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Biomechanically determined hand force limits protecting the low back during occupational pushing and pulling tasks

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ABSTRACT
Though biomechanically determined guidelines exist for lifting, existing recommendations for pushing and pulling were developed using a psychophysical approach. The current study aimed to establish objective hand force limits based on the results of a biomechanical assessment of the forces on the lumbar spine during occupational pushing and pulling activities. Sixty-two subjects performed pushing and pulling tasks in a laboratory setting. An electromyography-assisted biomechanical model estimated spinal loads, while hand force and turning torque were measured via hand transducers. Mixed modelling techniques correlated spinal load with hand force or torque throughout a wide range of exposures in order to develop biomechanically determined hand force and torque limits. Exertion type, exertion direction, handle height and their interactions significantly influenced dependent measures of spinal load, hand force and turning torque. The biomechanically determined guidelines presented herein are up to 30% lower than comparable psychophysically derived limits and particularly more protective for straight pushing.

Practitioner Summary: This study utilises a biomechanical model to develop objective biomechanically determined push/pull risk limits assessed via hand forces and turning torque. These limits can be up to 30% lower than existing psychophysically determined pushing and pulling recommendations. Practitioners should consider implementing these guidelines in both risk assessment and workplace design moving forward.

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Force limit; turn; psychophysical; lumbar spine

1. Introduction

Musculoskeletal disorders (MSDs) represent a major problem in modern occupational environments, with low back disorders (LBDs) being the most prevalent of all MSDs reported (BLS 2017; Dunning et al. 2010). Collectively, LBDs represent the most disabling medical condition to affect mankind worldwide (Hoy et al. 2014). Most literature reports that LBDs are strongly associated with occupational exposures related to manual materials handling (NRC 1999; NRC/IOM 2001).

As employers recognise the risks for LBDs associated with lifting, manual materials handling work has over time shifted away from lifting activities and towards pushing and pulling activities (de Looze et al. 2000). Unfortunately, pushing and pulling exposures may carry their own biomechanical risk. It has been estimated, for example, that 9–20% of LBDs may be associated with pushing or pulling (Klein, Jensen, and Sanderson 1984; Kumar 1995; Schibye et al. 2001). An internal analysis of more recent workers' compensation claims data from the Ohio Bureau of Workers' Compensation (Columbus, OH, USA) confirms that approximately 10% of LBD costs are associated with pushing and pulling. Moreover, these data also show that while the expenditures on non-pushing and pulling LBDs in Ohio have decreased in recent years, the costs associated with pushing and pulling related LBDs have increased over this same time period.

It should be noted that there is controversy in the epidemiological literature regarding the LBD risk associated with pushing and pulling. Hoozemans et al. (2002a, 2002b) and a systematic review paper from Roffey et al. (2010) conclude that it is unlikely that occupational pushing and pulling serve as independent causative factors for LBDs. However, the systematic review by Roffey et al. (2010) and others like it have been criticised by other commentators for excluding biomechanical studies from the analysis and the decision to use Bradford-Hill as 'criteria' rather than 'aspects' of causality (Takala 2010; Ward 2009). Several

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previous epidemiological studies have in fact shown an association between pushing and pulling and the risk of LBDs (Andersen, Haahr, and Frost 2007; Hoozemans et al. 1998; Plouvier et al. 2008; Yip 2004).

Biomechanical models and laboratory studies can complement epidemiologic studies by providing important causal pathway insights about the disorder development process (Keyserling 2000). While several prior biomechanical studies assert that biomechanical loads placed onto the lumbar spine are low during pushing and pulling (Hoozemans et al. 2004; de Looze et al. 1995; de Looze et al. 2000; Sandfeld, Rosgaard, and Jensen 2014; Schibye et al. 2001) relative to accepted tissue tolerance thresholds (Gallagher and Marras 2012; NIOSH 1981), the findings of these investigations may be dependent upon their specific methodology. For example, these investigations investigated only joint moments rather than tissue loads (de Looze et al. 2000), used a single-muscle equivalent (de Looze et al. 1995), used a 2D model (de Looze et al. 1995; Sandfeld, Rosgaard, and Jensen 2014; Schibye et al. 2001), or recruited a small subject pool (Hoozemans et al. 2004). More recent research predicting lumbar spine loads utilising a more complicated biomechanical model that is three-dimensional, dynamic, and accounts for the role of antagonistic co-contraction has shown high spinal loads during pushing and pulling exertions, particularly in anterior/posterior (A/P) shear (Knapik and Marras 2009; Marras, Knapik, and Ferguson 2009a, 2009b; Weston, Khan, and Marras 2017).

