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The objective of this study was to investigate potential associations between an individual's psychophysical maximum acceptable force (MAF) during pushing tasks and biomechanical tissue loads within the lumbar spine. Ten subjects (eight males, two females) pushed a cart with an unknown weight at one push every two minute for a distance of 3.9 m. Two independent variables were investigated, cart control and handle orientation while evaluating their association with the MAF. Dependent variables of hand force and tissue loads for each MAF determination and preceding push trial were assessed using a validated, electromyography-assisted biomechanical model that calculated spinal load distribution throughout the lumbar spine. Results showed no association between spinal loads and the MAF. Only hand forces were associated with the MAF. Therefore, MAFs may be dependent upon tactile sensations from the hands, not the loads on the spine and thus may be unrelated to risk of low back injury.

Practitioner Summary: Pushing tasks have become common in manual materials handling (MMH) and these tasks impose different tissue loads compared to lifting tasks. Industry has commonly used the psychophysical tables for job assent and decision of MMH tasks. However, due to the biomechanical complexity of pushing tasks, psychophysics may be misinterpreting risk.

Keywords: psychophysics; maximum acceptable weight; low back; push

1. Introduction

An abundant amount of research has been dedicated to evaluating the biomechanical risks associated with occupational manual materials handling tasks. In an attempt to reduce the risk of low back injury, these tasks are often converted from lifting to pushing and/or pulling (Hoozemans *et al.* 1998).

Pushing tasks may be associated with significant risk for low back disorder (LBD) (Snook 1978, Frymoyer *et al.* 1983, NIOSH 1997). As much as 20% of low back injury claims are associated with pushing or pulling (Hoozemans *et al.* 1998). Hence, there is a need to better understand the biomechanics of pushing and pulling tasks in order to mitigate the potential risks for LBD. Inadequate guidelines for the evaluation of pushing tasks may lead to the underestimation of the risk for LBD.

Various methods have been used to evaluate the LBD risk relative to spinal loads for pushing and pulling tasks. Many of the 'easy-to-use' biomechanical models are static and are difficult to justify for highly dynamic and complex tasks such as pushing. Adequate guidelines are lacking, therefore, psychophysics serves as an alternative for evaluating the acceptability of manual material handling tasks (Waters *et al.* 1993). The psychophysics tables are often used to determine the percentage of individuals who are able to push a specific force at a set handle height, distance and frequency (Snook 1978, Snook and Ciriello 1991). During these studies, participants selected acceptable hand forces by closely monitoring their perception of exertion and fatigue and then adjusted the pushing or pulling resistances to a maximum acceptable limit. However, few subjects were employed to establish these limits for pushing and it is unknown how these limits relate to biomechanical loads of the spinal tissues. Industry's reliance on psychophysical measures to determine task safety for employees may be problematic.

Psychophysics assumes that the subjective perception of an individual's maximum acceptable weight limit (MAWL) corresponds to biomechanical tolerance of his or her body (Snook 1978). However, the literature has shown that individuals are generally poor perceivers of load magnitude and often overestimate their lifting capacity (Karwowski *et al.* 1992). A study by Resnick and Chaffin (1995) found that participants performing a series of pushing and pulling tasks reported the arms and legs as the most stressed body regions, suggesting that they were not responding to stress in their lower back. The lack of perception of stress in the low back for asymptomatic

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individuals supports the postulate that discs contain few sensory organs to assess load even though the majority of the force exists in the nucleus and inner annulus of the disc (Adams *et al.* 1996). These findings raise questions regarding what individuals are responding to when deciding their exertion force and whether they are able to perceive risk in the lower back.

Studies that have evaluated psychophysical methods from a biomechanical perspective have concentrated primarily on occupational lifting tasks. Jorgensen *et al.* (1999) showed that predicted spinal forces and risk for LBD were found to be high at each subject's MAWL. Subjects were underestimating their risk based upon their perception of acceptable weight. However, no studies have proposed similar analyses for pushing tasks.

The literature suggests that spine loading during precision control should be considered in a pushing study. Marras *et al.* (2009a) found that when a cart had to be manoeuvred with precision control into a target, the forces created significantly higher anterior-posterior shear spinal loads which increase risk for disc pathology. Since control is commonly required in industrial tasks, psychophysically-determined maximum acceptable forces (MAFs) may be influenced by the degree of required control. However, a void exists in that we do not know how control affects the chosen MAF.

