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Loading along the lumbar spine as influence by speed, control, load magnitude, and handle height during pushing

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ABSTRACT

Background: Low back loading and risk associated with pushing activities have been poorly understood. Previous studies have demonstrated that increases in anterior/posterior shear forces are primarily initiated by antagonistic coactivity within the torso. Yet, few studies have considered the range of activities that might contribute to the antagonistic coactivation and subsequent spine loading.

Methods: Twenty subjects were tested to examine how various physical factors might influence spine loads during pushing tasks that workers might experience in industrial settings. Load magnitude, speed of push, required control, and handle height were varied while pushing both carts and overhead suspended loads. A biologically-assisted biomechanical model was used to assess compression, anterior/posterior shear, and lateral shear over the various levels of the lumbar spine.

Findings: Anterior/posterior shear loads were greatest at the upper levels of the lumbar spine and of a magnitude that would be of concern. Anterior/posterior shear was influenced by all experimental factors to varying degrees except for the nature of the load (cart vs. suspended).

Interpretation: This study confirms the notion that pushing and pulling is not as simple a task as once believed since it entails a complex biomechanical activity. Spine shear forces result from a complex coactivation of trunk muscle activities and spine orientations that are influenced by several occupational factors. This study may help explain why low back pain rates in some work environments associated with lifting may not be reduced even when lifting interventions (that change the task from lifting to pushing) are employed.

1. Introduction

There has been increased concern over pushing and pulling activities in recent years. It is common for these activities to replace lifting tasks as there is more awareness of the risks associated with lifting in the workplace. Pushing and pulling is commonplace in many manufacturing environments, warehouse and distribution setting, the service and delivery industry, as well as in patient handling activities. Studies have shown that pushing and pulling can contribute to risk of low back pain (LBP) (Hoozemans et al., 1998a,b, 2002a,b; Damkot et al., 1984; Frymoyer et al., 1983; Kelsey, 1975; NIOSH, 1997; Snook, 1978; Plouvier et al., 2008) but due to low compressive loads on the spine during pushing, the biomechanical risk associated with pushing and pulling may be underappreciated. Of particular concern is a recent study that indicates pushing and pulling increases the risk of low back problems with disc involvement (Plouvier et al., 2008).

Recent studies have indicated that the biomechanics of pushing and pulling is more complex than originally thought compared to lifting biomechanics. Early biomechanical assessments of pushing and pulling using static models report fairly modest magnitudes of spine compression unless very heavy carts were manipulated (de Looze et al., 1995; Resnick and Chaffin, 1995). Basic biomechanical models also report fairly low spine shear forces during pushing and pulling (de Looze et al., 1995; Laursen and Schibye, 2002; Schibye et al., 2001). However, most previous evaluations have assessed the spine force occurring at the lower lumbar levels (i.e. L5/S1). Other studies have shown that handle height during pushing and pulling had a dramatic influence on spine loading (de Looze et al., 2000; Hoozemans et al., 2004; Knapik and Marras, in press) as do the direction of applied force exerted on the handle and trunk angle during the exertion (Jansen et al., 2002). In addition, biologically-assisted modeling of the spine during pushing and pulling indicate that shear forces may be of concern (Knapik and Marras, in press; Nussbaum et al., 1999; Lett and McGill, 2006). A recent study suggests that because of lumbar lordosis and antagonistic coactivation, shear forces would be greatest at the mid to upper lumbar levels of the spine (Knapik and Marras, in press). In addition, this study indicates that the high levels of shear force were a result of the antagonistic trunk muscle coactivation occurring during the application of horizontally oriented force.

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The study concluded that anterior/posterior (A/P) shear forces could be the primary source of risk to the spine during pushing and pulling.

Increased spine loading and specifically increases in A/P shear forces are primarily initiated by antagonistic coactivity within the torso (Granata and Marras, 1995b). With increased antagonistic coactivity the oblique muscles are recruited to a greater degree. Since these muscles have a greater horizontal force component they contribute more to shear loading when activated (LBP) (Marras and Granata, 1995, 1997b).

It is hypothesized that activities associated with manipulation of pushed devices might require varying degrees of antagonistic trunk muscle coactivation and result in changes in spine loading. A previous study has shown that tasks associated with increased control requirements may increase spine forces (Davis et al., 2002). It might be insightful to consider other device characteristics and activities that might also contribute to the antagonistic coactivation of specifically the horizontally oriented trunk muscles. These device characteristics and activities might include the type of device manipulated (i.e. pendulum system or floor-based cart), the speed of pushing or pulling activity, and the degree of precision required to control a push or pull. Yet, there is a void in the body of literature that assesses the spine loading associated with these variables. Thus, the goal of this study was to consider the influence of these control related variables (type of system, speed, and precision) along with the previously reported variables that influence spine loading during pushing (load and handle height).

2. Methods

2.1. Approach

This study was intended to examine how various physical factors might influence spine loads during pushing tasks that workers might experience in industrial settings. Load weight and handle heights have been previously examined in a number of studies. In this study we consider these factors in addition to three other factors that might potentially influence antagonistic trunk muscle coactivity and subsequent spine loading. Hence, this study examines the loads on the lumbar spine as subjects perform a push task that varied according to: (1) type of device pushed, (2) load magnitude, (3) degree of controlled required, (4) push speed, and (5) handle height. An electromyography (EMG) – assisted biomechanical model was employed to assess compression, lateral shear, and A/P shear spine forces at the six disc levels that comprise the lumbar spine (Knapik and Marras, in press).