Additionally, while biomechanically based lifting guidelines are readily accessible to the field of ergonomics and have shown success at mitigating biomechanical risk (Ferguson, Marras, and Burr 2005; Marras et al. 1999; NIOSH 1981; Waters et al. 1993), biomechanically based pushing and pulling guidelines are still lacking. The only current pushing and pulling risk recommendations available within the literature are based on psychophysically determined limits, in which subjects pushed or pulled against a stationary bar measuring hand forces while walking on a treadmill. Limits were prescribed via subjects varying the push/pull resistance of the treadmill until they reached a level at which they believed they were working as hard as they could without becoming unusually tired, weakened, overheated. (Snook and Ciriello 1991). Though this approach and the other related guidelines that have been published since (Garg et al. 2014; Mital, Nicholson, and Ayoub 1997) set limits based on individuals' subjective perception of maximum acceptable external forces, these limits may not correspond to biomechanical tolerance, particularly in the lumbar spine. In fact, prior literature shows little association between spinal loads and psychophysically determined maximum acceptable forces (Davis, Jorgensen, and Marras 2000; Jorgensen et al. 1999; Le et al. 2012). This lack of association could be due to the fact that individuals are likely unable to sense biomechanical loading on critical tissues in the spine due to the lack of nociceptors in the intervertebral disc (IVD) (Adams, Mcnally, and Dolan 1996). Moreover, the parts of the body rich in nociceptors that could most easily perceive the loads being exerted (such as the hands) are located far distal in the kinematic chain relative to the low back.

Given the apparent prevalence of LBDs attributable to pushing and pulling exposures in manual materials handling and conflicting biomechanical risks of pushing and pulling determined via laboratory investigation, it is apparent that further studies are needed relative to occupational pushing and pulling. Thus, this study aimed to quantify biomechanical measures of lumbar spine load and hand force under several combinations of exertion type, handle height and exertion direction. Additionally, given the lack of objective biomechanically determined pushing and pulling guidelines available within the literature, this study also aimed to develop biomechanically determined hand force and turning torque limits for pushing and pulling exertions that are protective of the low back and can be implemented broadly in the workplace.

2. Methods

2.1. Approach

A laboratory study was conducted to understand the relationship between biomechanical measures of spinal load, hand force and turning torque throughout a range of pushing and pulling exposures. A biomechanical modelling approach was implemented to evaluate lumbar spinal loads in compression, anterior/posterior (A/P) shear, and lateral shear, while hand forces and turning torques were estimated via load cells.

The EMG-assisted biomechanical model implemented in this study to predict lumbar spine loads has been described extensively in the literature and has been validated for pushing and pulling exertions (Dufour, Marras, and Knapik 2013; Granata and Marras 1993; Hwang et al. 2016a, 2016b; Knapik and Marras 2009; Marras and Sommerich 1991a, 1991b). This dynamic model uses inputs of subject-specific anthropometry, MRI-derived muscle locations and sizes (Jorgensen et al. 2001; Marras et al. 2001), full body kinematics, kinetics, muscle activity for 10 power-producing muscles of the torso and tissue material properties as model inputs. The EMG data are combined with muscle size, length and contraction velocity information to predict dynamic outputs of muscle force. Muscle force data is then combined with torso cross-sectional area, muscle lines of action, muscle moment arms, vertebral angles and other geometric information to predict dynamic tissue loads.