It is also postulated that the mechanics of pushing changes depending on the orientation of the handles. Several studies have evaluated horizontal handle orientations (Snook and Ciriello 1991, Schibye *et al.* 2001, Laursen and Schibye 2002, Knapik and Marras 2009) while others have evaluated vertical handle orientations (Kumar 1994, Das and Wimpee 2002, Jansen *et al.* 2002, Marras *et al.* 2009a). A recent study from Seo *et al.* (2010) evaluated the upper extremity biomechanical differences of handle orientation between perpendicular and parallel orientations relative to the applied forces. However, it is still unclear what effect they have on biomechanical spinal tissue loads. Also, no studies have specifically compared the effects of horizontal and vertical handle orientation on spinal loading and the chosen MAFs.

While biomechanics and psychophysics have been reported independently, a void exists in the literature in that we do not know how these might be related. The objective of this research was to investigate whether or not there is an association between spinal loads, muscle forces and hand forces with psychophysically-determined MAF limits while changing the level of cart control and handle orientation.

2. Methods

2.1. Approach

A study was conducted to investigate the relationships between tissue loads within the lumbar spine and psychophysically determined MAFs of pushing tasks with two levels of cart control and two handle orientations. A validated, subject-specific electromyography (EMG)-assisted biomechanical model was used to calculate the muscle forces of 10 major power-producing muscles of the trunk and spinal loads at each of six intervertebral lumbar spinal levels.

2.2. Experimental design

The experiment consisted of a 2 × 2 counterbalanced, repeated measures design with a nested psychophysical adjustment variable. Each measure was performed twice and the counter-balance design was used to mitigate carry-over effects.

2.2.1. Independent variables

The study consisted of two independent variables: degree of required cart control (high or low) and handle orientation (vertical or horizontal). For the degree of cart control, the high control condition required subjects to navigate the cart on a specified path into a target that was 30% wider than the cart (Marras *et al.* 2009a). The low control condition required the subject to push the cart along a straight path for 3.9 m. For the two handle orientations, the vertical orientation had handles set up in the upright position where the hands were in a neutral position. The horizontal orientation had the handles set so that the hands were in a pronated position.

2.2.2. Dependent variables

Three classes of dependent variables were evaluated: hand forces, muscle forces and spinal loads. Hand forces and muscle electromyography (EMG) were measured directly during tasks. These measures were used as input to the

EMG-assisted model to predict spine loadings as a function of time. Spinal load measures consisted of compression, anterior-posterior (A/P) shear and lateral shear at all lumbar disc levels. Spinal loads were calculated at the superior and inferior endplates of the six lumbar intervertebral disc levels (L5/S1–T12/L1) using a subject-specific EMG-assisted biomechanical model (Marras and Sommerich 1991a, 1991b, Granata and Marras 1993, Granata and Marras 1995, Marras and Granata 1995, Marras and Granata 1997a, 1997b, Theado *et al*. 2007, Knapik and Marras 2009).

2.2.3. *Nested variable*

A nested psychophysical adjustment was used to determine the maximum MAF that the subject could push once every two minutes for a typical eight hour workday. Each experimental condition consisted of two series of trials using a method of limits: one series starting from a very high load and the other starting from a very low load (Gescheider 1985). A trial was defined as a single push within the series. A pilot study was conducted to determine an appropriate range of high and low starting weights and to establish weight change increments. The lowest starting cart weight was 70 kg and the highest starting weight on the cart was 425 kg.

2.3. *Subjects*

Ten subjects (eight males and two females) volunteered for this study. None of the subjects had experienced low back pain within six months prior to participating. Anthropometric measures for the subjects are listed in Table 1.

Table 1. Subject anthropometry.

	Mean	SD	Minimum	Maximum
Age	24.1	1.66	21	27
Weight (kg)	72.9	14.6	50.8	101.8
Height (cm)	176.4	10.02	163.6	189.4

2.4. *Procedure*

The experimental protocol was approved by the University's Institutional Review Board. Informed consent was obtained from the subjects prior to participation. Subjects were asked to wear comfortable apparel including athletic shoes with sufficient traction to reduce the chance of slipping. Upon arrival, subjects were briefed on the setup and the types of exertions that would be required throughout the study.

Anthropometric measurements were recorded and used as inputs into the subject specific EMG-assisted biomechanical model. Maximum voluntary exertions (MVEs) were collected during isometric trunk extension, flexion, right and left lateral bends and right and left twists. Two minutes of rest were given in between exertions to mitigate the effects of fatigue.

A series of calibration exertions were then performed on a force plate (Bertec 4060A, Worthington, Ohio) to allow subject-specific model calibration. During the calibration lifts, the subject was also equipped with a pelvic angle monitor and moment arm monitor. In combination, these two pieces of equipment track the location and orientation of L5/S1 relative to the force-plate's global reference frame. The accuracy and reliability of this method of tracking L5/S1 has been reported previously (Fathallah *et al.* 1997).

