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Lumbar spine forces during manoeuvring of ceiling-based and floor-based patient transfer devices

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Patient handling continues to represent a high risk task for low back pain (LBP) among health caregivers. Previous studies indicated that manual transfers of patients impose unacceptable loads on the spine even when two caregivers perform the transfer. Patient lift devices are considered a potential intervention; however, few biomechanical analyses have investigated the spine loads and LBP risk associated with these transfer devices. This study analysed the 3-D spine forces imposed upon the lumbar spine when 10 subjects manipulated ceiling-based and floor-based patient lifts through various patient handling conditions and manoeuvres. The results indicated that ceiling-mounted patient lift systems imposed spine forces upon the lumbar spine that would be considered safe, whereas floor-based patient handling systems had the potential to increase anterior/posterior shear forces to unacceptable levels during patient handling manoeuvres. Given these findings, ceiling-based lifts are preferable to floor-based patient transfer systems.

Keywords: low back pain; low back disorders; patient transfer; patient handling; patient lifting; safe patient handling; spine biomechanics

1. Introduction

An increased risk of low back pain (LBP) among health care workers has been recognised for quite some time (Stubbs *et al*. 1983, Harber *et al*. 1985, Jensen 1987, Pheasant and Stubbs 1992, Fuortes *et al*. 1994, Hignett 1996, Smedley *et al*. 1997, Colombini *et al*. 1999, Edlich *et al*. 2001, 2005, Smedley *et al*. 2005, Feng *et al*. 2007, Waters *et al*. 2007, Nelson *et al*. 2008). Specifically, patient handling has been recognised as a high risk activity (Garg *et al*. 1991, 1992, de Looze *et al*. 1998, Guo *et al*. 1999, Edlich *et al*. 2001, Evanoff *et al*. 2003, Schibye *et al*. 2003, Keir and MacDonell 2004, de Castro *et al*. 2006, Nelson and Baptiste 2006, Jang *et al*. 2007, Nelson *et al*. 2007, Waters 2007). LBP point prevalence rates of 17% have been reported in these environments, with annual prevalence rates as high as 40 to 50% and lifetime prevalence up to 80% (Hignett 1996). This situation can lead to significant lost time (Smedley *et al*. 1997). LBP rates among young and healthy nursing students have been estimated via prospective studies to be between 12 to 13% with a cumulative incidence of over 22% throughout a 2 year period (Baldasseroni *et al*. 1998). Such rates are particularly alarming since these rates are far greater than would be expected for a young, healthy cohort.

Historically, the biomechanics of patient handling tasks have been explored using both 2-D and 3-D static biomechanical models. 2-D analyses have generally indicated that patient transfer tasks as well as repositioning tasks result in excessive compressive loads (typically at L5/S1) (Garg *et al*. 1991, 1992, Garg and Owen 1992, Owen and Garg 1994, Owen 2000). Static analyses have also indicated that even two-person lifting of patients could lead to excessive compressive loads (Winkelmolen *et al*. 1994). More recently, 3-D static analyses have also indicated large compressive loads on the lower lumbar spine as a result of both patient lifting and patient repositioning activities (Skotte *et al*. 2002, Schibye *et al*. 2003, McGill and Kavcic 2005, Jang *et al*. 2007).

Dynamic movement can either increase or decrease spine tissue loads during an exertion. In order to assess the influence of realistic dynamic motion during patient lifting, Marras *et al*. (1999a) used a biologically assisted 3-D dynamic biomechanical model to evaluate various patient lifting and patient repositioning tasks performed by both one and two (experienced and inexperienced) caregivers. Nearly all tasks exceeded either the spine compression or shear tolerance limits for safe lifting. When two caregivers performed a patient transfer task, compression was generally lower (but often still excessive). However a trade-off occurred in that shear forces were often greater during two-person lifts. In addition, the patient lifted during these investigations was also relatively light weight (50 kg).

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Hence, it would be expected that patient handlers would typically be exposed to far greater loads than observed in this study under typical patient transfer situations. Therefore, the study concluded that it would be extremely difficult to reduce spine loading to safe levels using either one- or two-patient handler manual lifting techniques and recommended the use of patient transfer devices as a LBP risk intervention.

Several epidemiological studies have attempted to explore the effectiveness of patient handling devices (interventions). Several small sample studies have reported that injury rates were typically reduced by between 12 and 46% when patient lifting devices are provided to patient handlers (Garg *et al.* 1992, Owen *et al.* 2002, Evanoff *et al.* 2003). One large-scale study assessed the effectiveness of patient lifting devices in a sample of 100 work units in 86 different health care facilities (Fujishiro *et al.* 2005). This study reported a change in LBP incidence rates from 15.38 to 9.25 over a 3-year period when patient handling devices were available. However, these data also indicated mixed results of the intervention effectiveness. Over 27% of the units observed increases in incidence rates over the observation period. The increased risk may be due to patient lift device non-compliance or it might be due to a difference among patient lifting device effectiveness. It may be possible that some interventions may change the nature of the spine loading so that risk might increase.

Patient handling devices are typically either ceiling-based or floor-based systems. Ceiling-based systems typically have less friction but may introduce other problems, such as the inability to control inertial forces. Floor-based systems have more friction due to the floor–wheel interface but they may present other challenges such as increased resistance due to the floor surface and more friction during turning manoeuvres. Field studies have indicated that use of ceiling-based systems results in a reduction of incidence rates as well as lost days (Brophy *et al.* 2001, Chhokar *et al.* 2005). Evanoff *et al.* (2003) also reported a reduction of musculoskeletal injuries and lost days for caregivers using floor-based systems in both hospitals and long-term care facilities. However, a crude comparison of these studies indicates that the injury rate reduction appears to be greater for the ceiling-based systems (Brophy *et al.* 2001) compared to the floor-based systems (Evanoff *et al.* 2003).

