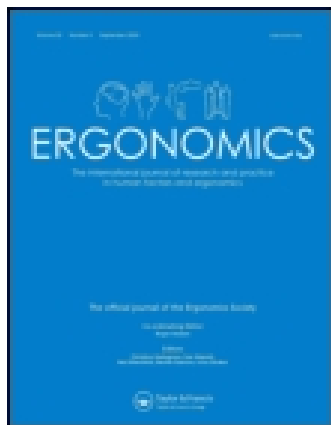


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Carrying and spine loading

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The advantages and disadvantages of different methods of carrying objects on spine loading are still not fully understood. Previous studies have either examined the effects of carrying using physiological measures or examined isolated spine segments using biomechanical models. Additionally, most studies have been restricted to only a small number of carrying conditions. Very few studies have attempted to examine the various factors influencing spine loading together. To improve understanding of interacting factors on carrying, this study assessed the lumbar spine loads of 16 subjects as they assumed six styles of carrying at two weight levels and two activity levels (walking vs. standing). Concurrent with each trial, a subject-specific biomechanical model was used to assess spine forces over the full lumbar spine. Most carrying methods in the trials resulted in relatively low levels of spine loading. Anterior/posterior (A/P) shear loading was the only spine-loading dimension that reached biomechanically meaningful levels. Two carrying conditions, with bins carried in front of the body, significantly increased A/P shear compared with other carrying styles. This increase appeared to be due to the greater moment arms occurring in these conditions. Many of the other carrying styles produced A/P shears that were similar to those observed when carrying nothing at all. Of all the tasks, the backpack carry characteristically produced especially low spine loads. The findings of the study suggest that to achieve optimal carrying in terms of spine loading, loads should be positioned close to the body, even when carrying relatively light loads.

Practitioner Summary: The risks carrying poses to the spine are still not fully understood. This study analysed forces on the lumbar spine for various realistic carrying styles. The findings indicate methods of carrying that increase the relative risk to the lumbar spine and others that have a minimal effect at the weights tested.

Keywords: carry; low back disorders; spine biomechanics; manual materials handling

1. Introduction

Musculoskeletal disorders constitute a large financial burden on industry with low back disorders (LBDs) being both prevalent and costly (National Research Council 2001; Kim et al. 2012). Numerous studies have linked LBDs with both lifting (Bernard 1997) and push–pull tasks (Hoozemans et al. 1998). Lifting tasks can place large compressive loads on the spine whereas push/pull tasks can create large shear loads on the spine. Carrying tasks can be considered a combination of these tasks. Even though carrying items is a common task in industry, the risks to the spine associated with various carrying styles have not been fully explored.

Previous studies have examined the effects of carrying on the human body through epidemiological, experimental and modelling methods. One epidemiological study reported an increased risk of LBD among workers who repeatedly carried heavy loads (Kelsey et al. 1984). Experimental studies have examined the costs of carrying loads by examining changes in whole body oxygen (O₂) consumption, heart rate and electromyography (EMG). Abe, Muraki, and Yasukouchi (2008) found that O₂ consumption dropped with the use of a backpack (BP) under certain conditions. Heart rate, however, was found to significantly increase with BP use (Holewijn 1990). Other studies have also found that EMG activity of some muscles decreases with BP use (Cook and Neumann 1987; Knapik, Harman, and Reynolds 1996), whereas other tasks significantly raise activity during various carrying styles such as anterior loading (Anderson et al. 2007). However, these dependent measures are not directly related to spine loading and the potential risk of LBD. Another study (Goh, Thambyah, and Bose 1998) examined compressive and shear forces in the lumbar spine; however, these forces were calculated using an inverse dynamics approach and did not factor in the considerable trunk muscle coactivity that would be expected to influence spine loading. In addition, only the forces imposed on L5/S1 were examined.

Thus, there remains a void in our knowledge in that the effect of carrying on the lumbar spine is still not fully understood nor is the link between carrying and potential LBDs. This study aimed to further the understanding of realistic carrying by analysing loading forces seen in the lumbar spine during a variety of typical carrying styles. It was hypothesised that carrying would produce trade-offs in shear and compressive spine loading depending on how the load was carried, the magnitude of the load and whether the load was carried while walking or standing.

