

Weight knowledge and weight magnitude: impact on lumbosacral loading

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Several factors can impact lumbosacral loads during lifting, including weight knowledge and weight magnitude. However, interaction between them has never been tested. This study investigated the interaction effect of these variables on lumbosacral forces and moments. Participants performed symmetrical lifts using three different weights. Weight knowledge involved known and unknown weight conditions. A biologically assisted dynamic model was used to calculate spinal loading parameters. Weight impacted all variables, while knowledge impacted only compression, by a moderate amount (5%), and spinal moments. Lifting a lightweight resulted in a difference of 16% and 7.2% between knowledge conditions for compression and anterior-posterior shear forces, respectively, compared with a negligible difference of < 1% when lifting a heavy weight. Increased spinal loading with light unknown weight can be attributed to increased muscular co-contraction. Weight knowledge is important to consider at low weight levels as it can increase tissue loading to values equivalent to lifting a heavier weight.

Practitioner Summary: Impact of weight knowledge and magnitude on lumbosacral loading was investigated. The results suggest that subjects changed their lifting manner when handling unknown lightweight that increased spine loading to levels equivalent to handling heavier weights. This may be important for high frequency lifting tasks common in modern distribution centres.

Keywords: knowledge of weight; magnitude; low back loads; manual lifting

1. Introduction

Health problems related to physical work represent a major socio-economical burden resulting in extremely high costs in terms of decreased productivity, increased medical coverage and personal suffering (Dagenais, Caro, and Haldeman 2008). Low back pain (LBP) is a common musculoskeletal problem occurring in the workplace with a lifetime prevalence of up to 87% (Hales and Bernard 1996). Manual materials handling (MMH), especially lifting, is associated with low back injuries (Bernard 1997; Norman et al. 1998). The high mechanical stresses, exceeding the tolerance level of the low back's intervertebral joints, are assumed to be a major cause of low back disorders (Frank et al. 1996; Ferguson et al. 2004).

Little attention has been paid to the role of load knowledge on spine loading during materials handling, even though it can be a common daily routine in certain jobs. Examples include refuse collection, luggage dispatching or even healthcare providers who commonly handle patients without knowing their body weight. Workers usually depend on their expectation of a load's mass when handling objects of unknown weight. They make such expectations in order to achieve a proper lifting approach, which requires neuromuscular co-ordination that matches the needed lifting effort. It has been found that this co-ordination during lifting of an unknown load mass can be adapted to the object's size and magnitude (Kingma, Van Dieen, and Toussaint 2005). Neuromuscular co-ordination is subject to learning effects, in that a worker's previous experience can help predict the needed effort to initiate a lift of a known mass. Novice workers had nearly similar spinal compressive loads when lifting different masses, while experienced workers showed varying compressive loads that matched the mass lifted (Marras et al. 2006). Handling objects of unknown mass depends on a worker's estimate of weight. A mismatch between an object's estimated weight and its actual weight can lead to inaccurate motor control behaviour in the form of inappropriate postural or muscular adjustments. Weight overestimation was found to produce uncontrolled, exaggerated execution of a lift causing trunk perturbations, which required restabilisation and led to muscular co-contraction and overloading of the back (Marras, Rangarajulu, and Lavender 1987; Patterson et al. 1987; Butler et al. 1993; Commissaris and Toussaint 1997; de Looze et al. 2000; Mawston, McNair, and Boocock 2007). Commissaris and Toussaint (1997) concluded that weight overestimation may contribute to increased risk of low back injury. It caused balance disturbance in 92% of the lifting trials, and a delayed (150 ms after box lift-off) increase of lumbosacral net torque.

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In contrast, van der Burg, van Dieen, and Toussaint (2000) found that weight underestimation did affect spinal loading although it increased forward trunk flexion, which also can increase co-contraction of the trunk muscles.