2.2. Subjects

Twenty subjects (10 males and 10 females) volunteered as subjects for this study. All subjects were inexperienced university students and had not previously been employed as materials handlers. None of the subjects were experiencing low back pain. The average (SD) age, weight, and height of the subjects were 23.1 (4.47) years, 72.59 kg (14.34), and 182.60 (6.13) cm for the male subjects and 21.90 (1.85) years, 60.22 (8.08) kg, and 166.23 (5.61) for the female subjects, respectively. The study was approved by the University's Internal Review Board (IRB) and all participants provided informed consent.

2.3. Experimental design

The experimental design consisted of a $2 \times 2 \times 2 \times 2 \times 3$ repeated measures design where the push device, load magnitude, degree of control, push speed, and handle height variables were controlled at different levels and each condition was repeated two times. Thus, overall, 96 exertions were collected from each subject.

Independent variables consisted of five variables. First, the push device employed (either overhead rail mounted or a floor-based cart). The overhead device consisted of a Zimmerman™ air balancer attached to Z-rail™ that permitted motion in two dimensions of travel (Fig. 1a) and formed a pendulum style push pull device. The length of the pendulum varied from 76 to 152 cm depending upon the handle height condition and the subject stature. The cart condition consisted if a 57 cm wide $\times$ 122 cm long $\times$ 118 cm tall cart with 15 cm diameter $\times$ 5 cm wide hard rubber wheels operating on a hard (cement) surface (Fig. 1b). Second, the loads were set at fixed at levels and consisted of a "light" load of 54.5 kg (120 lbs) and a "heavy" load of 145.5 kg (320 lbs). These load magnitudes were based upon unpublished field data collected in our laboratory. Third, the degree of push control required was set at two levels. One level did not constrain the load destination position (no constraint) and the other level required the subject to push the load through a target that was 15% larger than the load width on each lateral (horizontal dimension) edge of the load. Fourth, two push speed conditions (determined subjectively via a pilot test) consisted of a 0.7 m/s push speed (comfortable or slow)

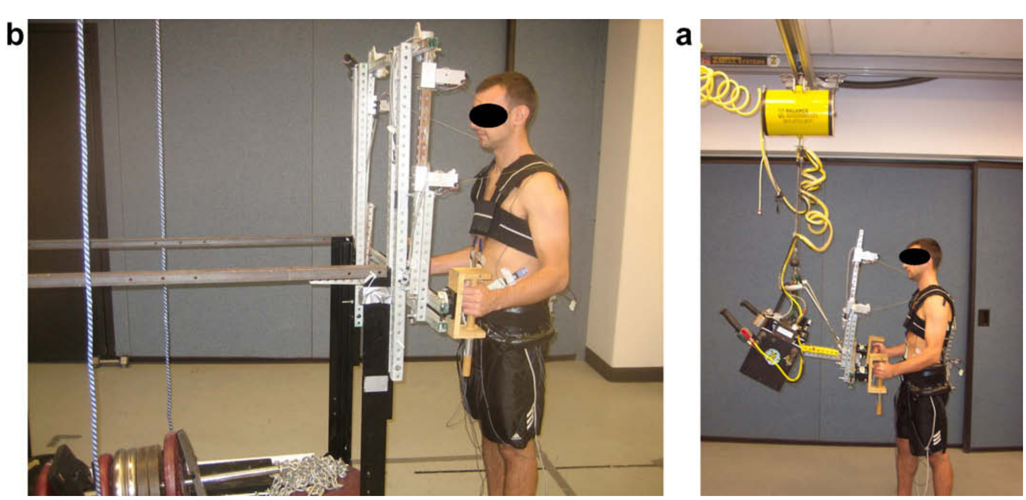

Fig. 1. Experimental tasks consisting of pushing an overhead pendulum style based device (a) and a cart (b).

and a 1 m/s push speed (hurried or fast). Finally, handle heights were fixed at 50%, 65%, and 80% of subject stature.

2.4. Spine loads

Since the lumbar spine is often the site of significant LBP during work activities, dependent measures consisted of predicted spinal loads at each disc level within the lumbar spine. A subject specific, biologically-assisted (EMG-assisted) biomechanical model that has been under continuous development and validation in our laboratory over the past 20 years was used to estimate spine forces resulting from the patient handling tasks (Granata and Marras, 1993, 1995a,b; Marras and Granata, 1995, 1997a,b; Marras et al., 1999, 2001, 2004; Marras and Sommerich, 1991; Mirka and Marras, 1993). Recently, the model has also been adjusted to be sensitive to pushing and pulling activities (Knapik and Marras, in press; Theado et al., 2007).

The dependent measures consist of the compression, anterior-posterior(A/P) shear, and lateral shear forces occurring at the inferior and superior endplate levels of each vertebrae between the first sacrum (S1) and the 12th thoracic level (T12). Thus, the analysis assessed the three-dimensional forces occurring over the entire lumbar spine of the subjects during the various pushing tasks.

2.5. Apparatus

Electromyographic (EMG) activity was collected using of bi-polar electrodes spaced approximately 3 cm apart at the ten major trunk muscle sites. The ten muscles of interest were: right and left erector spinae; right and left latissimus dorsi; right and left internal obliques; right and left external obliques; and right and left rectus abdominis. Standard locations of electrode placement for these muscles are described in Mirka and Marras (1993). The EMG-assisted biomechanical model used to estimate spinal loading requires calibration exertions using a force plate (Bertec 4060A, Worthington, OH, USA) and an L_5/S_1 locator (Fathallah et al., 1997).