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2. Methods

2.1. Approach

Many previous studies have focused on a single style of carrying such as BP (Bobet and Norman 1984; Negrini, Carabalona, and Sibilla 1999; Sagiv, Ben-Gal, and Ben-Sira 2000; Li, Hong, and Robinson 2003) or various types of bins (Cook and Neumann 1987; Anderson et al. 2007); however, no studies were identified that considered the various factors that could influence spine loading collectively. This study aimed to examine several factors of a variety of carrying methods in order to determine spine loading.

Subjects performed a variety of carrying tasks in order to determine the corresponding loads on the spine. Each task varied in: (1) weight carried, (2) style of carry and (3) level of activity (walking or stationary). Concurrent with each trial, a subject-specific biologically assisted biomechanical model was used to assess spine forces over the entire lumbar spine.

2.2. Subjects

Sixteen healthy individuals (8 male and 8 female) with no history of LBD volunteered to participate in this study. The subjects' ages ranged from 19 to 32 with an average age of 23.1 years. The average [standard deviation (SD)] stature of the subject population was 174.3 (10.1) cm, and the average weight was 72.9 (13.9) kg. All subjects reported right-hand dominance.

2.3. Experimental design

The study was a fully randomised design using six types of carry, two weight levels and two levels of motion. In addition, two 'no weight' (NW) control tasks (one at each level of motion) were included and used as reference tasks. Each task was performed twice for a total of 52 trials over a single session.

Independent variables consisted of those hypothesised to influence spine loads while carrying and included weight of lift (two levels), style of carry (six levels) and motion (walking or stationary). It is likely that the location of the weight being carried will alter the subjects' kinematics, and thus multiple loading locations were studied through seven styles of carrying. The tested styles consisted of backpack (BP; Figure 1(a)), bin with handles (BH; Figure 1(b)), bin supported underneath (BU; Figure 1(c)), briefcase (BR; Figure 1(d)), cross shoulder (CS; Figure 1(e)) and straight shoulder (SS; Figure 1(g)). Each style was representative of common carrying styles and varied the external weight's location as well as where the weight was supported by the body. When a weight was not placed centrally, it was situated on the side of the subject's dominant hand.

The two external weight levels consisted of a low weight of 5.7 kg (12.5 lbs) and a high weight of 11.3 kg (25 lbs). The high weight was chosen based on a previous study (Kelsey et al. 1984) which found an increased risk of prolapsed disc at this weight, and the low weight was arbitrarily chosen as one-half of the upper weight's magnitude. Two activity levels were used: stationary (S) and walking (W). For walking tasks, the subject walked 6.1 m (20 ft) at an approximate pace of 0.8 m/s. This distance was chosen based on observations from a previous study (Marras et al. 2010). Stationary tasks required that the subject remain motionless for 8 s (approximately the time of a walking trial).

Reference tasks were also included in the study in order to help interpret the 'costs' of carrying. These tasks required the subject perform trial without a carrying device (e.g. bin or BP) or other external loading. These tasks were referred to as NW carry conditions and were performed under both activity levels.

Dependent measures consisted of compression, anterior/posterior (A/P) shear and lateral shear at each lumbar disc level from L5/S1 to T12/L1. Inputs to these spine-loading measures consisted of (1) EMG collected from five left and right muscle pairs: erector spinae, latissimus dorsi, internal obliques, external obliques and rectus abdominis, (2) three-dimensional spine kinematics monitored using a lumbar motion monitor (LMMTM) and (3) subject anthropometry.

2.4. Spine load predictions

The model used to predict spine loads has been extensively described in the literature (Marras and Sommerich 1991a, 1991b; Granata and Marras 1993, 1995; Marras and Granata 1995, 1997; Davis, Marras, and Waters 1998; Knapik and Marras 2009) and has been shown to generate reproducible results (Granata, Marras, and Davis 1999). The biologically assisted model was calibrated according to subject-specific anthropometry (both the size and location of the subject's muscles), motion and muscle activity. The model determined trunk moments and tissue loading through the use of 10 equivalent muscle force vectors and the muscles' associated moment arms (Yoo, Herring, and Yu 1979; Schultz and Andersson 1981; McGill, Patt, and Norman 1988; Dumas et al. 1991). Muscle origins and insertions were determined based on regressions data from magnetic resonance imaging studies (Jorgensen et al. 2001; Marras et al. 2001).



Figure 1. Subject demonstrating various styles of carry: backpack (a), bin-handles (b), bin-under (c), briefcase (d), cross-shoulder (e) and straight shoulder (f).