2.2. Subjects

Sixty-two subjects (31 male: age 25.6 ± 4.7 years, stature 179.8 ± 8.3 cm, and mass 79.1 ± 13.1 kg; 31 female: 26.6 ± 7.6 years, stature 167.9 ± 7.1 cm, and mass 66.9 ± 13.8 kg) were recruited for this study. This sample size was found to be sufficient to detect a moderate effect size in variables of interest with a power of 0.85 and significance level (α) = 0.05. All subjects were asymptomatic for LBP and musculoskeletal injury such as shoulder pain in the past three years. The study was approved by the University's Institutional Review Board.

2.3. Experimental Design

A 3×3×2 repeated measures design was implemented for this study. Subjects performed three types of exertions (one-handed pull, two-handed pull, two-handed push) at three handle heights (81.3, 101.6, 121.9 cm) in one of two directions (straight or turn). The independent variables and their levels were selected based upon a database of field surveillance data collected by the authors; the database included pushing and pulling exposure conditions collected from 14 unique companies at 24 separate sites. To reduce order or fatigue effects, experimental conditions were counterbalanced such that an equal number of subjects started with turning and an equal number of subjects started with straight pushing and pulling; within each of these blocks, conditions were then randomised based upon handle height and exertion type. Subjects performed three repetitions of each type of trial back-to-back. A unique overhead magnetic particle braking system (Figure 1) designed specifically for this study incrementally added linear or rotational resistance as each trial progressed such that each trial ended when the subject was unable to move the rig any further.

Dependent measures consisted of three-dimensional spinal loads (compression, A/P shear, lateral shear) at the superior and inferior endplates of each spinal level extending from T12/L1 to L5/S1, the magnitude and mean angle of force application recorded at the hands, and net torque calculated for turning exertions. Lumbar spine loads were assessed via Adams software (MSC Software, Santa Ana, CA, USA) using the aforementioned EMG-driven lumbar spine model. Hand forces were summed and represented as a single three-dimensional vector, while net turning torques were calculated via summation of the torque-generating hand forces multiplied by their respective moment arms. Finally, the mean angle of force application recorded at the hands was calculated as the arctangent of the vertical and horizontal components of the three-dimensional hand forces produced by the subjects.

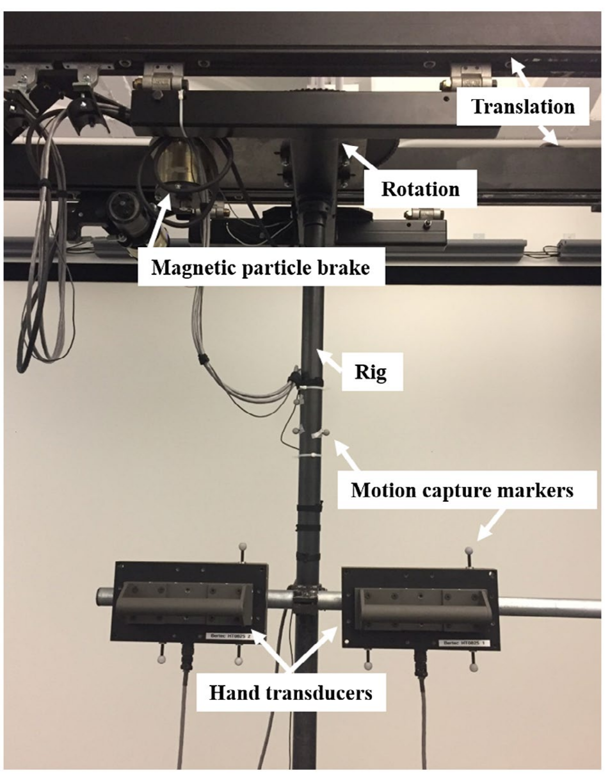

Figure 1. Experimental apparatus including an overhead rail and braking system allowing for translation and rotation and hand transducers for recording three-dimensional hand forces and moments

2.4. Apparatus

A custom-built overhead rail system allowed for two-dimensional translation and rotation of a rig connected to two-hand transducers during each exertion (Columbus McKinnon, Amherst, NY, USA), and a 3-axis magnetic particle braking system was implemented within the rail system (Placid Industries, Inc., Lake Placid, NY, USA). Resistance provided by the brakes was determined dynamically from the location of the rig as measured by optical motion capture and was controlled via voltage output from a custom Matlab application. The overhead rail system, magnetic particle brakes and hand transducers are shown in Figure 1.