Few comparisons of ceiling-based patient lifting systems and floor-based patient lifting systems are available in the literature (Zhuang *et al.* 2000, Keir and MacDonell 2004, Engst *et al.* 2005). One study reported differences in caregiver perceptions of the use of ceiling-based systems compared to floor-based lifts (Engst *et al.* 2005). In this study, staff preferred ceiling-based lifts to a floor-based system when lifting or transferring patients. In addition, the caregivers reported a reduction in perceived musculoskeletal risk. However, there was no perceived benefit for the patient repositioning tasks. Another study used a 3-D static biomechanical model to explore spine compression during use of ceiling- vs. floor-based lifts and suggested that both types of lift reduce back stress by about two-thirds at L5/S1 (Zhuang *et al.* 2000).

A recent study by Knapik and Marras (2008) has shown that pushing and pulling activities can greatly increase anterior–posterior (A/P) shear loads at the upper lumbar levels (L3 and above). Thus, risk associated with pushing and pulling, such as is the case during patient handling, may be best identified by assessing spine loads of the entire lumbar spine as opposed to just L5/S1.

While a limited number of studies have begun to explore the effects of patient lift intervention devices on healthcare provider perceptions and costs (Zhuang *et al.* 2000, Engst *et al.* 2005) as well as the static loads associated with patient handling (Zhuang *et al.* 1999, 2000, Engst *et al.* 2005), no studies have explored the biomechanical loads due to trunk muscle coactivation along the entire lumbar spine as a consequence of patient lifting device use while considering the realistic dynamic efforts associated with patient handling. Therefore, the objective of this study was to assess the spine loads occurring over the entire lumbar spine when operating ceiling-based and floor-based patient handling devices under typical of patient handling conditions.

2. Methods

2.1. Approach

This study was intended to examine the factors associated with patient handling devices that could influence spine loading. Since previous studies (Garg *et al.* 1991, Winkelmolen *et al.* 1994, Marras *et al.* 1999a, Skotte *et al.* 2002, Schibye *et al.* 2003) have thoroughly examined the influence of manual patient transfer tasks upon spine loading, this study focused upon the effects of patient handling intervention devices. Given that these interventions typically lift the patient via mechanical means, caregiver LBP risk would be expected to be associated with the pushing and pulling of the patient handling devices. Thus, the factors that influence spine loads associated with the movement of these devices supporting the patient were investigated.

A series of typical patient pushing and pulling tasks using two common patient handling devices (ceiling-based lift system and floor-based lift system) were evaluated as subjects performed a series of patient handling manoeuvres that varied according to: 1) floor conditions; 2) wheel size (for floor based system); 3) patient weight; 4) the degree of control required by the patient handling manoeuvre. A subject-specific biologically assisted biomechanical model was employed to assess spine forces over the entire lumbar spine as subjects performed these tasks.

2.2. Subjects

In total, 10 subjects (five males and five females) volunteered as subjects for this study. All subjects were inexperienced university students and had not previously been employed as patient handlers. None of the subjects was experiencing LBP. The average (SD) age, weight and height of the subjects were 24.2 (4.66) years, 70.66 (16.11) kg and 175.11 (11.98) cm, respectively.

2.3. Experimental design

The experimental tasks consisted of pushing a standard 'patient' supported by either a ceiling-based lift or a floor-based lift system through a course (path) that simulated patient handling conditions that are common in patient care facilities. Figure 1 shows the layout of the course.

Independent variables consisted of variables that could potentially influence caregiver spine loading during the use of the patient transfer systems. Thus, the independent variables consisted of the patient handling system (system), patient weight (weight), and control required to manoeuvre the course path (control). The two patient handling systems consisted of a ceiling-based (Likorail 243ES 230 kg capacity; Liko, Inc.^{TM}, Franklin, MA, USA) and a floor-based (Viking L 250 kg capacity; Liko^{TM}) patient transfer system. It is likely that the interface between the wheels and floor of the floor-based system might influence the force required to operate the system and the subsequent spine loading of the caregiver. Therefore, the floor-based system was further divided into four different floor interface conditions. The floor-based system was tested using two different wheel configurations (large wheel configuration – 5 inch (0.127 m) diameter rear wheels and 4 inch (0.1016 m) diameter front wheels composed of hard rubber; small wheel configuration – 3 inch (0.0762 m) diameter rear wheels and 2 inches (0.0508 m) diameter front wheels composed of hard rubber). All wheels used in this study were previously used on patient lift systems in health care facilities in order to provide systems with realistic wear characteristics. The use of the floor-based systems was also evaluated while the patient handling