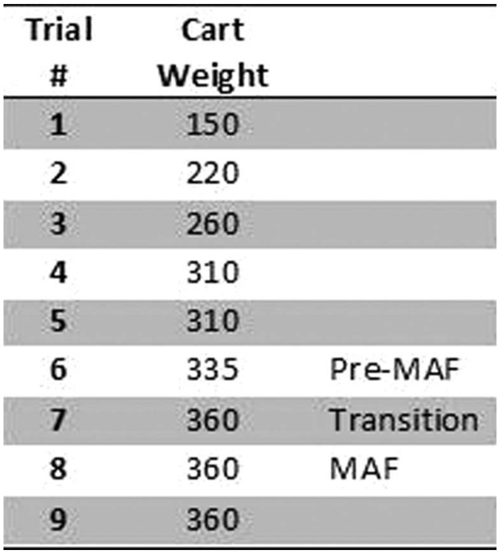
Subjects were then asked to perform the various experimental conditions as stated in the experimental design. After performing a push with the initial load, the subject was asked if that was the maximum acceptable load he or she could push once every two minutes for an eight hour day or if he or she could push more, less, much more, or much less weight. When the participant asked for 'more' or 'less' weight, between 10 and 25 kg was randomly added to or subtracted from the cart. When the subject asked for 'much more' or 'much less' weight, the range was 30–55 kg. These changes were referred to as the nested psychophysical adjustments.

The subjects were blinded to weight changes, and all weights were concealed within the cart to ensure that the subject was unaware of the weight that was on the cart. The subjects were given a two-minute rest after each pushing trial and a five-minute rest after a MAF limit was reached for the condition series.

At the start of each condition series, the subject was given a minimum of five trials to serve as a training period. After this point, when the subject settled on a weight for three consecutive pushes, the hand force associated with this weight was designated as the MAF. If the subject did not establish a MAF within 40 minutes, the series was discarded (based upon preliminary testing) and repeated at the end of the session.

The two critical push trials associated with the psychophysical adjustments were modelled and assessed for spinal loads, muscle forces and hand forces under each condition (Figure 1). The point at which the subject stopped changing the weight on the cart and settled on a MAF was regarded as the transition point. The trial before the transition point (pre-MAF) was compared to the trial after the transition point (MAF) to determine if any biomechanical changes occurred.

Average push velocity was controlled by requiring subjects to push the cart over a forward distance of 3.9 m in about six seconds (0.65 m s^{-1}). This velocity was similar to comfortable pushing velocities that have previously been reported in the literature (Marras *et al*. 2009a). Visual feedback was provided to help the subject reach the target in the allotted time. Trials were repeated if the subject failed to finish the task within half a second of the time requirement.



Trial #	Cart Weight	
1	150	
2	220	
3	260	
4	310	
5	310	
6	335	Pre-MAF
7	360	Transition
8	360	MAF
9	360	

Figure 1. An example of a condition in which the weight is increasing towards a MAF. The first trial of the three consecutive non-changing weight trials is labelled as the transition point. The second trial is labelled as the MAF.

2.5. *Apparatus*

2.5.1. *Electromyographic data*

Bipolar surface EMG electrodes (Delsys® Inc. Bagnoli™-16, Boston, MA, USA) were applied over the bulk of the following 10 major trunk muscles: right and left latissimus dorsi, erector spinae, rectus abdominis, internal obliques and external obliques. Location guidelines for electrode placement described by Mirka and Marras (1993) were followed. All EMG data were collected at 1000 Hz, high-pass filtered at 30 Hz, low-pass filtered at 450 Hz and notch filtered at 60 Hz. Signals were then rectified, smoothed with a 200 ms averaging window and normalised to MVE values.

2.5.2. *Kinematic data*

The lumbar motion monitor (LMM) (Biodynamic Solutions, Columbus, OH, USA) was used to monitor trunk motion. The LMM is a tri-axial electro-goniometer that can dynamically assess the instantaneous position of the lumbar spine in three-dimensional space. The accuracy and reliability of this device has been reported in the literature (Marras *et al.* 1992). Magnetic/gravitational sensors (Xsens Technologies™, Enschede, The Netherlands) were applied to the upper limbs and torso to track limb location and orientation. Reaction forces on the hands from the cart were measured with a pair of tri-axial force transducers (Bertec PY6–500, Worthington, OH, USA).

2.5.3. Cart

The cart used in this study was 57 cm wide × 122 cm long × 118 cm tall (Figure 2). The wheels closest to the subject were allowed to rotate freely, while the wheels farthest from the subject were fixed parallel to the length of the cart. The wheels were 15 cm in diameter and 5 cm wide and were made of a hard rubber material. All pushes were performed on a hard cement floor. The distance between the handles was 36 cm and the handle height was adjusted for each subject to 65% of his or her stature (Knapik and Marras 2009).