The lumbar motion monitor (LMM™) (Biodynamic Solutions, Columbus OH, USA) was used to monitor trunk kinematics necessary to estimate vertebral body orientation, trunk muscle length, and trunk muscle velocity. The LMM is essentially an exoskeleton of the spine in the form of a triaxial electro-goniometer that measures instantaneous three-dimensional position, velocity, and acceleration of the trunk. The design of the LMM allowed the data to be collected with minimal obstruction to the subject's movements. The LMM design, accuracy, and uses were described by Marras et al. (1992).

Magnetic/gravitational sensors (X Sens Technologies™ Enschede, The Netherlands) were placed upon the torso and limbs in order to track body postures and positions during the experimental tasks. Sensors were placed upon the upper and lower arm and legs as well as the torso in order to coordinate the movements between the back (LMM) and the other body parts.

A variable speed motor attached to a line with a target was used to pace the subject at the two pushing speeds.

2.6. Data collection and processing

All signals from the aforementioned equipment were collected simultaneously through customized Windows™-based software developed in the biodynamics laboratory. The signals were collected (after hardware filtering and processing) at 100 Hz and recorded via an analog-to-digital board. Fig. 1a and b shows pictures of fully instrumented subject performing an experimental pushing task.

The raw EMG signals were pre-amplified, high-pass filtered at 15 Hz, low-pass filtered at 1000 Hz, rectified, and integrated via a 20 ms sliding window hardware filter. The EMG and kinematic data were imported into the EMG-assisted model described earlier to calculate spinal forces.

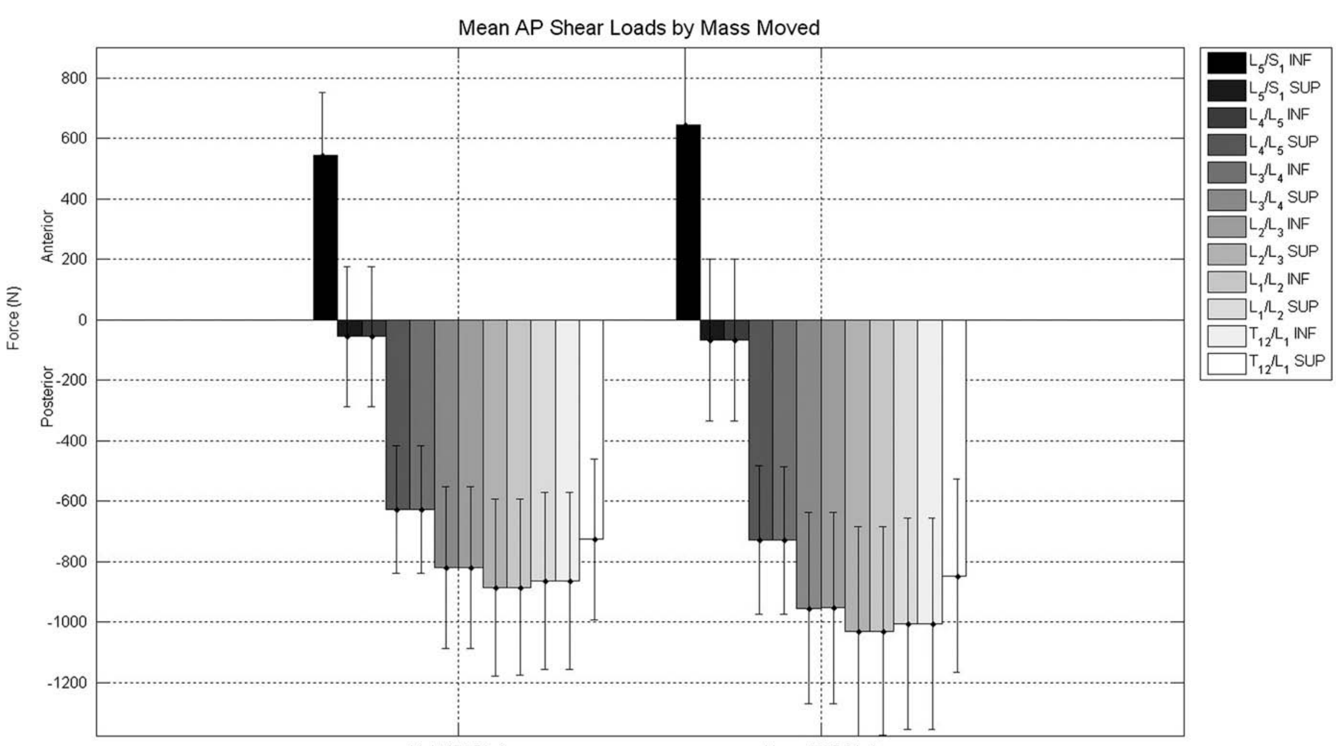

Fig. 2. Anterior/Posterior shear force at the various vertebral levels as a function of load magnitude (INF = inferior end plate; SUP = superior end plate).

2.7. Procedure

Upon arrival at the biodynamics laboratory, subjects were provided with a brief description of the study and tasks that they would be asked to perform and were asked to provide informed consent. Next, anthropometric measurements were collected on each subject necessary for spine model input. The order of the tasks was randomized within a given condition.