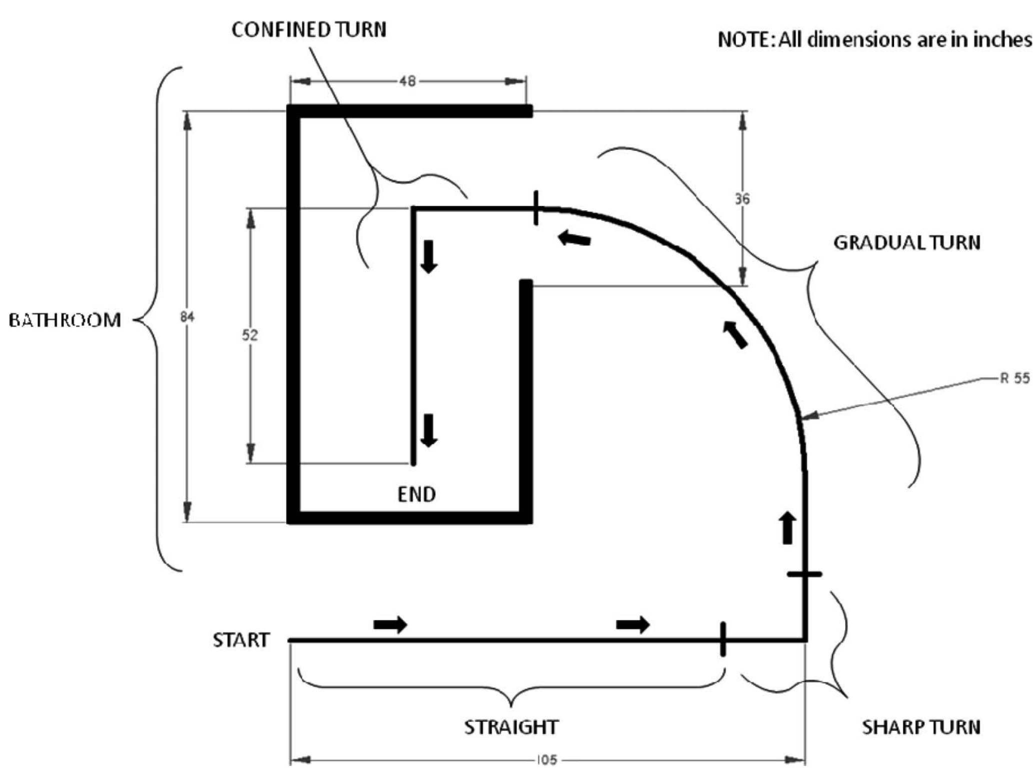

Figure 1. Patient handling course path. Course sections varied according to required caregiver control and included: 1) a straight section; 2) sharp turn section; 3) gradual turn section; 4) confined turn.

devices were used under two different floor conditions (hard floor surface and (short pile) carpeted floor common in assisted living facilities. Thus, the floor-based system was tested under four different wheel–floor surface combinations. Collectively, the combination of system design (ceiling- or floor-based) and the wheel/floor interface conditions were considered as the patient handling system.

Patient weight could also potentially influence the degree of caregiver spine loading during patient transfer activities and, therefore, was also used as an independent variable. Patients were represented by anthropometric 'dummies' of different mass. In order to simulate a range of patient weight conditions, three patient weights were selected consisting of 125 lb (56.8 kg), 160 lb (72.7 kg) and 360 lb (163.6 kg). The patient was obviously non-weight bearing as would be expected under patient handling device conditions.

One could also hypothesise that different levels of required control over the patient handling system could influence the degree of caregiver antagonistic muscle coactivation required and the subsequent spine forces (Davis *et al.* 2002). Therefore, the path over which the patients were manoeuvred was divided into four different sections that varied according to the degree of caregiver control required to operate the system. These sections are identified in Figure 1 and consist of: 1) straight (no turn section); 2) a sharp (90°) turn section; 3) a gradual turn (as would be expected when turning with no constraints); 4) a sharp (90°) turn within a confined space (intended to simulate a turn within a typical health care facility bathroom). Collectively, these manoeuvres were referred to as lift device system control.

2.4. Spine load predictions

Since the lumbar spine is often the site of significant LBP during work activities, dependent measures consisted of predicted caregiver spinal loads at each disc level within the lumbar spine. A subject specific, biologically assisted (electromyographic (EMG)-assisted) biomechanical model that has been under continuous development and validation in the Biodynamics Laboratory over the past 20 years was used to estimate spine forces resulting from the patient handling tasks (Marras and Reilly 1988, Reilly and Marras 1989, Marras and Sommerich 1991a,b, Granata and Marras 1993, 1995a,b, Mirka and Marras 1993, Marras and Granata 1995, 1997a,b, Davis *et al.* 1998, Granata *et al.* 1999, Marras *et al.* 1999b, 2001, 2002, Jorgensen *et al.* 2001). The model is unique to the individual subject and is calibrated to their specific anthropometry, muscle origins and insertions, as well as their specific EMG activities. Recently, the model has also been adjusted to be sensitive to pushing and pulling activities such as would be expected during the use of patient handling mechanical lifts. The model used in this analysis has been thoroughly described previously and will not be repeated here (Theado *et al.* 2007, Knapik and Marras 2008).

Specifically, the dependent measures consist of the compression, A/P shear and lateral shear forces occurring at the inferior and superior levels of each intervertebral disc levels between the first sacrum (S1) and the 12th thoracic level (T12). Thus, this analysis assessed the 3-D forces occurring over the entire lumbar spine of the caregivers during the patient handling activities.

2.5. Apparatus

EMG activity was collected using bi-polar electrodes spaced approximately 3 cm apart at the 10 major trunk muscle sites. Muscle EMG activities are used as one of the important model inputs to derive muscle force. The 10 muscles of interest were: right and left erector spinae; right and left latissimus dorsi; right and left internal obliques; right and left external obliques; right and left rectus abdominis. Standard locations of electrode placement for these muscles were described previously (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 L5/S1 locator (Fathallah *et al.* 1997).

The lumbar motion monitor (LMM) was used to measure trunk movements that are 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 3-D 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 have been described previously by Marras *et al.* (1992).

Magnetic/gravitation sensors (X Sens Technologies^{TM}, Enschede, The Netherlands) were used to track the motions of the body parts within the experimental space. 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.

All signals from the aforementioned equipment were collected simultaneously through customised Windows^{TM}-based software developed in the Biodynamics Laboratory. The signals were collected at 100 Hz and recorded via an analogue-to-digital board.

Figure 2 shows a fully instrumented subject performing the patient handling tasks.

2.6. *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 randomised within a given patient handling condition.

The surface electrodes were applied using standard placement procedures to sample the muscles of interest (Solderberg 1992). The subject was then 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 normalised (Mirka and Marras 1993). After each maximum exertion, at least 2 min rest was provided to reduce the effects of fatigue (Caldwell *et al*. 1974).

Prior to testing, subjects were provided with opportunities to practise using both of the patient handling systems. Subjects were allowed to practise until they felt comfortable operating both systems.

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 optimisation testing scheme (Prahbu 2005).

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

2.7. *Data analyses*

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

Statistical analyses consisted of a multivariate analysis of variance (MANOVA) using Wilk's Lambda significance criteria intended to identify significant differences in overall spine loading as a function of the independent variables. Significant multivariate findings were further evaluated using univariate ANOVA techniques with post hoc Tukey comparisons employed to identify significant trends. The error terms for the MANOVA were specified to ensure the appropriate degrees of freedom were used in the analysis. Contrasts were employed to evaluate the effects of the overhead system vs. all floor conditions, small wheel vs. large wheel and carpet vs. hard floor surface.