Kinematic data were captured via a 36 camera Prime 41 OptiTrack motion capture system (NaturalPoint, Corvallis, OR, USA) at a sampling frequency of 120 Hz; the data were low-pass filtered using a fourth-order Butterworth filter with a cut-off frequency of 10 Hz. Kinetic data were captured during model calibration trials via a FP6090-15 force plate (Bertec, Worthington, OH, USA) and for all experimental conditions via custom-built HT0825 hand transducers outfitted with handles to measure three-dimensional bilateral application of hand forces (Bertec, Worthington, OH, USA). The kinetic data measured tri-axial forces and moments and were captured at 1000 Hz. Finally, EMG data were collected using a Motion Lab Systems MA300-XIV system (Motion Lab Systems, Baton Rouge, LA, USA) at 1000 Hz using bipolar surface electrodes placed bilaterally onto the erector spinae, latissimus dorsi, rectus abdominis, external oblique and internal oblique muscles. EMG data were notch filtered at 60 Hz and its aliases and bandpass filtered between 30 Hz and 450 Hz; signals were rectified and further low-pass filtered using a second-order Butterworth filter with a cut-off frequency of 1.59 Hz (chosen from a time constant of 100 ms).

2.5. Procedure

Subjects were briefed on the study design and provided informed consent, and several anthropometric measurements were recorded. Subjects were then outfitted with EMG surface electrodes placed onto the aforementioned power-producing muscles of the trunk according to standard placement procedures (Mirka and Marras 1993) and 41 motion capture markers placed over the entire body in accordance with a custom marker set prescribed by the OptiTrack motion capture software used. Then, subjects stood on the force plate and performed a 'no-max' calibration procedure as described in Dufour, Marras, and Knapik (2013).

After model calibration, subjects were given the opportunity to practice a few submaximal pushing and pulling exertions to become comfortable with the overhead rail and braking system; once comfortable, the experimental conditions were collected. Before each exertion began, the resistance of the magnetic particle brakes was zeroed. Subjects were instructed to perform each exertion while pushing or pulling at a normal pace (Figure 2), walking with the rig as it was translated or rotated in space during each trial. Throughout the progression of each trial, magnetic particle brakes continuously and smoothly added linear or rotational resistance proportional to the change in the location of the hand transducers from their initial global position (the location where the resistance had been zeroed), as determined via motion capture. Subjects were instructed to smoothly increase hand force or torque throughout each exertion and to avoid jerking motions and pushed or turned until they could no longer translate or rotate the rig. A 1–2 min rest period was given between each exertion, and additional rest was given to subjects when they felt it necessary.

Subjects pushed or pulled on two-hand transducers with a horizontal handle configuration spaced 45.72 cm (18 in) apart; this handle width was also consistent with the field surveillance data collected by the authors. For all straight exertions, the hand transducers were equidistant from the rig (as is shown in Figures 1 and 2(a–c)). However, for turning exertions, the hand transducers were offset towards the right hand to increase the moment arm for turning (Figure 2(d–e)) so as to replicate a small radius turn. All one-handed pulls were completed with the right hand.

To increase moment exposure onto the spine, subjects performed each exertion in an upright posture (minimal trunk flexion). Maximising external moments onto the spine represented a 'worst-case' scenario in terms of biomechanical load such that the risk limits derived would be protective of any other self-selected postures by workers in industry. The posture was deemed as acceptable or