Kotowski, Davis, and Shockley (2007) found out that lifting an unknown weight resulted in significantly higher trunk kinematics, rating of perceived exertion, and reported risk, compared with measurements recorded during lifting of a known weight. Interestingly, a gender difference also was found. Females tended to make less trunk movement, by pulling the unknown mass towards them and then lifting it. Males, however, had a more straightforward approach, by directly lifting the unknown mass, which created more trunk movement. In spite of recording statistically significant kinematic difference, the authors clarified that the actual minimal differences recorded might be of limited clinical importance. They strongly recommended the measurement of muscular activity and spinal loading to clarify the true clinical impact of their results. Butler et al. (1993) used shoulder movement as an indicator for whole trunk movement and found a significant increase of shoulder velocity when lifting a mass of unknown weight. That study was simplified by reporting data from single lifts of different weights with and without load weight knowledge. Furthermore, the authors did not record trunk muscular activity as trunk moments were predicted from kinetic and kinematic data of lower limbs and trunk.

Further studies showed that lifting an object of unknown weight can significantly impact the response of trunk structures and trunk loading pattern. de Looze et al. (2000) found that lifting a box of unknown weight resulted in 10% and up to 16% higher readings for trunk moment and trunk extensor muscle activity, respectively. However, they used only two load magnitudes (6 and 16 kg), which provided subjects with a limited number of weight variations that may have made it easier for them to predict the unknown weight. Moreover, authors did not measure spinal loads. They measured only L4/L5 flexion–extension torque. van der Burg et al. (2000) found a sudden burst of increased abdominal muscle activity, but with minimal impact on trunk moments, immediately after rapidly picking up a heavier than expected box. Rapid trunk motions may have confounded these results according to the muscle force–velocity relationship. Patterson et al. (1987) found higher L4/L5 peak sagittal moments and forces with the no-knowledge lifting condition compared with the with-knowledge condition. However, these results were not based on trunk electromyographic (EMG) data. Finally, Meyers and Keir (2003) found that the lack of knowledge about a load's centre of mass did not affect the activity of back muscles during lifting, although the position of centre of mass did impact erector spinae peak activity.

It is apparent that earlier studies concerned with lifting an object of unknown weight either used a limited number of weight variations or did not provide measurements of trunk loading patterns, including moments and forces, that are derived from trunk muscular activity. Furthermore, the interaction between load weight knowledge and magnitude was not of primary interest for any of the previous studies. Therefore, this study had the following aims: first, to investigate the impact of load weight knowledge on lumbosacral three-dimensional loads and moments, for which this hypothesis was tested: lifting a load of unknown weight will result in significantly higher lumbosacral loads and moments than lifting a known weight. Second, to determine whether weight magnitude can impact the effect of load weight knowledge, for which the following hypothesis also was tested: impact of load knowledge will be dependent on the magnitude of weight lifted.

2. Methods

2.1 Subjects

Eighteen subjects (14 males and 4 females), with a mean (standard deviation) age of 26.8 (4.9) years, were recruited from a university population. This uneven male-to-female ratio was an attempt to match gender mix that is typical in many industries (BLS 2012). Subjects were healthy, non-athletic persons with no history of back pain or any other musculoskeletal injury. They had no MMH job for at least a year prior to the study. All subjects signed a consent form approved by the Institutional Review Board of the Ohio State University. The anthropometric measurements collected included weight (73.3 (14.8) kg), height (176.5 (9.6) cm), and other trunk dimensions necessary for the biomechanical model.

2.2 Experimental design

This was a repeated measures, within-subject design study. Subjects performed lifting trials of three different weights (1.1, 5 and 15 kg) and two levels of weight knowledge (known and unknown weight) resulting in six experimental conditions. Each condition was repeated three times resulting in a total of 18 lifts/subject. Conditions were completely randomised to control for possible carry-over effects.