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

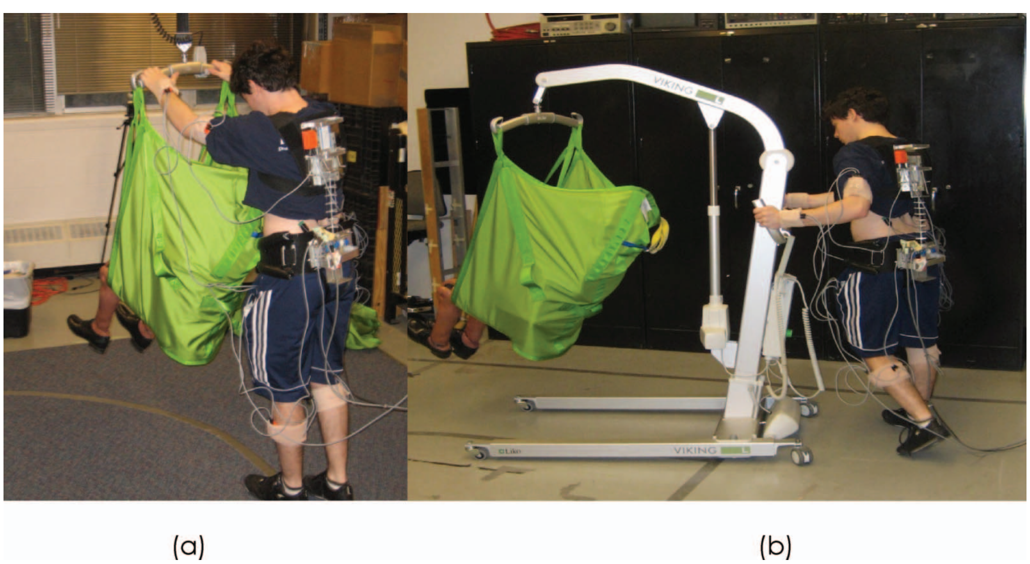

Figure 2. Subject using a ceiling-based patient lift device (a) and a floor-based patient lift device (b).

3. Results

3.1. *Spine force magnitudes*

Table 1 describes the mean (SD) peak compression, A/P shear and lateral shear forces observed at the different lumbar spine levels as a function of the various patient lift system conditions. This table indicates that compressive forces tended to be greatest at the lower lumbar levels and decreased significantly at the upper levels of the lumbar spine. It is also notable that the magnitude of these forces was generally well below the tolerance threshold value (3400 N) that would be expected to initiate end plate microfractures (National Institute for Occupational Safety and Health 1981).

Lateral shear forces tended to increase at upper lumbar levels compared to L5/S1. However, the magnitude of these forces was also relatively small and it is doubtful that they were of sufficient magnitude to cause tissue damage.

A/P shear forces also increased in magnitude at higher lumbar levels. However, while the magnitude of these forces was sufficient to cause damage to the discs at many lumbar levels, peak forces were noted at L3 and above.

3.2. *Overall spine force trends*

Statistically significant (MANOVA) differences among the various experimental conditions upon overall spine force development (over all lumbar levels) are summarised in Table 2. As indicated in this table, the patient lift system configuration significantly influences spine compression, lateral shear and A/P shear values. Patient weight only had a significant effect on spine lateral shear forces. The required lift system control significantly influenced all three dimensions of spine loading.

Several interactions among the variables also had significant spine loading influences. The patient lift system configuration interaction with lift system control requirements significantly affected all three dimensions of spine loading. In addition, the interaction of the lift system configuration and the patient weight also uniquely influenced lateral shear forces on the spine. Finally, the three-way interaction between lift system configuration, patient weight and the required system control uniquely influenced overall spine compression and A/P shear forces.

3.3. *Lift system configuration*

As noted above, the lift system configuration had a significant influence on spine compression, lateral shear and A/P shear. However, only the A/P shear forces would be of sufficient magnitude to exceed the tissue tolerance (1000 N) (McGill 1997). Figure 3a–j shows (where statistically different) how A/P shear forces vary as a function of the patient lift system (along with required system control) at the various lumbar spine levels. Follow-up comparisons indicated significant differences between the ceiling lift and all of the floor-based lift system configurations at all lumbar levels except for the L5 endplates. As indicated in Figure 3, the ceiling lift system resulted in mean peak A/P shear forces that generally never exceeded 500 N. However, the floor-based systems had the potential to incur peak A/P shear forces that could be double the load of the ceiling lift system. The A/P shear forces appear to peak around the L2 vertebral body.

Figure 3a–j also indicates a significant influence of the floor surface interface with the lift system wheels upon A/P spine loading. At the spine levels where A/P shear was the greatest (L3 and above), operating the floor-based lift system on carpet generally induced the greatest levels of A/P shear on the spine. Even during

Table 1. Mean peak (SD) lateral shear, compression and anterior–posterior (A/P) shear as a function of endplate level between T12 and S1 over all experimental conditions.

Endplate Level	Lateral Shear (N)	Compression (N)	A/P Shear (N)
L5/S1 Inferior	100.12 (59.43)	1032.55* (672.24)	531.04 (269.19)
L5/S1 Superior	98.83 (61.81)	1145.53* (694.77)	44.80 (230.80)
L4/L5 Inferior	98.80 (61.80)	1145.07* (694.75)	44.67 (230.73)
L4/L5 Superior	105.39 (72.65)	1058.72* (640.57)	483.38* (303.26)
L3/L4 Inferior	105.33 (72.62)	1058.10* (640.52)	483.22* (303.28)
L3/L4 Superior	122.86 (91.42)	938.10* (589.47)	673.57* (415.95)
L2/L3 Inferior	122.79 (91.38)	937.56* (589.42)	673.31* (415.94)
L2/L3 Superior	139.84 (105.90)	866.12* (576.15)	735.51* (474.77)
L1/L2 Inferior	139.78 (105.88)	865.62* (576.08)	735.21* (474.74)
L1/L2 Superior	156.37 (117.07)	858.73* (577.34)	716.80* (505.49)
T12/L1 Inferior	156.21 (117.05)	858.30* (577.25)	716.56* (505.43)
T12/L1 Superior	178.00 (131.83)	942.98* (592.85)	581.68* (497.04)

*Indicates absolute values.

