.T.J., Vink, P., Frings-Dresen, M.H.W. (2005). Effectiveness of measures and implementation strategies in reducing physical work demands due to manual handling at work. *Scandinavian Journal of Work Environment & Health*. 31 suppl, 75-87.

Yeung, S.S., Genaidy, A., Deens, J., Alhemood, A., Leung, P.C. (2002). Prevalence of musculoskeletal symptoms in single and multiple body regions and effects of perceived risk of injury among manual handling workers. *Spine.* 27, 2166-2171.