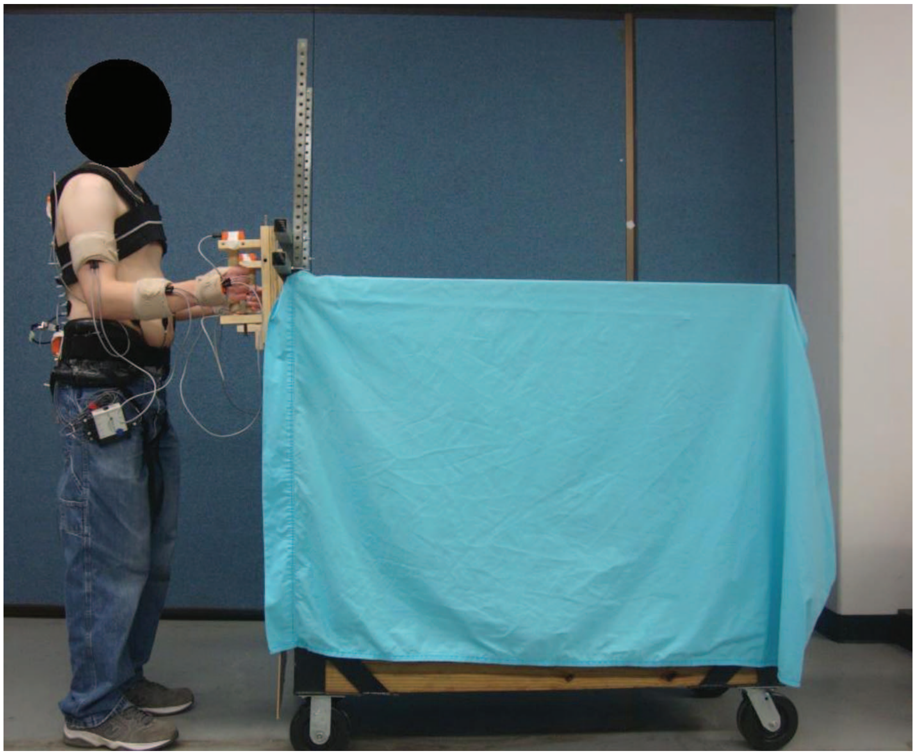


Figure 2. Covered cart used for experimental tasks. Subject was blinded to weight on cart and weight changes.

2.6. Statistical analysis

The data were analysed using univariate analysis of variance (ANOVA) using a $p \leq 0.05$ as a significance limit. Main effects as well as two-way interactions were assessed for each independent measure (degree of control, handle orientation and psychophysical level). Post-hoc Tukey tests were used to examine the differences between levels of the independent measures. Results were evaluated relative to statistical significance as well as biological and biomechanical plausibility.

3. Results

Statistical significant differences as a function of each of the measures relative to the independent variables and their interactions with spinal forces at each endplate level, muscle forces and handle forces can be found in Tables 2–5, respectively.

As a univariate, the psychophysical response was not statistically significant for the spinal loads at each endplate level (Tables 2 and 3). When considering the interaction between the psychophysical response and cart control variables, lateral shear was statistically significant at from L5/S1 to the inferior endplate of L1/L2 ($p < 0.05$). Anterior/posterior shear was also statistically significant for the interaction at the superior endplate of L3/L4 ($p = 0.0470$). The interaction between psychophysical response and handle orientation was not significant.

The only muscle force that was significant for the psychophysical response was the right erector spinae ($p = 0.0101$) (Table 4, Figure 3). For the interaction between the psychophysical response and cart control variables

Table 2. Summary of spinal loads relative to the psychophysical maximum acceptable force and the preceding push trial.