Although originally designed to analyse lifting tasks, the model has been expanded and validated to assess more complex tasks by adjusting the length–force relationship and velocity–force properties of muscles and accounts for torso mass during leaning as well as the angles of vertebrae in the lumbar spine (Theado, Knapik, and Marras 2007; Knapik and Marras 2009).

2.5. Apparatus

EMG activity used in the spine load model was collected from five pairs of trunk muscles at 1000 Hz using bipolar surface EMG electrodes (Bagnoli[™]-16, Delsys[®], Inc., Boston, MA, USA). Placement of the electrodes was performed as described previously (Mirka and Marras 1993). EMG signals were normalised relative to six maximum voluntary contractions (MVCs): flexion, extension, right/left lateral bend and right/left twist. Calibration of the EMG data was performed using a force plate (Bertec 4060A, Worthington, OH, USA) and an L5/S1 locator (Fathallah et al. 1997).

Kinematic data (Marras et al. 1992) used in the spine load model were collected using an LMM. The LMM is designed to provide minimal obstruction to the subject's movements and is visible on a subject's back in Figure 1(b)–(c).

2.6. Procedure

Before experimentation began, a potential subject received a brief description of the study and signed the university's Internal Review Board consent form. Next, anthropometric measures were collected followed by the placement of EMG

surface electrodes. The subject then performed a series of maximum voluntary exertions in order to normalise EMG signals collected during the experiment. The LMM was placed on the subject who then performed a series of standard lifts while standing on the force plate. These lifts permitted the determination of muscle gains necessary for the spine model (Fathallah et al. 1997; Prahu 2005).

Subjects then received instruction on how to perform each carrying task. To begin a task, a weight was inserted into the carrying device which was then placed onto the subject's body (i.e. placing a bag's strap onto the shoulder) or into his or her hands. Subjects were directed to either walk the designated distance or to remain stationary. A 2-min rest followed each trial to minimise fatigue. The order of tasks was fully randomised for each subject.

2.7. Data processing

Raw EMG signals were band-pass filtered at 30–450 Hz, notch filtered at 60 Hz and rectified and integrated using a 200-ms sliding window. This filtered data were imported into the spine load model described earlier along with the kinematic data collected using the LMM and other devices.

2.8. Statistical analyses

General linear statistical models were developed for each dependent measure at every level of the lumbar spine from L5/S1 to T12/L1 (SAS Institute 1990). Each of the statistical models were tested for significance of main effects and interactions at $\alpha = 0.05$. The models were examined in conjunction with the recorded spine loads to identify the disc levels that demonstrated both statistical and biological significance for each dimension of spine force. If no disc level yielded both the statistical and biological changes for a given spine dimension, then no further analysis was performed. Post hoc multiple comparison Tukey's tests were performed to determine the presence of significant differences between tasks.

3. Results

A summary of the statistically significant findings (via p values) for experimental main effects and interactions of this study are presented in Table 1 for all the disc levels of the lumbar spine. The three main effects resulted in statistically significant differences as a function of conditions at every disc level of the lumbar spine and for all but one of the two-way interactions (Table 1). These results were examined in conjunction with their associated spine forces to focus further analysis. The L2/L3 disc level experienced the greatest A/P shear magnitude over the conditions and was indicative of the general A/P shear trends observed at most levels. The magnitude of the compression and lateral shear forces at all disc levels were low enough to not be considered biomechanically relevant (NIOSH 1994; Gallagher and Marras 2012) and were not believed to represent a significant risk. Therefore, they were not considered further.

3.1. A/P shear

Figure 2 and Table 2 indicate that A/P shear loads imposed on the L2/L3 inferior endplate varied as a function of weight for most tasks under both activity levels. All but three tasks demonstrated statistically different A/P shear loads between the 5.7- and 11.3-kg weight levels. The cross-shoulder (CS) stationary task did not vary significantly by weight nor did the BP task at either level of motion.

Two tasks (Figure 2) were of sufficient magnitude (> 700 N) to potentially cause damage to the tissues of the lumbar spine (Gallagher and Marras 2012): bin-under (BU) walking at 11.3 kg (830.0 N) and bin-handles (BH) walking at 11.3 kg (855.8 N). The spine loads for all other tasks remained under the 700-N threshold.