The surface electrodes were applied using standard placement procedures to sample the muscles of interest (Soderberg, 1992; Mirka and Marras, 1993). The subject then was placed into a structure that allowed maximum exertions to be performed in six directions, while a constant resistance was held against the subject. These maxima were performed to allow all subsequent EMG data to be normalized (Mirka and Marras, 1993). After each maximum exertion, at least two minutes of rest was provided to reduce the effects of fatigue (Caldwell et al., 1974).

Before starting the first set of lifting conditions, the subject completed a set of calibration lifts. Muscle gains (required for the biomechanical model) were assessed using a device that tracks external moment (Fathallah et al., 1997) in conjunction with an optimization testing scheme (Prahbu, 2005).

After completing the set of calibrations, the subjects performed the various combinations of experimental tasks.

2.8. Data analyses

The statistical significance of each of the dependent measure was determined using univariate analysis of variance (ANOVA) based upon a split plot analysis. Main effects and two-way interactions were assessed for each factor of interest (push device, load magnitude, degree of control, push speed, and handle height). Test statements were used in order to specify the error term in each main effect and two-way interaction. Post hoc Tukey tests were used to examine significant differences in main effects and least square means were employed to examine differences in two-way interactions. All tests were performed with subject as a blocking factor.

Interpretation of the results was based upon the biomechanical and biological significance of the findings. Thus, even though a finding was statistically significant, unless the finding was biologically/biomechanically significant it was not considered further.

3. Results

3.1. Overall spine loads

Descriptive summary of the spine loads imposed upon the various superior and inferior end plate levels of the lumbar spine collapsed over the various experimental conditions are available for examination in the Supplementary Material. Based upon this information, it can be seen that the compression and lateral shear forces observed under these conditions were of magnitudes (below 3400 N and 1000 N, respectively) that would not be expected to be problematic from a biomechanical or biological standpoint (NIOSH, 1981, 1994). However, A/P shear forces were often of sufficient magnitude (above 1000 N) to cause damage to the lumbar tissues (Cyron and Hutton, 1978; McGill, 1997). Therefore, this analysis will focus primarily upon factors that resulted in significant differences in the A/P shear forces at the various spinal levels.

A summary of statistically significant effects on spine loading at each end plate level is shown in Table 1. In general, this summary indicated that load weight, handle height, load control, and speed of activity all influenced spine compression, lateral shear, and A/P shear loads except for the A/P shear forces acting on the superior and inferior endplates surrounding L5 that were not statistically different as a function of load, load control or speed acting on the L5 vertebrae. It should also be noted that there were no statistically significant influences of the type of system employed (overhead pendulum vs. cart) upon spine loading.

Table 1 also indicates that several interactions among the variables investigated influenced lateral shear primarily between L5/S1 and L2/L3. In addition, some variable interactions affected primarily compression at lumbar levels above the L2/L3 disc level. It is interesting to note that many of these significant effects involved interactions with the system employed (pendulum vs. cart) and its interaction with load, handle condition or load control. The other significant interactions typically involved interactions with the load control variable. However, it should also be noted that none of these significant interactions significantly influenced A/P shear (where the magnitude of the load was sufficient to initiate disc damage).

3.2. A/P shear loads

Fig. 2 shows the A/P shear loads imposed upon the various disc levels as a function of load magnitude. This figure indicates that the L5/S1 inferior end plate is loaded in a direction opposite (anterior) the rest of the lumbar vertebrae. The figure also indicates that the magnitude of the A/P shear loads surrounding the L5 vertebrae are of generally of low magnitude regardless of load weight (although manipulation of the heavier weight does begin to approach levels of concern for L5/S1). The A/P shear values for vertebrae at the L4 level and above result in potentially problematic levels of loading with A/P shear loads peaking at the L2/L3 superior and L1/L2 inferior end plate levels.

The influence of handle height is shown in Fig. 3 for A/P shear forces acting at the various lumbar levels. The pattern of load among the vertebrae is fairly similar to that observed as a function of load magnitude. However, A/P shear loads were lowest at the 65% stature level but still of sufficient magnitude to cause damage.

A/P shear loads imposed upon the lumbar spine as a function of load control is shown in Fig. 4. While the load pattern among the vertebral levels is similar to that observed as a function of load magnitude and handle height, the requirement of precision placement of the load destination increased peak A/P shear loads by nearly 12%.

The effects of pushing speed on A/P shear loads are shown in Fig. 5. This figure indicates that increasing speed of push had a dramatic impact on A/P shear force magnitude with peak A/P shear increasing by nearly 30% as subjects increased push speed from 0.7 m/s to 1 m/s.

4. Discussion

Previous studies have identified load magnitude and handle height as significant factors affecting spine loading (de Looze et al., 2000; Hoozemans et al., 2004; Knapik and Marras, in press). Using a state-of-the art EMG-assisted biomechanical model, this study has confirmed the influence of these factors on spine loading. In addition, this study has shown that A/P shear forces at the mid to upper levels of the lumbar spine place the spinal tissues at greatest risk for excessive load.

This study has also demonstrated that there are other factors that can significantly influence A/P shear spine loading. Specifically, increased push speed and increases in the required control of the load position can significantly increase the A/P shear forces occurring in the lumbar spine. Comparison of Figs. 2–5 shows that increases in push speed had the greatest influence on increases in

Table 1
Summary of statistically significant effects and two-way interactions (*p*-values).