2.3 Instrumentation

Peak EMG activity recorded from ten trunk muscles (erector spinae, internal oblique, latissimus dorsi, external oblique and rectus abdominus on both sides of the body) was used as input for the EMG-assisted biomechanical model. EMG data were

recorded using surface bipolar electrodes, approximately 2 cm apart, placed on specified locations over the muscles (Mirka and Marras 1993). A Model 12 Neuradata Acquisition System (Grass Technologies West Warwick, RI, USA) was used to collect data at 1000 Hz. The signal was band-pass filtered at 30–500 Hz, notch-filtered at 60 Hz, rectified and averaged using a 40 ms sliding window filter and then normalised relative to maximum voluntary contractions (MVCs) values collected prior to experimental testing.

A triaxial goniometer known as Lumbar Motion Monitor (LMM) (Biodynamics Solutions, Columbus, Ohio USA) was used to measure instantaneous three-dimensional lumbosacral kinematics including position, velocity and acceleration. The validity, accuracy and reliability of the LMM have been reported previously (Marras et al. 1992). A force plate (Bertec 4060A; Bertec, Worthington, Ohio, USA) was used to measure the subject's three-dimensional ground reaction forces. Pelvic orientation and spinal position relative to the force plate were evaluated using a goniometric system (Fathallah et al. 1997). Data from the force plate and the goniometric system were used to calculate trunk moments.

All biomechanical data provided input for the dynamic EMG-assisted three-dimensional spine model. This model is used to predict spinal loads under realistic occupational conditions (Marras and Sommerich 1991a, 1991b). The main advantage of this model is that it is subject-sensitive as it accounts for individual variability in trunk muscle activity and, thus, estimated spinal loads. The model was validated for robustness in sagittal bending (Granata and Marras 1993), lateral bending (Marras and Granata 1997) and axial twisting (Marras and Granata 1995), as well as in lowering (Davis, Marras, and Waters 1998) and repetitive exertions (Marras et al. 2006). The model has also been adjusted to incorporate compression and shear calculations at each level of the lumbar spine (Knapik and Marras 2009).

2.4 Experimental procedures

Before starting the lifting session, subjects were informed about the range of the weight to be lifted. After gathering the needed anthropometric measurements (for model input) from each subject, surface EMG electrodes were placed over the specified trunk muscles, and the signals were checked for noise. Subjects, then, were placed in a rigid reference frame and performed a series of isometric MVCs of the trunk muscles; they were used during data analysis to normalise the EMG signals. The LMM was then properly placed on the back of the subject. Subjects, then, stood on the force plate to start performing the lifting tasks.

Each task consisted of symmetric lifting of a box to the chest level. The box was placed on a shelf at the subject's knee level, 45 cm in front of the subject's heels. Three identical looking boxes (width \times depth \times height = 44 \times 24 \times 34 cm) were used, each containing a different amount of weight. Boxes had two side openings (9 \times 3 cm) used for grasping and lifting. After each lift, the subject was asked to turn away from the box and close the eyes while the researcher changed the box with the new weight for the next lifting trial. After all lifts were completed, the subject stepped off the force plate and had the LMM removed.

Measurement outputs included lumbosacral loads and moments predicted by a validated EMG-assisted biomechanical model. Compression, anteroposterior (A/P) shear and lateral shear loads, as well as sagittal, lateral and axial moments, were all predicted by this model. Data were collected and analysed across the entire lifting trial period, starting at the moment subjects held the box and ending when they positioned it steadily at chest level. Peak measurements were calculated and averaged over the three trials of each experimental condition and then used for presenting output measures.