Statistical post hoc multiple comparison tests of the A/P shear loadings indicated that the NW stationary condition was not statistically different from 6 of the 12 other stationary tasks (BP 5.7 and 11.3 kg, briefcase (BR) 5.7 kg, CS 5.7 and 11.3 kg and straight-shoulder (SS) 5.7 kg). For the walking tasks, 4 of the 12 other tasks were not statistically different from the NW walking condition (BP 5.7 and 11.3 kg, CS 5.7 kg and SS 5.7 kg).

4. Discussion

These results indicate that carrying can be considered a complex biomechanical task with many factors affecting spine loading. As indicated in Figure 2 and Table 2, A/P shear loading represented the only spine-loading dimension that varied in a meaningful manner between conditions and suggests that, because of the load magnitudes, it was the most likely contributor to increases in musculoskeletal risk relative to other tasks within the study. Two tasks contributed to the greatest A/P shear loads observed under both levels of motion: BH and BU. These tasks also exhibited the greatest magnitudes of

Table 1. Summary of statistically significant main effects and interactions.

Level of spine	Task			Weight			Motion			Task × Weight			Task × Motion			Weight × Motion		
	A/P	Comp.	Lat.	A/P	Comp.	Lat.	A/P	Comp.	Lat.	A/P	Comp.	Lat.	A/P	Comp.	Lat.	A/P	Comp.	Lat.
T12/L1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0019	<0.0001	<0.0001	<0.0001	0.0026	0.0170	0.0771
L1/L2	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0006	<0.0001	<0.0001	<0.0001	0.0023	0.0177	0.0410
L2/L3	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0002	<0.0001	<0.0001	<0.0001	0.0023	0.0168	0.0200
L3/L4	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0220	0.0123	0.0098
L4/L5	0.0042	<0.0001	<0.0001	0.0013	<0.0001	<0.0001	0.0006	<0.0001	<0.0001	0.0002	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0092	0.0085	0.0179
L5/S1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0044	0.0071	0.0377