			Pre-MAF		MAF	
Spinal level	Endplate level		Mean (*N*)	Std dev	Mean (*N*)	Std dev
L5/S1	Inferior	AP	428.03	162.92	417.69	144.77
		COMP	–1105.44	397.34	–1067.46	385.19
		LAT	–14.07	106.12	–6.71	113.19
	Superior	AP	4.94	133.13	7.38	131.32
		COMP	–1172.70	426.10	–1131.33	405.36
		LAT	–24.63	107.67	–6.57	115.88
L4/L5	Inferior	AP	4.83	133.12	7.27	131.32
		COMP	–1172.36	426.10	–1131.01	405.36
		LAT	–24.63	107.66	–6.57	115.87
	Superior	AP	–552.99	167.32	–529.40	155.88
		COMP	–1046.37	405.49	–1010.23	384.51
		LAT	–39.79	111.13	–17.93	121.66
L3/L4	Inferior	AP	–552.94	167.32	–529.36	155.89
		COMP	–1045.97	405.48	–1009.84	384.50
		LAT	–39.79	111.12	–17.94	121.64
	Superior	AP	–706.74	223.37	–678.41	208.61
		COMP	–945.06	391.76	–914.55	371.81
		LAT	–50.64	120.56	–27.22	132.90
L2/L3	Inferior	AP	–706.63	223.37	–678.31	208.61
		COMP	–944.70	391.75	–914.19	371.80
		LAT	–50.64	120.55	–25.19	133.23
	Superior	AP	–750.93	242.86	–721.24	227.89
		COMP	–904.99	392.42	–876.75	372.26
		LAT	–53.83	133.64	–34.22	144.51
L1/L2	Inferior	AP	–750.79	242.86	–721.12	227.87
		COMP	–904.62	392.39	–876.38	372.22
		LAT	–53.83	133.62	–34.22	144.49
	Superior	AP	–747.95	246.12	–719.14	234.64
		COMP	–905.36	391.00	–876.55	368.59
		LAT	–67.69	142.25	–33.68	157.99
T12/L1	Inferior	AP	–747.82	246.11	–719.04	234.63
		COMP	–905.01	391.00	–876.21	368.59
		LAT	–67.68	142.22	–33.67	157.97
	Superior	AP	–658.60	223.10	–633.54	217.55
		COMP	–973.08	392.18	–939.70	368.14
		LAT	–81.47	158.18	–51.57	174.42

only the left erector spinae ($p = 0.0297$) was shown to be significant. The interaction between the psychophysical response and handle orientation was not significant for any of the muscle forces.

Hand forces (Figure 4) for the vertical ($p = 0.0199$), lateral ($p = 0.0093$) and resultant ($p = 0.0364$) directions were significant for the psychophysical response variable (Table 4). The forward force (Fz) was not significant. The interactions between the psychophysical response and cart control and between the psychophysical response and handle orientation were not significant.

4. Discussion

The results indicated that spinal loads were not associated with psychophysically-determined MAFs. Individuals are not likely to choose a MAF relative to their perception of biomechanical spinal tissue tolerance. Instead, their choices appear to be dependent on tactile sensations from the upper extremities (arms and shoulders) translated from hand forces during the pushing tasks.

Previous psychophysical lifting studies from Jorgensen *et al.* 1999 and Davis *et al.* 2000 support the theory on the lack of perception of spinal loading patterns. The decision to change the weights towards and at the MAWL was not affected by the spinal loading patterns (Jorgensen *et al.* 1999). Instead, muscle forces were better indicators of weight change during lifting than spinal loading (Davis *et al.* 2000). However, it is important to note that our modelling approaches have evolved and were different between the three studies. First, the lifting studies calculated

Table 3. Summary of statistically significant effects and two-way interactions (*p*-values) for spinal loads.