2.5 Statistical analysis

Descriptive statistics of all dependent variables were computed across experimental conditions. A two-way repeated measures analysis of variance (ANOVA) with a 2 \times 3 within-subject statistical design was used to test main and interaction effects of the independent variables. The independent variables were weight knowledge and weight magnitude. The dependent variables included lumbosacral loads (compression, A/P and lateral shear loads) and moments (sagittal, lateral and axial moments). All significant effects were further analysed using Tukey's *post hoc* test. To confirm the main effects of weight knowledge, simple effects analysis was done using pairwise comparisons of the two knowledge conditions at each weight level. To reduce experiment-wise error rate, Bonferroni correction was applied, and level of significance was adjusted to $p = 0.0084$ (0.05/6).

3. Results

Different statistically significant outcome measures are summarised in Tables 1 and 2. Weight knowledge significantly ($p < 0.01$) affected compressive force with the average unknown weight condition (2300 (779) Newtons (N) being higher than the known weight condition (2191 (822) N) by about 109 N. As expected, box weight significantly impacted all spinal forces ($p < 0.01$). All forces increased as box weight increased with a difference of 47.4%, 38.0% and 53.0% recorded

Table 1. Summary of statistically significant p values for different conditions.

	Compression	A/P shear	Lat. shear	Sag. mom.	Lat. mom.	Axial mom.
Repeated measures ANOVA (main and interaction effects of weight and knowledge)						
Knowledge	0.001*	0.023	0.009	0.001*	0.003*	0.008*
Weight	0.001*	0.001*	0.001*	0.001*	0.001*	0.001*
Knowledge \times weight	0.001*	0.002*	0.309	0.001*	0.180	0.430
Pairwise comparison [simple effects analysis of weight as a function of knowledge conditions (known vs. unknown)]						
1.1 kg	0.001*	0.001*	0.010	0.001*	0.018	0.026
5 kg	0.026	0.912	0.261	0.099	0.287	0.358
15 kg	0.666	0.627	0.055	0.759	0.015	0.044

Note: * indicates significant effect ($p < 0.0083$). Simple effects analysis indicates that weight knowledge has a significant effect only at low weight magnitudes (1.1 kg).

Table 2. Mean (SD) values of lumbosacral forces (N) and moments (Nm) for both main and interaction effects of weight knowledge and weight magnitude.

	KWC	UWC	1.1 kg	5 kg	15 kg
Main effects					
Compression	2192 (822)	2300 (779)	1646 (426)	1962 (428)	3129 (585)
A/P shear	347 (103)	353 (102)	278 (63)	320 (63)	451 (87)
Lat. shear	46 (34)	52 (40)	34 (22)	41 (26)	72 (47)
Sag. mom.	101 (46)	106 (43)	72 (24)	89 (26)	149 (38)
Lat. mom.	11 (8)	12 (9)	8 (5)	10 (6)	17 (11)
Axial mom.	7 (5)	8 (6)	5 (3)	6 (4)	12 (7)
Interaction effect					
Compression	KWC		1525 (365)	1926 (448)	3121 (561)
	UWC		1766 (449)	1996 (406)	3140 (612)
A/P shear	KWC		268 (50)	319 (68)	451 (84)
	UWC		289 (73)	320 (59)	449 (90)
Lat. shear	KWC		31 (21)	40 (25)	68 (40)
	UWC		36 (22)	43 (27)	77 (53)
Sag. mom.	KWC		66 (21)	88 (27)	149 (38)
	UWC		78 (26)	91 (25)	150 (38)
Lat. mom.	KWC		7 (5)	10 (6)	16 (10)
	UWC		8 (5)	11 (6)	18 (11)
Axial mom.	KWC		5 (3)	6 (4)	11 (6)
	UWC		6 (4)	7 (4)	12 (7)

Note: Bold numbers indicate significant effect ($p < 0.0083$). SD: Standard Deviation, KWC: known weight condition, UWC: unknown weight condition

between the highest and lowest values for compressive force, A/P and lateral shear forces, respectively. *Post hoc* test showed significant difference between different box weights for compression and A/P shear forces. Meanwhile, a significant interaction was found between the independent variables. The significantly different compression ($p < 0.01$) and A/P shear ($p < 0.01$) forces, obtained during lifting different box weights, were dependant on knowledge of the box weight (Figures 1 and 2).