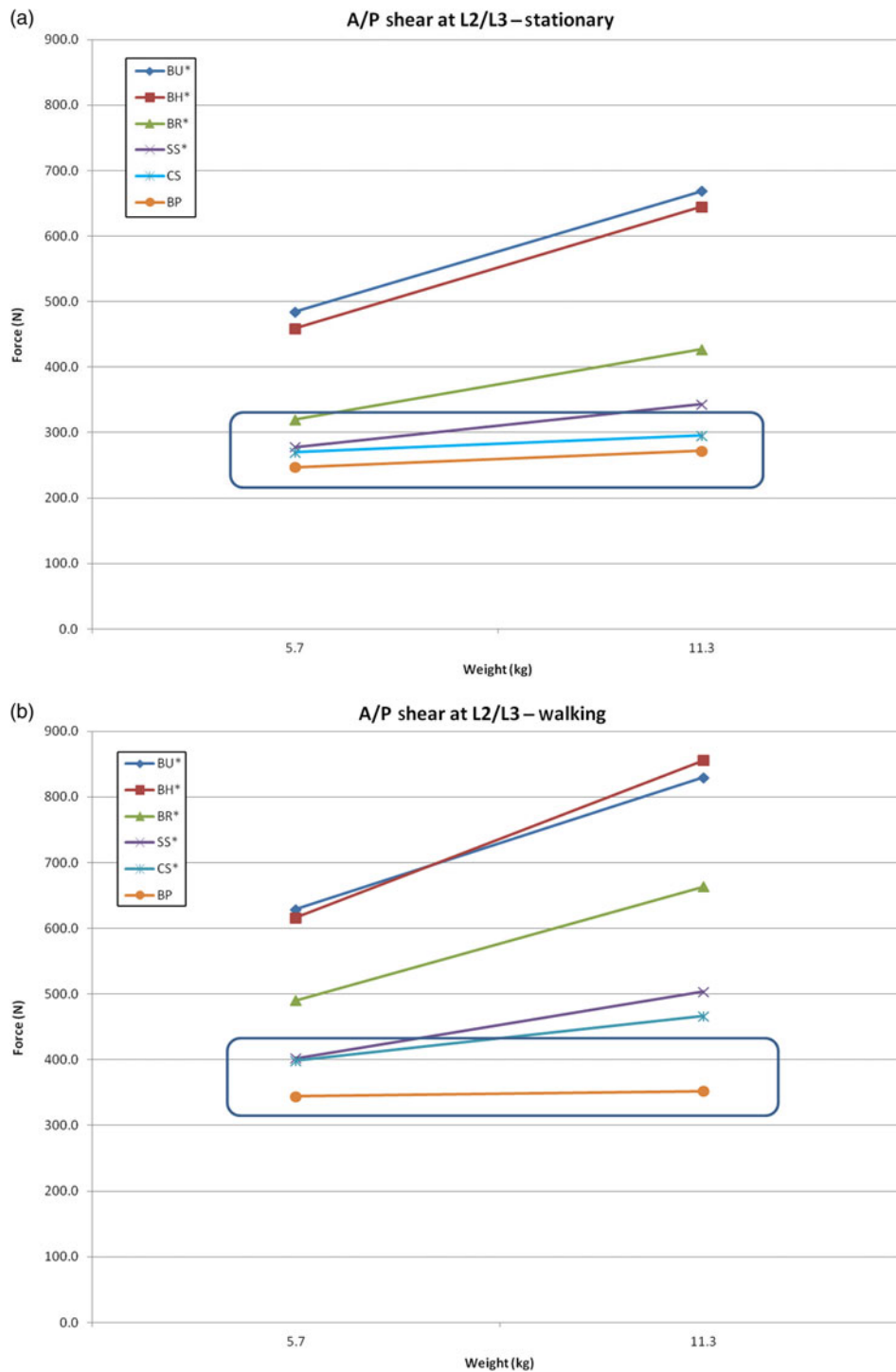


Figure 2. Mean peak A/P shear force at L2/L3 as a function of weight for stationary tasks (a) and walking tasks (b). Tasks marked with an * are statistically different ($\alpha = 0.05$) between weight levels. Tasks contained within a boxed area are not statistically different from the appropriate NW task.

compression and lateral shear (data not shown) and therefore could be considered the most taxing on the musculoskeletal system. These greater loadings were most likely because these tasks imposed the largest moment arms about the spine compared with the other carrying conditions. Because these larger external moments needed to be counterbalanced by trunk muscle at a mechanical disadvantage, spine loads increased substantially.

Table 2. Maximum values for A/P shear at L2/L3 for stationary (a) and walking (b) tasks.

Weight (kg)	Task	Mean (SD) (N)
<i>(a) A/P shear at L2/L3 – stationary</i>		
0	NW	251.0 (79.9)
5.7	BP	246.9 (83.0)
	BH	459.1 (126.5)
	BU	484.5 (138.0)
	BR	320.0 (95.0)
	CS	270.1 (87.1)
11.3	SS	277.7 (84.2)
	BP	272.1 (96.2)
	BH	645.1 (185.3)
	BU	668.9 (208.2)
	BR	426.9 (119.8)
	CS	295.4 (87.8)
	SS	343.5 (103.8)
<i>(b) A/P shear at L2/L3 – walking</i>		
0	NW	378.6 (121.6)
5.7	BP	344.5 (108.5)
	BH	616.3 (145.2)
	BU	628.9 (170.2)
	BR	490.6 (150.6)
	CS	398.5 (116.9)
11.3	SS	402.5 (119.4)
	BP	352.3 (107.7)
	BH	830.0 (257.0)
	BU	855.8 (233.3)
	BR	663.4 (219.2)
	CS	466.4 (141.9)
	SS	503.7 (143.0)

During the bin-carrying tasks, the bin was held at roughly a forearm's length away from the body. This distance imposed a larger moment compared with most other carrying conditions. Although this contributed to greater spine loads under both weight-carrying conditions, only the 11.3-kg walking carries for both bin-handling conditions resulted in loads great enough to potentially damage the spinal tissues because they exceeded the 700-N threshold. This analysis suggests a potential causal pathway that could explain epidemiological findings relative to carrying in which workers who frequently carry more than 11.3 kg were identified as having increased odds of developing a prolapsed lumbar disc (Kelsey et al. 1984).

The large spine loads associated with these tasks could be partially attributed to the high erector spinae and internal oblique muscle activities (Figure 3). Because these muscles function as extensors of the torso, they are capable of opposing the moment created by the bins and, in doing so, place stress on the tissues of the spine due to their poor mechanical advantage relative to the bin. A study by Cook and Neumann (1987) also found significant increases in erector spinae activity when loads of 10% and 20% of body weight were carried in front of the chest. Similarly, Anderson et al. (2007) found similar results with a 43% increase in trunk muscle EMG activity when a barbell was held in front during walking trials than was found in stationary trials. Several studies concluded that locating the load mass closer to the body reduced the amount of energy expended during carrying (Malhotra and Gupta 1965; Soule and Goldman 1969; Winsmann and Goldman 1976).