Spinal loads			System	Load	Handle	Load control	Speed	System × load	System × handle	System × load control	System × speed	Load × load control	Handle × load control	Load control × speed
L5/S1	Inferior	COMP	0.6510	<.0001	<.0001	<.0001	<.0001	0.3821	0.0963	0.0823	0.1863	0.2922	0.5824	0.2704
		AP	0.2398	<.0001	0.0271	0.0002	<.0001	0.2255	0.4422	0.5929	0.0660	0.2621	0.7060	0.1864
		LAT	0.8463	<.0001	0.0018	<.0001	<.0001	0.0134	0.8795	0.0544	0.2174	0.8815	0.0305	0.1136
	Superior	COMP	0.4587	<.0001	<.0001	<.0001	<.0001	0.3977	0.1802	0.2527	0.0909	0.2226	0.7877	0.2166
		AP	0.7066	0.3170	<.0001	0.7932	0.1841	0.7609	0.2513	0.9468	0.8996	0.6540	0.4822	0.9489
		LAT	0.6008	<.0001	0.0032	<.0001	<.0001	0.0177	0.8343	0.0277	0.1752	0.7683	0.0085	0.0776
L4/L5	Inferior	COMP	0.4572	<.0001	<.0001	<.0001	<.0001	0.3981	0.1839	0.2555	0.0916	0.2264	0.7912	0.2146
		AP	0.6289	0.3472	<.0001	0.7461	0.1669	0.7325	0.3318	0.9749	0.9686	0.6980	0.3824	0.9953
		LAT	0.5929	<.0001	0.0037	<.0001	<.0001	0.0178	0.8324	0.0270	0.1730	0.7776	0.0090	0.0755
	Superior	COMP	0.4172	<.0001	0.0003	<.0001	<.0001	0.2507	0.1252	0.2777	0.0861	0.1148	0.5272	0.0490
		AP	0.5878	<.0001	<.0001	<.0001	<.0001	0.7399	0.2827	0.2649	0.5263	0.9446	0.4418	0.8517
		LAT	0.5036	<.0001	0.0030	<.0001	<.0001	0.0262	0.7054	0.0257	0.1635	0.6625	0.0040	0.0574
L3/L4	Inferior	COMP	0.4182	<.0001	0.0003	<.0001	<.0001	0.2464	0.1270	0.2722	0.0859	0.1185	0.5411	0.0525
		AP	0.5889	<.0001	<.0001	<.0001	<.0001	0.7533	0.2746	0.2691	0.5238	0.9584	0.4377	0.8524
		LAT	0.5050	<.0001	0.0028	<.0001	<.0001	0.0286	0.7272	0.0253	0.1683	0.6472	0.0034	0.0565
	Superior	COMP	0.4696	<.0001	<.0001	<.0001	<.0001	0.1429	0.0449	0.1584	0.1291	0.0634	0.2845	0.0110
		AP	0.4418	<.0001	<.0001	<.0001	<.0001	0.6993	0.4610	0.4506	0.2562	0.8479	0.3872	0.7608
		LAT	0.7147	<.0001	0.0019	<.0001	<.0001	0.0394	0.5400	0.0434	0.2099	0.5768	0.0046	0.0436
L2/L3	Inferior	COMP	0.4697	<.0001	<.0001	<.0001	<.0001	0.1378	0.0466	0.1587	0.1334	0.0581	0.2736	0.0108
		AP	0.4455	<.0001	<.0001	<.0001	<.0001	0.7086	0.4572	0.4481	0.2494	0.8565	0.4002	0.7483
		LAT	0.7098	<.0001	0.0019	<.0001	<.0001	0.0427	0.5083	0.0434	0.2049	0.5592	0.0058	0.0439
	Superior	COMP	0.5141	<.0001	<.0001	<.0001	<.0001	0.0979	0.0257	0.0800	0.1855	0.0330	0.1579	0.0053
		AP	0.3795	<.0001	0.0002	<.0001	<.0001	0.6867	0.5025	0.5536	0.1999	0.7759	0.3843	0.7037
		LAT	0.9908	<.0001	0.0011	<.0001	<.0001	0.0669	0.4686	0.0870	0.2282	0.4502	0.0105	0.0488
L1/L2	Inferior	COMP	0.5108	<.0001	<.0001	<.0001	<.0001	0.0976	0.0251	0.0806	0.1755	0.0315	0.1607	0.0052
		AP	0.3753	<.0001	0.0002	<.0001	<.0001	0.6801	0.4964	0.5465	0.1982	0.7711	0.3846	0.6995
		LAT	0.9849	<.0001	0.0011	<.0001	<.0001	0.0672	0.4543	0.0881	0.2215	0.4386	0.0103	0.0487
	Superior	COMP	0.5031	<.0001	<.0001	<.0001	<.0001	0.1071	0.0328	0.1010	0.1714	0.0321	0.2042	0.0060
		AP	0.3491	<.0001	0.0002	<.0001	<.0001	0.6846	0.4295	0.5131	0.2339	0.7677	0.4763	0.6757
		LAT	0.6969	<.0001	0.0005	<.0001	<.0001	0.0958	0.4462	0.1552	0.3008	0.3385	0.0210	0.0664
T12/L1	Inferior	COMP	0.4993	<.0001	<.0001	<.0001	<.0001	0.1065	0.0321	0.0992	0.1696	0.0308	0.2069	0.0058
		AP	0.3568	<.0001	0.0002	<.0001	<.0001	0.6858	0.4328	0.5083	0.2441	0.7743	0.4705	0.6699
		LAT	0.7022	<.0001	0.0005	<.0001	<.0001	0.0979	0.4645	0.1483	0.2897	0.3532	0.0225	0.0667
	Superior	COMP	0.4272	<.0001	<.0001	<.0001	<.0001	0.1869	0.0900	0.2230	0.1048	0.0622	0.4491	0.0155
		AP	0.3753	<.0001	<.0001	<.0001	<.0001	0.7040	0.2434	0.3324	0.3930	0.8883	0.7114	0.6431
		LAT	0.5209	<.0001	0.0003	<.0001	<.0001	0.1531	0.4391	0.1988	0.3612	0.2837	0.0315	0.0823