Table 2. Multivariate ANOVA summary (*p*-value Pillai's Trace (most common)) of statistically significant influences of the experimental variable upon lateral shear, compression and anterior/posterior shear forces experienced by the lumbar spine.

	Lateral Shear	Compression	Anterior/Posterior Shear
Patient Handling System (System)	0.0001*	0.0001*	0.0001*
Patient Weight (Weight)	0.0036*	0.0519	0.0607
Required Control over System (Control)	0.0005*	0.0037*	0.0003*
System*Weight	0.0034*	0.1633	0.0869
System*Control	0.0233*	0.0001*	0.0001*
Weight*Control	0.4673	0.7263	0.5156
System*Weight*Control	0.1137	0.0285*	0.0355*

*Indicates statistical significance at $p = 0.05$.

the least taxing system control conditions (straight push) A/P shear increased by 50% (compared to the ceiling-based lift) and increased the shear forces to levels that could challenge the tolerance of the disc.

While the wheel size did result in statistically significant differences in A/P shear, the magnitude of the differences was not biomechanically relevant when operating the floor-based system on carpet. The use of large wheels on hard floor surfaces did result in statistically and biomechanically relevant reductions in A/P shear forces. However, the observed peak load variance (SD bars) indicated that damaging loads could still be expected.

3.4. *Lift system required control*

The degree of lift system control had a statistically significant and biomechanically profound effect on A/P shear forces over much of the lumbar spine. Figure 3a–j also indicates the influence of this required control. Over nearly all lumbar levels A/P shear increased as more control was required. The straight line section of the course path (Figure 1) always resulted in the lowest levels of A/P shear at all lumbar levels. These values were typically at levels that would not be expected to result in tissue damage. Peak A/P shear forces generally increased by around 100 N at the vertebral levels above L4 when 90° turns were required. Once these turns were performed, A/P shear values often reached levels that could lead to tissue damage, especially at the upper lumbar spine levels. No statistically significant differences between the gradual or sharp 90° turns were noted in their influence on A/P shear. However, when turns were performed within the confined space (bathroom) A/P forces increased by around 200 N at vertebral levels above the L4/L5 superior endplate.

Figure 3 demonstrates how this A/P shear trend was significantly amplified when the control manoeuvres were performed on carpet and with small wheels using the floor-based system.

3.5. *Patient weight interactions*

The weight of the patient manoeuvred interacted with the patient lift systems and the required control conditions in unexpected ways to significantly influence A/P shear. This significant three-way interaction is illustrated in Figure 4a–c for the L3/L4 superior endplate. As can be seen in this figure, patient weight had little effect as a result of ceiling-based system use regardless of the required system control requirements. However, when using the floor-based patient lift system the conditions of use interacted strongly with patient weight. Under the lowest patient weight condition (56.8 kg) the greatest A/P shear forces occurred when turning, especially when turning under confined space conditions (Figure 4a). These spine forces were largest when using the floor-based system with small wheels on carpet and these A/P shear forces were significantly reduced (yet still potentially problematic) when operating the system with small wheels on a hard surface or large wheels on carpet. However, as patient weight increased, the relationship between the system configuration and the required control changed its influence on spine loading. Figure 4c indicates that, even when pushing the floor-based system without turning, A/P shear forces are significant and equivalent to the non-confined 90° turn conditions when operating the system with small wheels on carpet. This figure also indicates that all small wheel and carpet conditions result in harmful A/P shear forces when operating the floor-based system in confined spaces. In fact, the large wheel–carpet combination results in greater A/P shear forces than the small wheel–carpet condition. Even the large wheel–hard floor surface condition was capable of resulting in forces that could damage spine tissue when manoeuvring the heaviest patient under confined space conditions.

Similar A/P shear force trends were observed at many of the other vertebral levels.