Numerous tasks were not statistically different from the NW carries during both the stationary and walking conditions (Figure 3). During stationary carrying, 6 of the 12 other tasks could not be differentiated from the associated NW carry in terms of spinal loads. For walking tasks, this number dropped to 4 of the 12 other tasks. Thus, several methods of carrying 5.7- and 11.3-kg items exist that produce A/P shear loads analogous to carrying nothing at all. Hence, it appears that there are some carrying styles that keep the external moment close enough to the body that the additional muscle activity needed to support (counterbalance) the load was minimal, and these conditions resulted in very low additional loading of the lumbar spine. Practically, this indicates that when possible, it may be advisable to replace other carrying methods with one of these methods in order to reduce spine loading. It is important to note, however, that several of these carrying methods were only applicable at the lower weight level of 5.7 kg. The two methods indistinguishable from the NW condition at 11.3 kg from the appropriate NW carry are the BP (stationary and walking) and CS (stationary) carries.

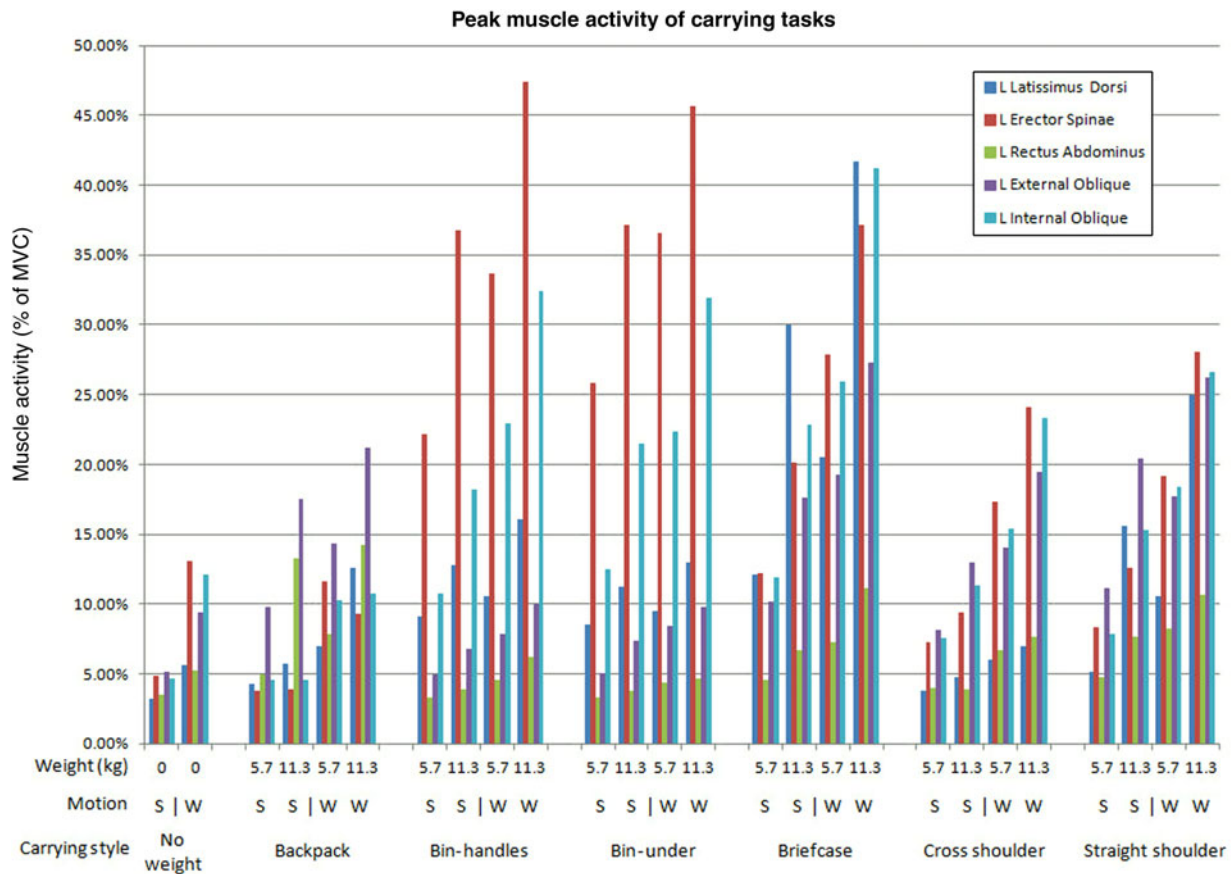


Figure 3. Peak muscle activity of carrying tasks reported as a percentage of subjects' MVCs. S, stationary; W, walking.