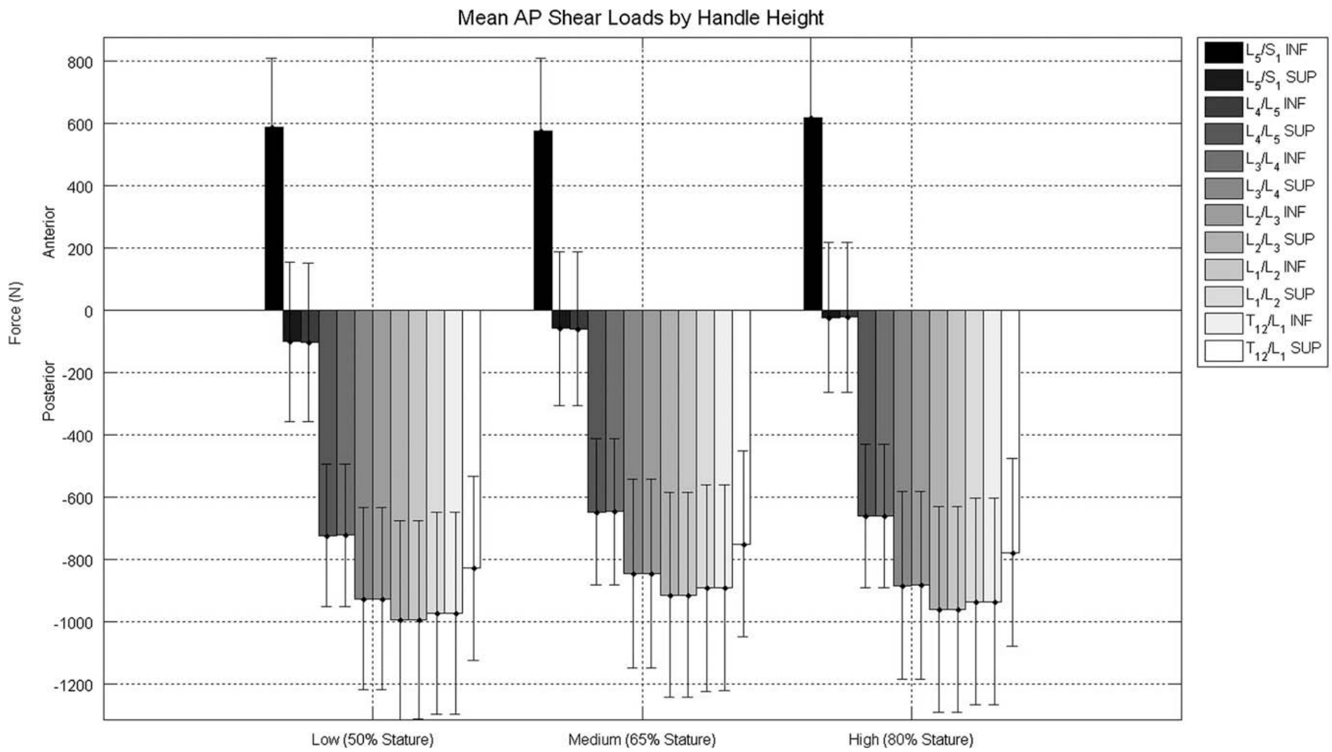

Fig. 3. Anterior/Posterior shear force at the various vertebral levels as a function of handle height (INF = inferior end plate; SUP = superior end plate).