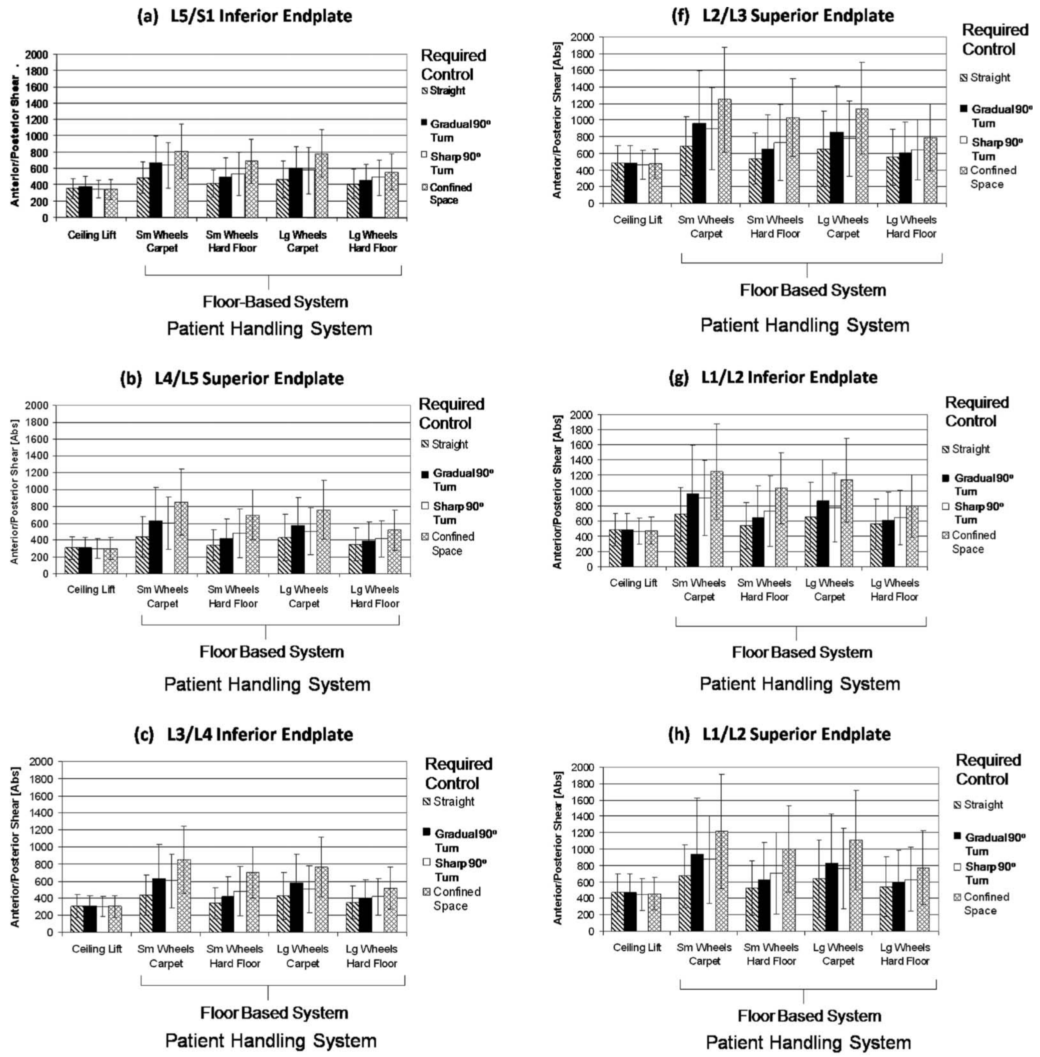

Figure 3. Mean peak (SD) anterior–posterior (A/P) shear force at the inferior and superior disc endplates as a function of the patient handling system (and floor–wheel conditions for the floor-based system) and the required control associated with the course sections. (a) – (j) show A/P shear forces for endplates between T12 and S1.

4. Discussion

4.1. Patient lift-assist devices vs. manual lifting of patients

The benchmarks or thresholds for spine loading have been well established for biomechanical loading of the lumbar spine. It has been generally accepted that the spine can safely tolerate up to 3400 N of compression load (National Institute for Occupational Safety and Health 1981) and between 750 and 1000 N of shear loading (McGill 1997). Above these levels, damage to the end plate and the disc can be expected to occur, at least for some portion of the population. An earlier investigation (Marras *et al.* 1999a) found that spine compression forces at L5/S1 can easily exceed the 3400 N limit when either one- or two-person lifting of relatively lightweight patients (50 kg) is performed. In addition, A/P shear forces as well as lateral shear forces (under some conditions) approached or exceeded 1000 N when performing these same tasks regardless of whether the lift was performed by one or two caregivers. Hence, it is not difficult to understand why LBP incidence rates are so high among patient handling staff.

This study has shown that, compared to manually lifting a patient, mechanical patient lift-assist devices can significantly reduce compressive spine loads experienced by the caregiver during a patient handling task. None of the spine compression forces observed during this study approached the 3400 N threshold for endplate damage regardless of whether a ceiling-based system or a floor-based system was used. Similarly,

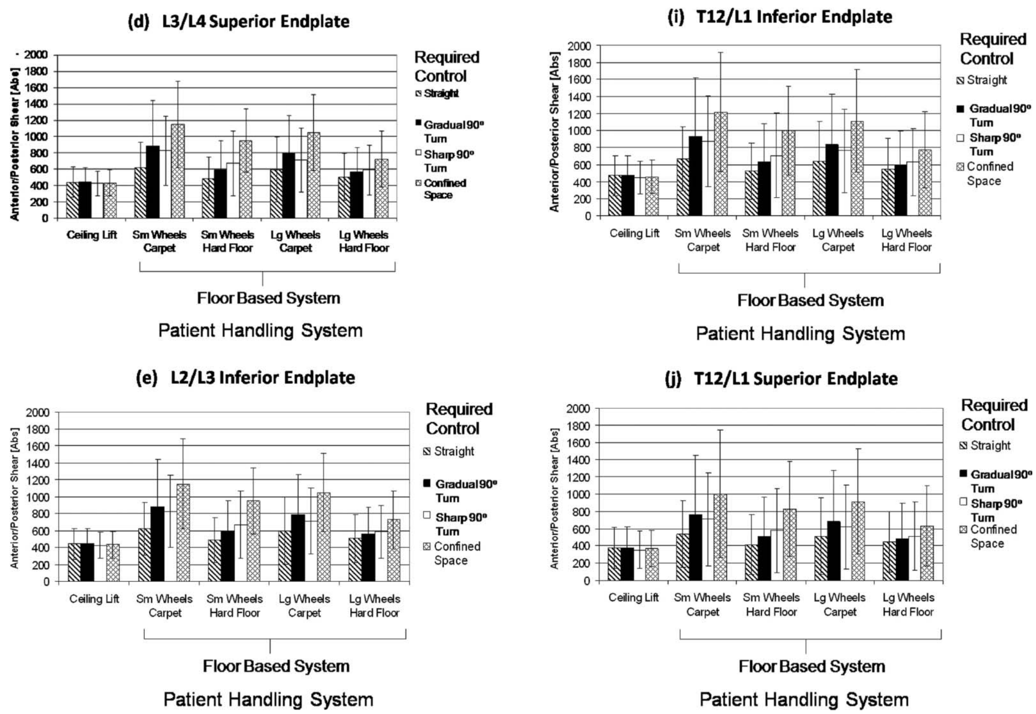

Figure 3. (*Continued*).

generally non-damaging lateral shear forces were observed. However, a significant difference was observed in A/P shear forces when the ceiling-based lift system was used compared to the floor-based system. When the ceiling-based lift system was used to handle patients, no conditions yielded A/P shear forces of sufficient magnitude to cause disc damage. However, when the floor-based patient lift system was used, certain conditions of use could be expected to initiate disc damage regardless of patient weight. Manipulating the floor-based patient handling device in a confined area, such as a bathroom, yielded the highest and most damaging levels of A/P shear. Next, any turning of the floor-based patient handling device (either sharp or gradual turns) significantly increased A/P shear forces. These forces were particularly great when operating the floor-based system on carpet and when the patient lift system had small wheels. These forces were of sufficient magnitude to cause problems even when lightweight patients were handled. These forces were also problematic when manipulating patients of heavier weights regardless of the floor and device wheel conditions. Thus, while patient handling systems do have the potential to minimise risk of LBP, using the floor-based systems under certain conditions can still represent a significant risk to the caregiver.