Spinal moments were affected by the independent variables according to the same trend. Box weight significantly impacted spinal moments ($p < 0.01$). Lifting the 15.0 kg and the 1.1 kg boxes produced the highest and lowest values, respectively, with a recorded difference of 51.4% for sagittal moment, 53.6% for lateral moment and 53.9% for axial moment. The unknown weight lifting conditions resulted in significantly higher spinal moments than those recorded during known lifting conditions. A significant difference was found of 5%, 9% and 10% for sagittal, lateral and axial moments, respectively. The interaction between weight knowledge and box weight significantly impacted sagittal moment ($p < 0.01$). As shown in Figure 3, lifting different box weights resulted in higher sagittal moments for the unknown weight condition compared with moment values recorded when the weight was known.

Simple effects analysis revealed a significant effect ($p < 0.01$) of weight knowledge on compression, A/P shear and sagittal moment, when lifting light weights (1.1 kg) only. A very similar pattern was found for both compression and A/P shear forces. Significant differences between the two weight knowledge conditions were found when lifting the 1.1 kg box, for both

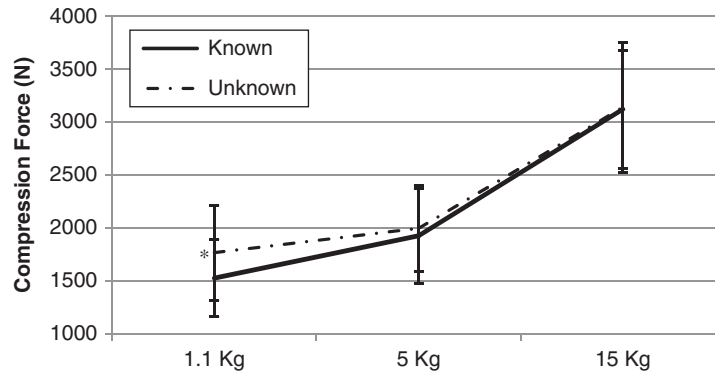


Figure 1. Mean compression force as a function of knowledge and box weight interaction ($p < 0.01$). Asterisk (*) indicates a significant simple effect of knowledge at different weight levels, only at low weight magnitudes (1.1 kg).

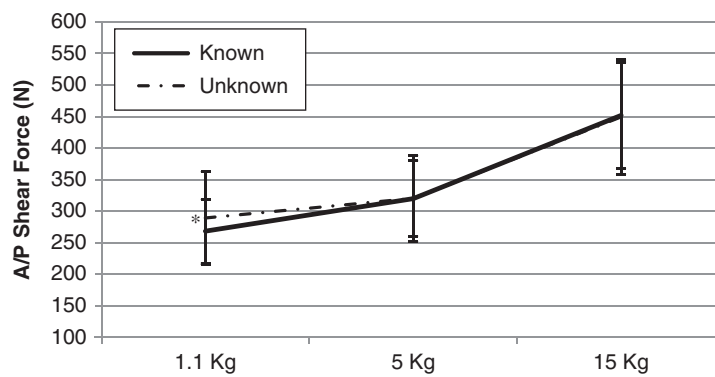


Figure 2. Mean A/P shear force as a function of knowledge and box weight interaction ($p < 0.01$). Asterisk (*) indicates a significant simple effect of knowledge at different weight levels, only at low weight magnitudes (1.1 kg).