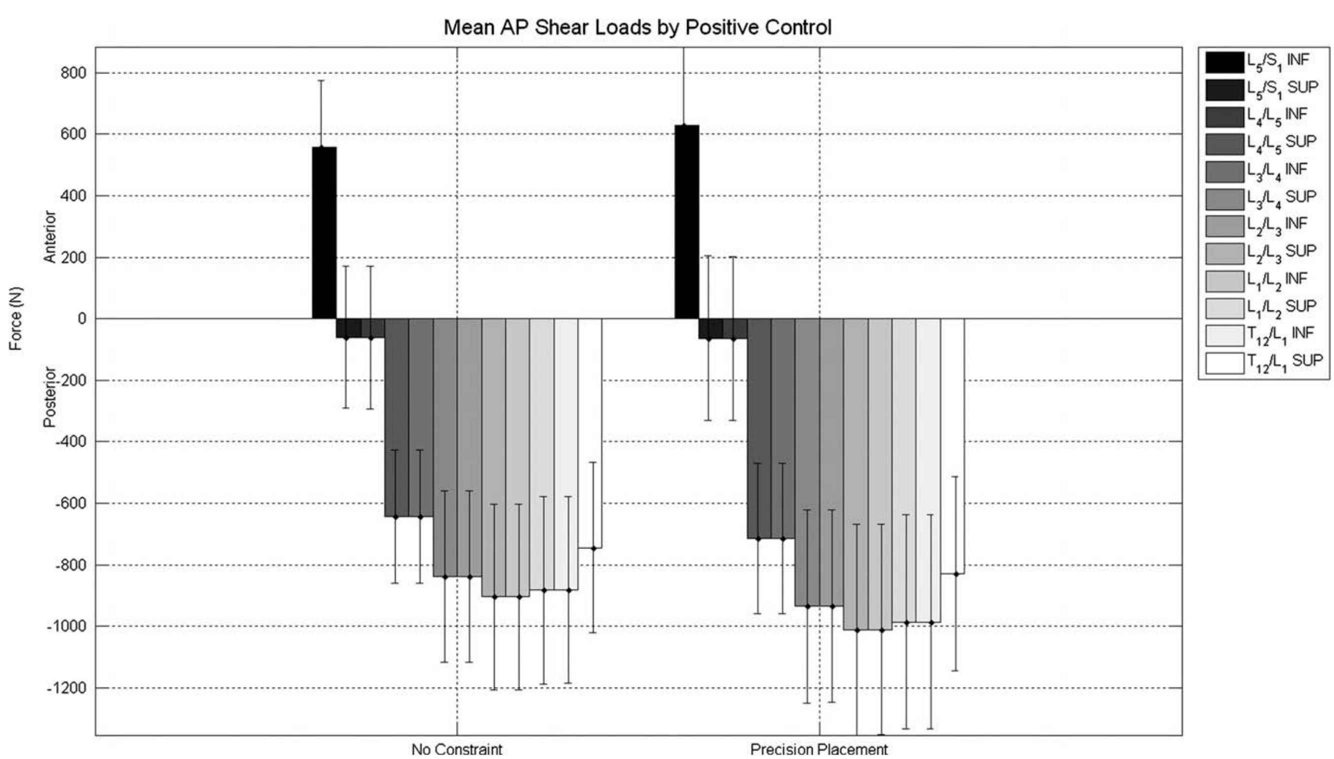

Fig. 4. Anterior/Posterior shear force at the various vertebral levels as a function of load control (INF = inferior end plate; SUP = superior end plate).

A/P shear loads compared to the load magnitudes, handle heights, or degree of control variables examined in this study.

A previous study has explored the influence of speed of operation while using manipulator-assisted devices (as opposed to pushing as was investigated in our study) upon spine loads at L5/S1 (Nussbaum and Chaffin, 1999). This study reports 10% higher spine forces at L5/S1 when operating the manipulator at 20% faster speeds. By contrast, our results indicate a 26% increase in anterior shear at L5/S1 and a 30% increase in posterior shear at the L3 vertebrae with a 43% increase in push speed regardless of the type of