4.2. *Biomechanical response during patient handling device usage*

A comparison of the predicted biomechanical spine load magnitudes can be made with those reported by Zhuang *et al.* (1999). Their predictions agree with earlier predictions of spine compression due to manual patient handling (Marras *et al.* 1999a). However, comparisons of the Zhuang study with the current patient lift device evaluations suggest that predictions of spine compression loads were much lower than those in their study. There may be several explanations for these differences. First, Zhuang and associates did not limit their investigation to only the push and pull portions of device use as did the present study. Second, their assessments only report spine compression, whereas the present predictions evaluated the 3-D loads in compression and shear (and their trade-offs) occurring at the various lumbar spine levels. Third, the current assessments were capable of assessing load due to dynamic activity, whereas their efforts assessed loads in a quasi-static manner.

In-depth analyses of the muscle recruitment patterns associated with patient handling tasks indicated that the increase in A/P shear load experienced by the lumbar spine during use of the floor-based systems was associated with an increase in antagonistic coactivation of the torso muscles. Specifically, the trunk muscles with a more horizontal orientation are capable of contributing to a horizontal (shearing) force on the lumbar spine. The internal and external oblique muscles demonstrate increased activity under these conditions and influence the load on the mid to upper lumbar spine. This increased antagonistic coactivation in combination with the orientation of the lumbar vertebrae (lordosis) during these activities maximises A/P shear at these levels. Hence, pushing, particularly when turning or manipulating the device under confined conditions, can significantly increase the antagonistic coactivation of the trunk muscles and this increased activation can subsequently increase the A/P shear force experienced by the spine.

Such trade-offs between compression and shear under pulling and pushing conditions and their association with increased A/P shear loading have also been observed in other push–pull studies (Knapik and Marras 2008). This previous study has also demonstrated that vertical position of the handle on the lifting-assistance device has a large influence on spine loading.

4.3. Patient handling device characteristics and spine loading

This investigation suggests some rather non-intuitive observations that provide insight into how the use of patient handling devices can influence the biomechanical functioning of the device operator. First, the ceiling-based system never resulted in a situation where the health care provider's spinal loads approached levels of concern. The ceiling-mounted devices provided essentially 2 dimensions of unrestricted load manipulation (forward and sideways) with rather low levels of resistance or device friction. This system resulted in no appreciable change in device resistance and no subsequent large increases in trunk muscle antagonistic coactivation (and resulting increase in A/P shear) as the caregiver turned the patient or manoeuvred the patient in a confined space. Hence, the effort to push the patient forward with the ceiling lift was approximately the same as the effort to push the patient sideways (as would occur during a turn).

During use of the ceiling-based lift system, the patient weight had little effect on the magnitude of the spine loading regardless of the control manoeuvre attempted (Figure 4). Again, this is because the ceiling system had a low level of device friction regardless of the direction of intended movement. The floor-based patient handling system operation characteristics were very different.

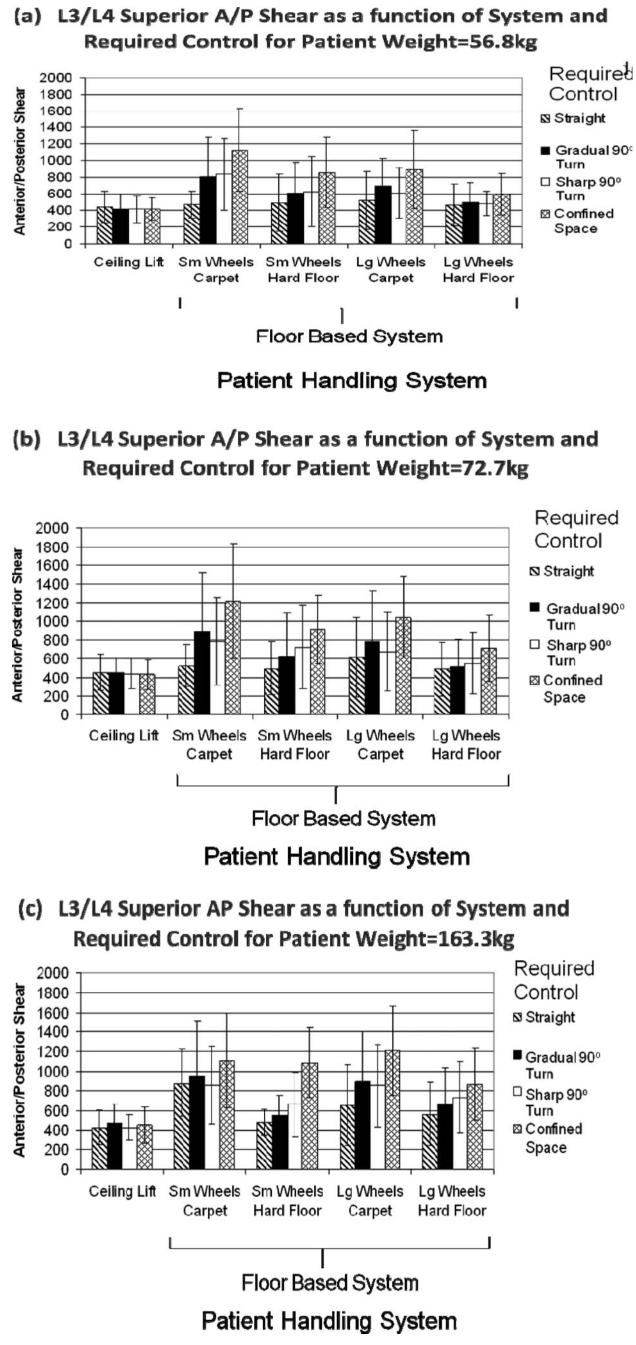

Figure 4. Mean peak (SD) anterior–posterior (A/P) shear force at the L3/L4 superior endplate as a function of the patient handling system (and floor–wheel conditions for the floor-based system) and the required control associated with the course sections for patient weights of (a) 56.8 kg (125 lb); (b) 72.7 kg (160 lb); (c) 163.3 kg (360 lb).