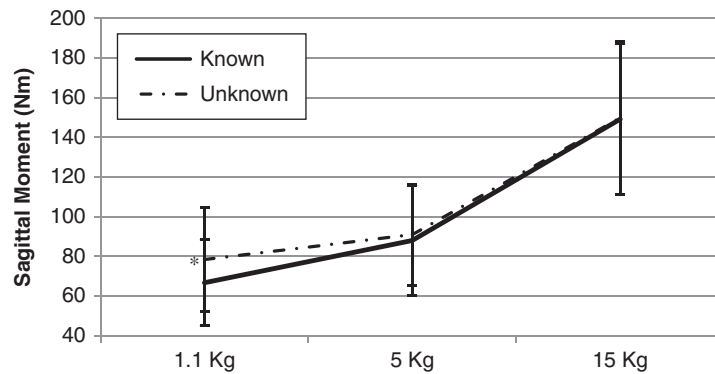


Figure 3. Mean sagittal moment as a function of knowledge and box weight interaction ($p < 0.01$). Asterisk (*) indicates a significant simple effect of knowledge at different weight levels, only at low weight magnitudes (1.1 kg).

compression (16%) and A/P shear (7.2%), compared with lifting the 15 kg box (<1%). Similarly for the sagittal moment, the highest difference between the two weight knowledge conditions (11%) was recorded when lifting the 1.1 kg box.

4. Discussion

It is common, in the working environment of a worker, to handle an object without having previous information of its mass. In addition, workers usually handle objects of variable weights. These two conditions deserve more attention and in-depth experimental investigation to explore its effect on a worker's lumbosacral loads during MMH.

In this study, weight knowledge was found to significantly affect only spinal compressive force, particularly at lower levels of weight. Although it did not significantly affect A/P or lateral shear forces, a trend was noticed where unknown weight condition revealed higher force magnitudes.

The results of this study are in good agreement with earlier studies, which reported that lifting boxes of unknown weight produces higher mechanical demands on the lumbar spine compared with that of the known weight condition (Patterson et al. 1987; Butler et al. 1993; Commissaris and Toussaint 1997; de Looze et al. 2000). The 100 N difference in lumbosacral compression between weight knowledge conditions cannot be considered biologically significant in terms of increased risk during most single lifts, however, they may be important in defining risk during cumulative loading. The increased compression can be attributed to increased trunk muscles co-contraction in response to lack of weight knowledge. A possible reason for the exaggerated muscular co-contraction could be over-preparation (weight expectation) of the subject in response to lifting an unknown mass. Since subjects performed weight familiarisation lifts, and the experimental conditions were randomised, it can be assumed that a subject's expectation of unknown weight included overestimation (e.g. a 1.1 kg box that might have been expected to contain a 15 kg load) and underestimation (e.g. a 15 kg box that might have been expected to contain a 1.1 kg load). Commissaris and Toussaint (1997) reported that spinal loading was significantly impacted by overestimation of box weight, while van der Burg and van Dieen (2001) reported that underestimation of box weight did not affect spinal loads. Taken together, it provides a possible explanation for the small compression difference and the insignificant results obtained for lateral and A/P shear forces.

Results showed that all lumbosacral loads had a significant, direct relationship with box weight. This agrees with the results of multiple studies that showed that weight magnitude is critical for determining amount of spinal loading (Hoozemans et al. 2008; Davis et al. 2010). It can be due to increased exertion of trunk muscles with heavier loads. Furthermore, co-contraction between agonistic (back) and antagonistic (abdominal) muscles was reported to have a major role in predicting magnitude of spinal loading and ensuring more trunk stability (Granata and Marras 1995; van Dieen, Kingma, and van der Bug 2003). Because of its location relative to the spine, trunk muscles have a very short moment arm compared with that of the external load lifted. This means that it has to contract more to balance external load, creating a higher level of mechanical burden on spinal structures (Jorgensen et al. 2001; Marras et al. 2001).