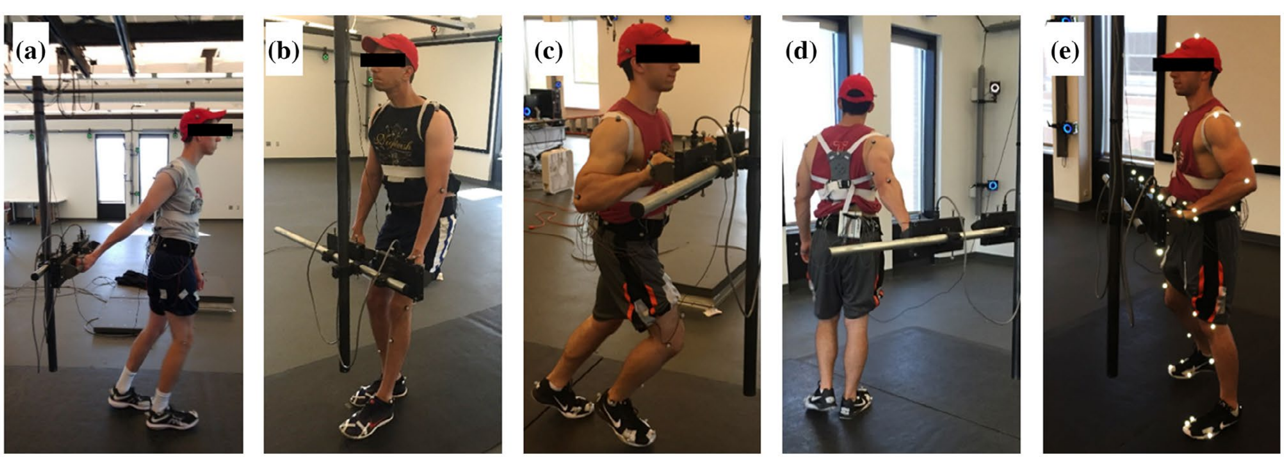

Figure 2. Example of subjects performing (a) a one-handed pulling exertion, (b) a two-handed pulling exertion, (c) a two-handed pushing exertion, (d) a one-handed turning exertion, and (e) a two-handed turning exertion (two-hand push: counterclockwise; two-hand pull: clockwise). Subjects were instructed to maintain an upright posture to increase moment exposure onto the spine, representing a 'worst-case scenario' in terms of biomechanical load.

unacceptable via careful assessment by the researcher responsible for data collection, and unacceptable repetitions were repeated. Subjects also performed each exertion on an anti-fatigue mat to allow for increased friction with the floor to prevent slipping.

2.6. Analysis

Data were log-normalised where appropriate prior to statistical analysis to account for skew in the data. Post-processed peak spinal loads, peak resultant hand forces (straight push/pull trials) and peak net turning torques (turning push/pull trials), were analysed using JMP 11.0 (SAS Institute, Cary, NC, USA) with a repeated-measures ANOVA for the independent measures of exertion type, handle height and exertion direction. Post hoc Tukey tests were performed where appropriate. Individual factors of gender, stature and mass were also included as potential covariates, and all data were interpreted relative to a significance level $\alpha = 0.05$.

To determine biomechanically based thresholds for pushing and pulling that can be easily implemented by practitioners, it was important to relate biomechanical risk to the low back (assessed via spinal load) to resultant hand force (straight exertions) or resultant turning torque (turning exertions), as hand force and torque can easily be measured in the field. Resultant hand forces were used in analysis rather than horizontal hand forces because they were more closely associated with spinal loads. Independent samples from each trial were obtained measuring the resultant hand force or turning torque corresponding to 25, 50, 75 and 100% of the range between the minimum and peak spinal loads for the trial. Each direction of spinal loading (compression or shear) was considered separately, such that eight total data points were recorded from each trial. After confirming that hand force and turning torque were indeed linearly related to spinal load, these relationships were derived via a mixed modelling approach. In each model, exertion type, handle height and spinal load were used as fixed effects, while repeated measures of subject and trial type were accounted for as random effects. Separate models were run for spinal compression and shear and for straight and turning exertions such that a total of four models resulted. In every model, hand force or torque served as the dependent variable. After beginning with a simple model using main effects only, model selection utilised a forward stepwise method to introduce relevant interaction terms minimising the Akaike information criterion (AIC) and maximising Adjusted R^2.