Next, the floor-based system was capable of producing excessive loads on the lumbar spine, especially when patient turns were performed. The manoeuvre conditions resulting in the least amount of spine loading was the straight push portion of the effort. However, even this condition could exceed the lower threshold for disc damage for some of the population as evidenced by the standard deviation bars exceeding the 750 N level (for the mid lumbar vertebrae) even for the large wheel on hard surface condition (see Figure 3f). Compared to the ceiling-mounted lift, the floor-based system's interface between the floor and the wheels resulted in increased resistance. This increased resistance required more operator trunk muscle antagonistic coactivation compared to the ceiling-mounted system. In fact, Figure 3 shows that even under the best floor/wheel conditions, the floor-based system resulted in significantly more A/P shear forces on the lumbar spine of the order of around 100 N. As floor conditions become less ideal and the lift system wheels age, this spine loading would be expected to increase. In addition, one would expect that, since it takes more time to operate floor-based systems, cumulative loading of the spine would also be greater with the floor-based system.

The floor-based system resulted in even greater spine loading when turning manoeuvres were performed. As shown in Figure 3, any turn dramatically increased the A/P shear loading and the A/P shear levels often exceeded the threshold limit for disc tolerance. It was expected that the A/P shear would increase when making sharp turns compared to gradual turns. However, the advanced analyses indicated that any type of (unconfined) turn increased A/P shear to about the same level. This off-axis (lateral) movement greatly increased the resistance of the system regardless of the wheel/floor conditions. When turns were attempted with the floor-based system, it was necessary for the wheels to turn and the resistance to turning required the operator to recruit more of the antagonistic muscles and increase coactivation, which increased spine A/P shear. As indicated in Figure 3, this situation became much worse when turning under confined space conditions, such as when entering a bathroom. Figure 3 shows that even under the best floor/wheel conditions (hard floor with large wheels) the A/P force variance (observable by noting the SD bars) could reach dangerous levels. Overall, the conditions that negatively impacted A/P shear forces (increased the forces) were, first, operating the system on carpet and, second, operating the system with small wheels. As health care facilities become more 'home based' and try to simulate home environments, it is more common to observe carpeting in patient rooms and to observe small wheels incorporated in these systems so that the lift devices can fit under furniture. This study suggests that this could be a dangerous combination for spine health.

When the effect of patient weight was considered along with the floor-based system conditions, many of these trends were exacerbated. Figure 4 demonstrates the increases in A/P shear observed as a function of system configuration, control manoeuvre and patient weight for one spine level. As evident from this figure, as patient weight increases, the spine loading conditions become far worse with regard to A/P shear. In fact, under the confined patient turning conditions the A/P shears can double when turning heavy patients compared to the ceiling lift conditions. Again, the operators' attempt to control the patient's path while in a confined space invited a muscular recruitment pattern that increases antagonistic coactivation, which greatly increases the A/P shear forces on the spine. It was expected that, as the patient weight conditions increased, the lift system wheels deformed more and produced a 'flat' interface with the floor or carpet. This situation increased the push resistance and required more trunk muscle antagonistic coactivation in order to operate the device. The A/P shear forces subsequently reached levels that can cause damage to the disc.

4.4. System design improvements

Given the nature of the risk associated with floor-based systems, it may be possible to change the design of such systems to reduce the spine A/P shear loads experienced by the lumbar spine. As has just been observed, it is the turning manoeuvre that greatly increases the A/P shear forces that can introduce risk. Several solutions might be considered. First, a larger mechanical advantage may, potentially, reduce the A/P shear forces to acceptable levels. Designers may consider system handles that provide more of a mechanical advantage for turns by spreading the handles out more laterally. However, one needs to consider the impact of such designs on operating the device in confined spaces as well as the potential detrimental effect on the shoulders of the operator.

Next, better wheel designs may make it possible to decrease the force levels necessary to operate the floor-based systems. It may be possible that larger, thinner and harder wheels may minimise the trunk muscle coactivation needed to turn and control floor-based systems. A development study could certainly optimise such systems.

Finally, these results suggest that a motor assist in such devices (at least for the turning manoeuvres) may be needed. Industrial systems in recent years have incorporated servomechanisms in material handling devices that can even build in virtual walls to protect the product. Similar principles may be considered for floor-based systems. However, the cost of such systems may make it more cost effective to install ceiling-based systems.

4.5. *Study limitations*

These findings should be considered in perspective with the conditions of this experiment. Specifically, these results might have been different if different patient lifting systems were used, or the floor, carpet or floor-based device wheel characteristics were different. However, to the degree that these conditions match those observed in health care facilities, it is believed that these results may be generalised to classes of patient lift device use.

5. Conclusions

This study has shown that ceiling-based patient lift systems have little spine biomechanical loading risk associated with the manipulation of these devices. Ceiling patient lift systems provide marked benefits compared to either one- or two-caregiver manual patient handling techniques. Floor-based patient handling systems also provide a benefit over manual lifting of patients. In generally, they are associated with low levels of spine compression. However, under many of the floor-based system patient handling manoeuvres observed in this study, A/P shear forces were found to be of a magnitude sufficient to lead to disc damage and degeneration for the caregiver. These damaging forces occurred at the mid to upper levels of the lumbar spine and became particularly problematic as the caregiver attempted turning manoeuvres and especially when turns were made in confined spaces, such as bathrooms. In addition, patient weight had no effect on the spine load of caregivers using ceiling-based lifts, whereas A/P spine shear forces became much greater when attempting to turn floor-based lift systems. Therefore, ceiling-based lifts are preferable to floor-based patient lift systems. If floor-based systems must be used, the floor surface and device wheel conditions must be considered in order to reduce LBP risk exposure. Finally, several suggestions have been made to minimise the risk associated with the design of floor-based patient handling systems.

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