Lumbosacral compression and A/P shear forces were significantly impacted by the interaction between weight knowledge and weight magnitude, while lateral shear forces were not. Meanwhile, simple effects analysis revealed that the effect is significant only at lower weight levels (1.1 kg). Although such a small weight may be considered inconsequential, it increased compressive forces by about 240 N (16%) when lifted without prior knowledge of its magnitude. Increasing lumbosacral compression by such amount per lift is not a trivial issue, particularly when considering spine loading throughout an entire workday (cumulative load). One can argue that it increased spinal loading to a level equivalent to lifting weights that are a few kilograms heavier. Results of the lumbosacral forces obtained as a function of the interaction between independent variables can be attributed to the lifting approach used in the study. The symmetric lifting approach used has less effect on lateral shear forces (Marras, Davis, and Granata 1998). Moreover, symmetric lifting of unknown weight, particularly lightweight, may have caused momentary balance disturbance anteroposteriorly (de Looze et al. 2000), which could be controlled by increasing trunk muscle activation to increase spinal stability in the anterior-posterior direction. This can lead to more compressive and A/P shear spinal forces.

Lumbosacral moments were all sensitive to lack of weight knowledge, with higher moments recorded in the unknown weight condition, which is similar to the results of previous studies (Patterson et al. 1987; Butler et al. 1993; de Looze et al. 2000). Lumbosacral moments reflect variations in lifting behaviour. Increased lumbosacral moments when lifting a box of unknown weight can be due to occurrence of a jerky upward movement of the trunk, particularly when lifting a light unknown weight. This uncontrolled lifting may have caused a rapid upward (extension) movement of the trunk that increases the inertia of trunk movement and consequently increases the magnitude of spinal moments recorded.

The interaction between weight knowledge and weight magnitude affected only sagittal moments. L5/S1 moment results showed that greater differences were recorded when lifting lightweights relative to heavier weights, which agrees with earlier studies (Butler et al. 1993; de Looze et al. 2000). This difference is attributed to the higher trunk angular velocity that was recorded during lifting light unknown weight compared with that recorded during lifting heavier weights.

Box weights used in this study (5 and 15 kg) are comparable to those used in another study, which were 6.7 kg and 16.7 kg (Commissaris and Toussaint 1997). In spite of reaching the same conclusion, the L5/S1 sagittal moment magnitudes from that study (approximately 300 N m) were higher than that recorded here (approximately 150 N m). The difference in moment values can be due to two reasons. First, their load masses were higher than ours, which should result in higher spinal moments. Second, they used a different lifting approach. The subjects were asked to lift boxes as fast as they could once it was grasped. These authors were trying to minimise the subject's ability to estimate the actual box weight before lifting it. Lifting a box rapidly was found to generate higher trunk moments compared with slow, normal lifting (Lavender

et al. 1999). Subjects recruited for this study were not asked to lift boxes rapidly, since we thought this could confound the loading results.

Some limitations should be addressed to clearly understand the implications of this study in context. First, the independent variables had a limited number of levels. Using only two levels for weight knowledge might have underestimated its impact. Testing more levels of weight knowledge (e.g. known, overestimated unknown and underestimated unknown) may have revealed a more significant and stronger interaction with other variables. Second, symmetric lifting used in the study limited trunk movement to the sagittal plane only. Sagittal plane lifting might have contributed to the insignificant results obtained with some variables. Third, there was a sample size mismatch between male and female subjects. Kotowski et al. (2007) identified a gender-based impact on unknown weight lifting approach. Fourth, subjects were not experienced workers, as they had no previous MMH experience. Experience was found to have an impact on spinal loading characteristics (Marras et al. 2006).

4.1 Conclusion

The results suggest that handling objects of unknown weight can increase mechanical demands on the lumbosacral region, particularly at lower levels of weight. Furthermore, the sagittal moment results suggest that participants changed the manner in which they lifted the unknown weights, resulting in increased compression at lighter load to levels that were equivalent to a few kilograms of load. Caution should be practiced in such situations, to avoid disturbed balance and increased risk of back injury. This is applicable to MMH workers performing high frequency lifting tasks, as well as healthcare providers who commonly handle disabled patients, as in transfer activities, without knowing their weights.

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