Of all the tasks, the BP carry characteristically produced especially low spine loads. One hypothesis that may explain this is that this type of carry minimises moment arms by placing the weight close to the spine. These moment arms are countered by small thin abdominal muscles that did not load the spine to the extent that of the erector spinae muscles had when the load was placed in front of the body.

The dual-strap BP design distributes the weight evenly across both shoulders, thus preventing the need for unilateral muscle recruitment to compensate for uneven loading. Hence, these results demonstrate the importance of external load balance. Several studies have also found that BP use, when compared with unloading walking, decreased erector EMG activity (Bobet and Norman 1984; Cook and Neumann 1987) or lowered the energy cost of the task (Datta and Ramanathan 1971; Abe, Muraki, and Yasukouchi 2008). A recent study found that carrying a balanced load of 60 kg (30 kg in each hand) greatly reduced compression in the lumbar spine when compared with carrying a lesser weight of 30 kg in one hand (McGill, Marshall, and Andersen 2013).

One of the most common methods used to replace carrying tasks consists of pulling the load, as seen in the recent popularity of wheeled luggage. In order to compare this activity with carrying, we also asked subjects to perform an additional task consisting of pulling wheeled luggage behind them (Figure 4) following the same protocol as described earlier. Under this condition, A/P shear, compression and lateral shear were found to be relatively low. Mean (SD) values of A/P shear were 258.2 (84.8) and 377.0 (115.0) N for 5.7 kg stationary and walking, respectively. For the 11.3-kg tasks, values were 255.7 (90.2) and 389.6 (131.3) N for stationary and walking, respectively. None of the luggage pulling tasks were statistically different from the NW task, and, within both weight levels, the 5.7- and 11.3-kg tasks were not statistically different. The use of pulled luggage appears to be an effective and low-risk method of transporting loads.

Finally, potential study limitations should be acknowledged. First, this experiment was conducted in a laboratory setting using specific bags and bins for experimental testing. Thus, the results would be expected to vary with different designs of bags and bins. However, our results could be considered to generically represent the relative influence of spine loading on various methods of carrying loads. Second, bags and bins used in this study were weighted using a solid material firmly restrained within each container. Other commonly carried fill materials, such as water or loose gravel, can place greater



Figure 4. Subject demonstrating a luggage task.

strain on individuals as the material's weight distribution may shift during transport. Thus, the use of solid weights allows for the formation of better baseline values by eliminating random variables and increasing the uniformity of environmental conditions across subjects. Third, each subject was asked to move at a pace comfortable for him or her. Spine loading may have been altered based on the speed that each subject chose. The comfortable pace was chosen to get spine loads representative of what would be seen in each subject outside of the experiment, minimising one potential confounding factor. Fourth, subjects were recruited from the local healthy college population and may not be representative of the average workforce. However, given that these subjects were relatively healthy, they represent a best case scenario, and one would expect the risk to increase for an older and/or less fit population. Fifth, this study investigated the spine loads associated with carrying two different weight levels. However, given that a specific individual's tolerance to tissue forces vary, one should consider the trends identified in this study as relative risks associated with the various carrying methods. Thus, we would expect that carrying lighter or heavier loads would influence spine loads in a relative fashion compared with the other methods.

5. Conclusion

This study quantitatively assessed spine forces associated with carrying tasks. Most carrying task resulted in relatively low levels of spine loading. However, two carrying conditions (both bins carried in the front of the body) significantly increased A/P shear compared with other carrying styles. This increase in load appeared to be due to the large moment arms imposed in front of the body during carrying. Many of the carrying styles produced A/P shears that were similar to those observed when carrying nothing at all. Overall, this study has identified methods of carrying that increase relative risk to the lumbar spine and others that have a very minimal effect at the weight levels tested.

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