Spinal level	Endplate level		Control	Hand	MAF	Control × hand	MAF × control	MAF × hand
L5/S1	Inferior	AP	**0.0014**	**0.0382**	0.4304	0.4016	0.0974	0.8745
		COMP	**0.0079**	**0.0206**	0.2121	0.8115	0.0777	0.5191
		LAT	**0.0001**	0.3321	0.3463	0.8254	**0.0248**	0.8414
	Superior	AP	**0.0340**	0.0638	0.9320	0.4828	0.7887	0.1753
		COMP	**0.0062**	**0.0222**	0.1715	0.8872	0.0704	0.5712
		LAT	**0.0002**	0.1748	0.5079	0.7002	**0.0226**	0.9295
L4/L5	Inferior	AP	**0.0339**	0.0638	0.9320	0.4830	0.7888	0.1754
		COMP	**0.0062**	0.2222	0.1717	0.8871	0.0703	0.5713
		LAT	**0.0002**	0.1740	0.5093	0.6995	**0.0225**	0.9298
	Superior	AP	**0.0211**	0.0722	0.0852	0.9867	0.0634	0.3255
		COMP	**0.0041**	**0.0166**	0.1747	0.8183	0.0697	0.5543
		LAT	**0.0002**	0.2085	0.7074	0.5691	**0.0384**	0.9679
L3/L4	Inferior	AP	**0.0212**	0.0722	0.0853	0.9874	0.0634	0.3261
		COMP	**0.0041**	**0.0166**	0.1748	0.8183	0.0696	0.5542
		LAT	**0.0002**	0.2078	0.7088	0.5687	**0.0381**	0.9682
	Superior	AP	**0.0174**	0.0719	0.0727	0.9073	**0.0470**	0.3410
		COMP	**0.0033**	**0.0134**	0.2036	0.6714	0.0766	0.5831
		LAT	**0.0002**	0.5983	0.6204	0.5080	**0.0341**	0.9064
L2/L3	Inferior	AP	**0.0174**	0.0719	0.0729	0.9069	0.0646	0.3417
		COMP	**0.0033**	**0.0134**	0.2037	0.6716	0.0766	0.5830
		LAT	**0.0002**	0.5891	0.6320	0.5130	**0.0323**	0.8992
	Superior	AP	**0.0177**	0.0792	0.0719	0.8747	0.0752	0.3669
		COMP	**0.0030**	**0.0117**	0.2258	0.5932	0.0903	0.5914
		LAT	**0.0002**	0.9414	0.5059	0.5473	**0.0404**	0.7110
L1/L2	Inferior	AP	**0.0177**	0.0792	0.0721	0.8741	0.0751	0.3676
		COMP	**0.0030**	**0.0117**	0.2259	0.5933	0.0903	0.5913
		LAT	**0.0002**	0.9417	0.5073	0.5476	**0.0401**	0.7106
	Superior	AP	**0.0196**	0.0708	0.0784	0.9250	0.0781	0.3847
		COMP	**0.0029**	**0.0123**	0.2220	0.6326	0.0862	0.5959
		LAT	**0.0002**	0.7394	0.4242	0.6200	0.0770	0.6088
T12/L1	Inferior	AP	**0.0196**	0.0707	0.0787	0.9244	0.0779	0.3857
		COMP	**0.0029**	**0.0123**	0.2221	0.6326	0.0862	0.5960
		LAT	**0.0002**	0.7388	0.4246	0.6204	0.0768	0.6096
	Superior	AP	**0.0239**	0.0573	0.0978	0.9324	0.0838	0.3507
		COMP	**0.0032**	**0.0152**	0.1887	0.8022	0.0680	0.5807
		LAT	**0.0002**	0.4771	0.4324	0.6736	0.1174	0.6016

Note: Statistically significant variables ($\alpha \leq 0.05$) are bold-faced. Hand refers to the handle orientation and the MAF refers to psychophysical response.

Table 4. Summary of statistically significant effects and two-way interactions (*p*-values) for muscle forces.

Muscle forces	Control	Hand	MAF	Control × hand	MAF × control	MAF × hand
RLD	**0.0044**	0.2193	0.9578	0.0752	0.7405	0.5237
LLD	**0.0154**	0.6442	0.4890	0.5421	0.6204	0.9451
RES	**0.0357**	**0.0141**	**0.0101**	0.2055	0.0843	0.1428
LES	**0.0064**	0.0576	0.4416	0.8701	**0.0297**	0.2152
RRA	**0.0097**	0.4579	0.8083	0.1891	0.9191	0.9417
LRA	0.8750	0.6689	0.2619	0.3233	0.5407	0.2897
REO	**0.0042**	0.7435	0.0958	0.3920	0.7890	0.4759
LEO	**0.0019**	0.1508	0.6211	0.1967	0.4738	0.7941
RIO	**0.0394**	0.5823	0.5423	0.6895	0.1047	0.9069
LIO	**0.0084**	0.7946	0.6043	0.2000	0.3206	0.4233

Note: Statistically significant variables ($\alpha = 0.05$) are bold-faced. Hand refers to the handle orientation and the MAF refers to psychophysical response.

spinal forces from L5/S1, but the EMG-assisted biomechanical model has since been advanced to accommodate pushing and pulling, and include the spine levels of T12-S1 (Theado *et al*. 2007, Knapik and Marras 2009). Second, the lifting studies evaluated the variables involved during the changes that led to the decision of the MAWL. This

Table 5. Summary of statistically significant effects and two-way interactions (*p*-values) for hand forces.

Hand forces	Control	Hand	MAF	Control × hand	MAF × control	MAF × hand
Fx	**0.0275**	0.0549	**0.0199**	0.3961	0.3741	0.2489
Fy	**<.0001**	0.4583	**0.0093**	0.3360	0.1800	0.1811
Fz	0.9682	**0.0311**	0.0977	**0.0107**	0.6025	0.2058
Fr	0.0788	**0.0143**	**0.0364**	**0.0343**	0.1389	0.2165

Note: Statistically significant variables (α=0.05) are bold-faced. Hand refers to the handle orientation and the MAF refers to psychophysical response.