2.7. Biomechanically Determined Risk Thresholds

To develop risk limits for the low back, point estimates of the hand forces or turning torques correlating with risk thresholds for spinal loading (3400 N compression or 700 N A/P shear reported by NIOSH (1981) and Gallagher and Marras (2012), respectively) were determined for each combination of exposure conditions. At this level of hand force or turning torque derived via point estimate, 50 per cent of the population was assumed to encounter spinal loads above spinal tissue tolerance thresholds. Hand force or torque values causing other percentages of the population (90, 75, 25, 10%) to cross the risk thresholds for spinal loading were determined using the standard normal distribution of the mixed model's residuals. Whichever dimension of spinal loading that led to more protective (lower) force limits between spinal compression and spinal shear were reported.

The biomechanically determined limits derived for the low back were also compared to past psychophysically determined thresholds developed by Snook and Ciriello (1991). The closest sources of comparison were the maximum acceptable hand forces for initial 2.1 m two-handed pushes or pulls at a 93.9 cm (37 in) handle height at a frequency of once every five minutes. This push or pull distance was chosen because it was most comparable to the distance travelled by the subjects in the laboratory during each trial; subjects were able to exert and walk with the rig for about 3 m before the necessary push/pull forces required to sustain motion of the rig exceeded their strength capabilities. Likewise, the source of comparison for push/pull frequency was selected to match the frequency of loading prescribed for the A/P shear tissue tolerance of 700 N used to estimate biomechanical risk (Gallagher and Marras 2012); the 700 N limit was set for frequent loading (about 100 exertions throughout a workday), which corresponds to about one push or pull every five minutes in an eight-hour workday. The data presented for males and females by Snook and Ciriello (1991) were pooled via weighted average to make a comparison that is not dependent on gender. Pooling of data for males and females is scientifically sound considering the large differences in strength that exist for pushing and pulling in addition to the consideration that gender cannot typically be controlled for in the workplace.

3. Results

Independent measures of exertion type, handle height and exertion direction were all found to significantly influence dependent measures of spinal load, hand force and turning torque. Gender was also found to significantly influence the dependent measures. A snapshot of the statistically significant main and interaction effects and each effect's significance level is shown in Table 1.

3.1. Spinal load

The model predicted peak values for spinal compression to be found at the L3/L4 Inferior endplate and peak values for A/P and lateral shear spinal loads at the L5/S1 Superior endplate; these endplate levels served as the basis for subsequent analysis so as to develop guidelines that protect the tissues experiencing the highest loads. Because all lateral shear values were determined to be below tissue tolerance limits for spinal loading, lateral shear was determined to be of low biomechanical risk and was not investigated any further. However, peak compressive spinal loads and peak A/P shear spinal loads did surpass the 3400 N and 700 N risk thresholds for spinal loading in 11.3% and 30.2% of all trials, respectively. As shown in Figure 3, peak spinal loads (compression and A/P shear) were generally larger at lower handle heights ($p < 0.0001$) and were always highest for two-handed pulls ($p < 0.0001$). Compressive and A/P shear spinal loads were also larger for male subjects ($p = 0.018$ and $p = 0.012$, respectively).

Peak L3/L4 compression was subject to an exertion x direction interaction effect in which peak compression was higher for turning in two-handed pushing and pulling but the trend was reversed in one-handed pulling ($p < 0.0001$). An exertion x direction interaction effect was also observed for peak L5/S1 Superior A/P shear, in which peak shear was slightly reduced in turning pull exertions

Table 1. Statistically significant results.

	Exertion	Direction	Height	Exertion direction*	Exertion height*	Gender
Peak Spinal Loads						
L3/L4 Sup. Compression	***	***	***	***		***
L5/S1 Sup. A/P Shear	***	***	***	***	***	***
L5/S1 Sup. Lateral Shear	***	***	*	***		***
Hand Force						
Resultant Hand Force	***	N/A	***	N/A	***	***
Turning Torque	***	N/A	***	N/A	***	***
Angle Force Application	***	N/A	***	N/A	***	

Notes: *p<0.05; **p<0.01; ***p<0.001.

compared to straight pull exertions, but was increased for turning push exertions relative to straight push exertions ($p < 0.0001$). Likewise, a different interaction effect was also observed for peak L5/S1 Superior A/P shear, in which peak A/P shear load was increased at lower handle heights for all pulls but was lower at the 101.6 cm handle height relative to the other two heights in two-handed pushing ($p < 0.0001$).