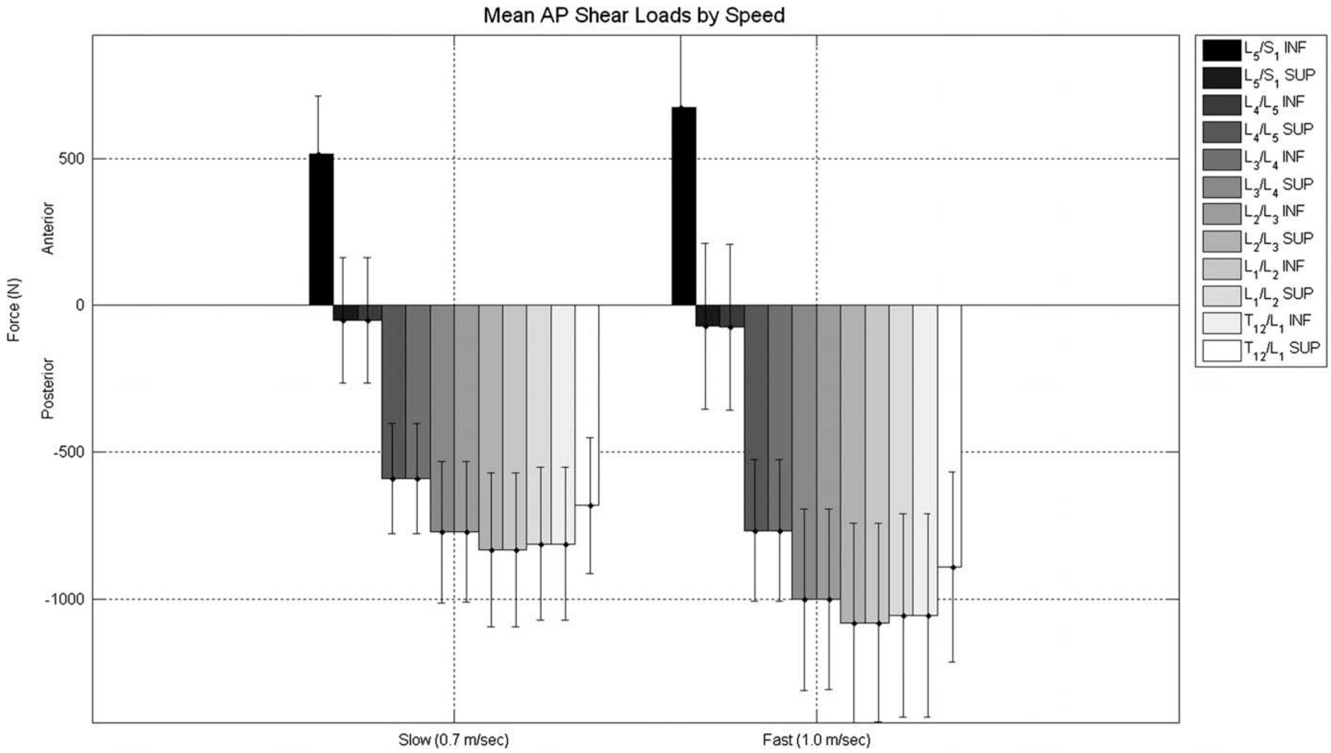

Fig. 5. Anterior/Posterior shear force at the various vertebral levels as a function of push speed (INF = inferior end plate; SUP = superior end plate).

device pushed. In addition, mean peak A/P shear forces at the L3 vertebrae are well outside the range of what would be considered safe (Callaghan and McGill, 2001; Gunning et al., 2001; McGill, 2002, 2004a,b). Collectively these studies suggest that as push speed increases the biomechanical cost to the lumbar spine increases particularly with respect to A/P shear. Hence, we can conclude that push speed is an important, underappreciated, risk factor for spine loading.

This study has also demonstrated that increasing the degree of control required by the subject during pushing can increase mean peak spine A/P shear forces at L3 by up to 12% and can result in potentially damaging shear forces. While some studies have investigated hand forces and psychophysical ratings associated with pushing and pulling of material materials handling devices, no assessment of spine forces have been reported with these activities (Resnick and Chaffin, 1996). However, other studies have shown that increased control in lifting destination as well as lifting speed was indeed associated with increased spine forces (Davis et al., 2002). Such activities are common in many work environments as workers are required to place objects in specific positions or as they attempt to manipulate cart or overhead devices through restricted spaces or doorways. Therefore, the control required during pushing could be another potentially, under recognized risk factor for low back loading.

It is also interesting to note that few biomechanically relevant interactions among variables were identified (Table 1). While some interesting interactions were associated with lateral shear and compressive loading the magnitudes of these loads were relatively insignificant from a biomechanical standpoint. We were particularly interested in interactions associated with A/P shear force since these magnitudes were potentially the most harmful to the spine tissues. However, no significant interactions were identified. Hence, we can conclude that all of the variables explored in this study acted relatively independent of one another.

All of the variables found to increase spine load during pushing (push speed, load magnitude, handle height, and degree of control required) all appear to increase spine loads through a common biomechanical pathway. Many previous studies have shown that increased spine loading, especially shear loading, occur as a result of increases in antagonistic trunk muscle coactivation (Granata and Marras, 1995b, 1999; Granata and Orishimo, 2001; Knapik and Marras, in press; Marras and Granata, 1995, 1997b; Marras et al., 2006). Examination of the muscle activities monitored in the current study indicate that antagonistic coactivation is also the primary mechanism of increased spine loading associated with the variables investigated in this study. Thus, any factors that would be expected to increase trunk muscle coactivation during pushing would be expected to increase spine loads.

Based upon a previous investigations (Marras et al., in press; Knapik and Marras, in press) we had hypothesized that there would be a difference in biomechanical loading of the spine as a result of a ceiling-based (pendulum cable) lift device compared to a cart floor-based system. We expected that a load attached to a cable would behave as a pendulum and require different application of hand forces compared to cart. We would expect that operation of the ceiling-based system would have a similar effect as changing handle heights since as one pushed the system, the device inertia would require the subject to elevate the handles in order to achieve a mechanical advantage over the lift device attached to the overhead rail system. However, we found no differences in spine loading between these devices. Several factors might have contributed to this lack of differences. First, the path of motion required little deviation from a straight path. One would expect that greater lateral control would be required during turning that would accentuate differences between systems. A recent study of floor-based vs. ceiling-based patient handling systems reported large differences in shear forces when turning was required (Marras et al., in press). Second, the overhead rail system had very little prior use and, thus, offered little resistance. Therefore, the system was easy to move and any motion in the cable may have resulted in easy movement of the lifting device along the rail. A system with more wear or a system with more friction might have produced very different effects. Third, the ceiling height was relatively low compared to ceiling heights in some environments where lifts might be used. Pendulum length varied from 30 to 60 in. depending upon subject stature. Thus, these short pendulum lengths might have prohibited the expected handle movements expected. Collectively, these considerations suggest that there may indeed be significant differences in spine loading when pushing overhead mounted lifts vs. carts, however, our experimental set up did not permit us to identify these differences if they are present.

This study confirms the notion that pushing and pulling is not as simple a task as once believed since it entails a complex biomechanical activity. This may help explain why LBP rates in some work environments (associated with lifting) may not be reduced even when lifting interventions are employed (Fujishiro et al., 2005).

Finally, potential study limitations should be acknowledged. First, as with any study, the implications of these findings apply only within the experimental conditions investigated in this study. This study was designed to investigate potential interactions between five variables so few levels of each variable were assigned. Future studies might consider exploring the potentially complex interactions among more levels of variables. Second, all subjects were young, inexperienced college students. Older subjects or those with experience in operating the devices might have produced different results. None the less, this study has provided some significant insights to the mechanics of pushing devices.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.clinbiomech.2008.10.007.

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