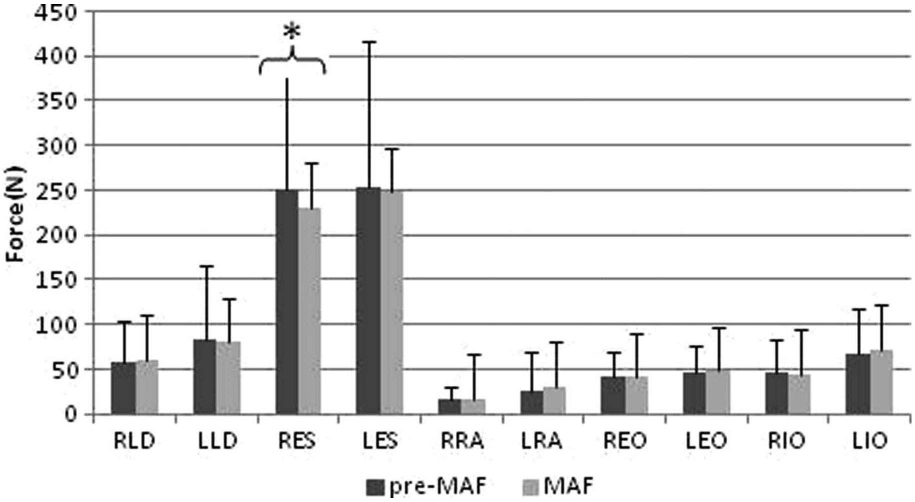


Figure 3. Muscle forces as a function of psychophysical response. The muscles are labelled on the plot from left to right as latissimus dorsi (RLD, LLD), erector spinae (RES, LES), rectus abdominis (RRA, LRA), external oblique (REO, LEO), internal oblique (RIO, LIO).

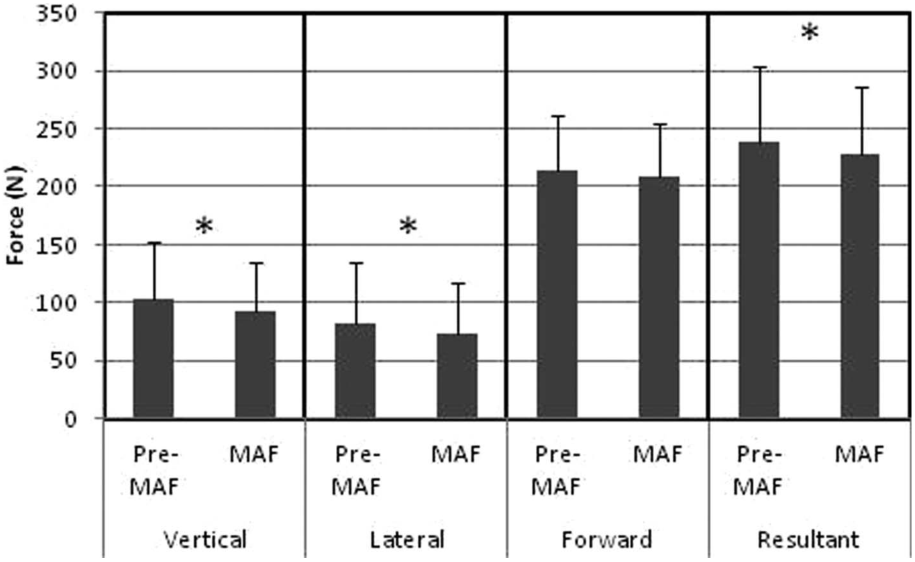


Figure 4. Hand forces as a function of psychophysical response.

study evaluated the spinal load, muscle forces and hand forces in relation to the MAF. The trial preceding the MAF to understand was also analysed to see if there was a link to the final decision to stay at a particular weight.

The lack of significance in the MAF relative to the spinal loads during pushing indicates that subjects were not responding to an increase in perceived force or stress in the lumbar spine, despite explicit instructions to focus on the low back. When asked about the most stressed part of the body after each set of pushes, arms accounted for 50% of responses and shoulders accounted for 21%. However, the low back accounted for only 6% of the total responses, further indicating that subjects were generally not perceiving stress in the lumbar spine.

The lack of pain response may be related to the limited sensory in asymptomatic intervertebral discs. Few nociceptors exist within the inner annulus layers and nucleus of the disc even though the majority of the compressive forces occur there (Adams *et al.* 1996). When the load/tolerance relationship is exceeded in the vertebral endplates due to high spinal loads, microdamage occurs. Yet it is doubtful that this is perceived by the subject. Over a period of repeated microdamage, scar tissue builds up on the endplates and disrupts the nutrient flow to the disc, eventually weakening the structural integrity of the disc and possibly resulting in disc pathology and pain. Using psychophysical limits to design pushing tasks, workers may be overestimating their MAF due to the lack of pain sensation in the discs. Repeated overestimation of the MAF may lead to cumulative microdamage and disc pathology. In this study, many of the calculated A/P shear loads for the reported MAFs from the superior endplate of L4/L5 to the superior endplate of T12/L1 were higher than the proposed A/P shear limit of 500N (McGill *et al.* 1998). In some cases, A/P shear loads were as high as 949N. Therefore, injury may occur even with the report of a MAF despite the perception of a safe exertion.