3.2. Hand Force and Turning Torque

Peak resultant hand force and torque values are shown in Table 2. In straight exertions, peak resultant hand force was higher in two-handed pulling than two-handed pushing ($p < 0.0001$). Peak resultant hand force was also increased at lower handle heights in pulling exertions, yet increased at higher handle heights in pushing ($p < 0.0001$). In turning, higher axial torque was recorded at higher handle heights for both two-hand pushing and pulling ($p < 0.0001$), with no significant handle height effect observed for one-hand pulls. Peak hand force and peak torque were increased for males ($p < 0.0001$).

The mean angle of force application relative to horizontal was recorded in both hands for all exertions. For a more direct comparison between trial types (i.e. a direct comparison to the one-handed pull), angle of force application in the right hand was used as the basis for subsequent analysis. As shown in Figure 4, the direction of force application was largely affected by exertion type, handle height and an exertion x handle height interaction ($p < 0.0001$). In pulling exertions, lower handle heights were accompanied by steeper pulling angles relative to horizontal; at the highest handle heights, pulling forces were applied nearly horizontally. Pushing exertions noted a different trend, in which push forces at the lowest handle height were applied downward, at the middle handle height were applied nearly horizontally, and at the highest handle height were applied upward. Angle of force application was also affected by stature of subjects ($p < 0.0001$).

3.3. Biomechanically determined guidelines

Four mixed models were fit to obtain biomechanically meaningful guidelines for pushing and pulling exertions (L3/L4SuperiorCompression vs. Resultant HF, L5/S1Superior A/P Shear vs. Resultant HF, L3/L4 Superior Compression vs. Turning Torque, and L5/S1 Superior A/P Shear vs. Turning Torque). Exertion type, handle height, spinal load and two-way interactions were used as significant predictors of hand force or torque in each model. The addition of gender or any two-way interactions involving gender did not explain enough variability in the data (average increase in Adjusted R^2 of just 0.01) to warrant the