Biomechanical loading patterns in pushing are different than those during lifting. For lifting, the spinal loads contributing to risk are in the lower segments of the lumbar spine and are attributed to compression. During pushing tasks, the forces of concern occur in the upper segments of the lumbar spine in A/P shear. However, with the lack of nociception in asymptomatic discs, compressive loads as well as shear loads are not perceived very well in the lumbar spine. Nerve growth within the discs would be the primary source of pain transmission, but this may only happen after disc or endplate damage. Since our subjects were young, asymptomatic, and had no history of back disorders, it was difficult for them to perceive lumbar loading.

During pushing tasks it is inevitable that some level of control is necessary to manoeuvre the cart. Many factors are important to consider, from the flooring surface (Jansen *et al.* 2002, Laursen and Schibye 2002), wheels (Jansen *et al.* 2002), handle orientation (Seo *et al.* 2010), handle height (Al-Eisawi *et al.* 1999) to precision placement (Marras *et al.* 2009b). Hence, control is an important factor to consider when evaluating pushing tasks. Previous studies have shown that when a high level of control is required, A/P shear loads may exceed acceptable levels which place the worker at risk for disc pathology (Marras *et al.* 2009a, 2009b). However, it was unclear how cart control and spinal loading patterns could be related to psychophysical MAF. This study found that spinal loading patterns for the interaction of cart control relative to the reported MAF and the interaction of the handle orientation relative to the MAF were not statistically significant. When evaluating the muscle forces, the left erector spinae force for the interaction between control and the psychophysical MAF showed statistical significance. However, biological significance of this result is questionable because the power-producing muscles influence the spinal loads and the spinal loads were not significant. No statistical or biological significance was found in the spinal loads relative to the psychophysical response; hence the muscle force is not biologically significant.

Hand forces were statistically significant for the psychophysical MAF responses which support the subjective reports of the perceived location of discomfort or pain. In industry, hand forces are generally used in conjunction with the psychophysical tables to determine the maximum amount of load that should be on the cart. However, the force is usually measured through unidirectional hand force gages and the tables assume a forward directional force during pushing. Interestingly, this study found that the forward hand force did not show a significant difference for the MAF. Instead, significant differences were seen in the vertical, lateral and resultant force directions. By only considering the forward hand force when establishing a MAF, the amount of force exerted and the risk involved can be severely underestimated.

According to the psychophysical tables (Snook and Ciriello 1991), when considering the initial hand forces for both males and females, at a frequency of one push every two minutes for a distance of 2.1 m at elbow height, the MAF for 90% of the population is 26 kg (255.1 N) for males and 18 kg (176.58 N) for females. When comparing our initial hand forces with the psychophysical tables, the MAFs recorded were considered acceptable for 75%–90% of the population. However, A/P shear loads exceeded suggested spinal tissue tolerances, which indicate psychophysics may be underestimating risk to the low back.

A few limitations of the current study should be noted. First, the results are relative to a set of controlled conditions (frequency, distance, handle height, flooring and wheels) specific to this experiment and may be different if those variables change. Second, more males participated than females in this study. However, subject demographics represented typical manual materials handlers in the industrial workplace (BLS 2010). Third, subjects were inexperienced workers, although a similar trend is suspected amongst experienced workers. A future study with experienced workers would confirm this postulate. Aside from the stated limitations, the benefits from the findings shed a light on some of the potential issues with using psychophysics for the evaluation of pushing tasks.

Future research should continue to investigate the relation between biomechanics and psychophysics to discover the internal response that occurs when a worker determines a maximum force limit for manual work. Results show that sensitive, dynamic biomechanical modelling is needed to accurately show internal bodily responses. Without these models, biological responses to external forces cannot be accurately calculated and tissue damage may easily go undetected until after harm has been done. In addition, since work typically involves a mixture of risks it is difficult to partition out the contribution of the various risk factors in any other manner.

In conclusion, this study has shown that psychophysics may not provide an adequate estimation of low back injury risk during pushing. Subjects did not change their psychophysical response relative to spinal loading patterns in the discs; rather the response was associated with tactile sensation translated to the upper extremities from the hands. As a higher degree of control was needed for pushing tasks requiring navigation of the cart into a target, some of the A/P shear spinal loads rose above suggested tolerance limits, which increases the risk for LBD. Therefore, caution should be taken when using psychophysics for the evaluation of pushing tasks.

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