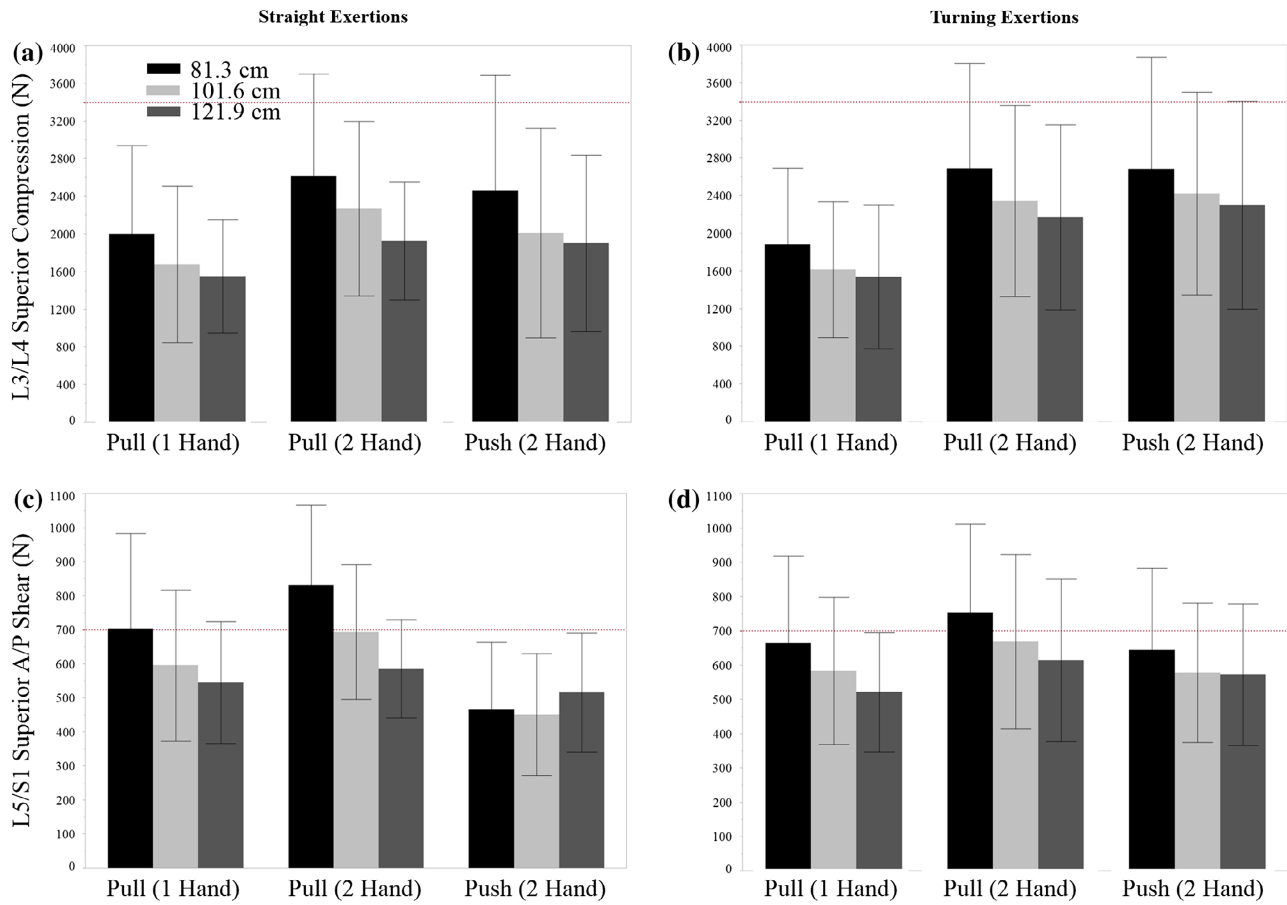

Figure 3. Peak spinal loads as a function of handle height and exertion type. (a) L3/L4 Superior compressive spinal load for straight exertions, (b) L3/L4 Superior compressive spinal load for turning exertions, (c) L5/S1 Superior A/P shear spinal load for straight exertions, and (d) L5/S1 Superior A/P shear spinal load for turning exertions.

development of separate pushing and pulling guidelines for males and females.

The L3/L4SuperiorCompression vs. Resultant HF model produced more conservative limits for straight pushes (Adjusted R^2 0.75), while the L5/S1 Superior A/P Shear vs. Resultant HF model produced more conservative limits for straight one and two-handed pulls (Adjusted R^2 0.86). Meanwhile, the L5/S1 Superior A/P Shear vs. Turning Torque produced more conservative limits for all turning exertions (Adjusted R^2 0.76). Proposed biomechanically determined pushing and pulling limits are presented in Table 3; the table presents multiple risk limits for each experimental condition related to the particular percentage of the working population that is expected to be protected from biomechanical risk if the risk limit were set at that level. Likewise, Table 4 compares hand force limits proposed within this investigation to past psychophysically determined thresholds developed by Snook and Ciriello (1991) for straight two-handed pushes and two-handed pulls at a comparable handle height. Because Snook and Ciriello (1991) reported horizontal hand forces only, the resultant hand force limits presented herein were adjusted for the horizontal component of hand force using the mean angle of force application for that particular exertion type and handle height before comparisons were made.

4. Discussion

Repeated loading of the lumbar spine past the recommended action limits for spinal loading (Gallagher and Marras 2012; NIOSH 1981) are often utilised when estimating biomechanical risk. Consistent with results presented by Knapik and Marras (2009), peak spinal loads most frequently exceeded tissue tolerance values in A/P shear (30.2% all trials), suggesting that shear loads to the lumbar spine should be of greater concern than compressive loads during occupational pushing and pulling. It is no surprise, then, that the models relating A/P shear spinal load to hand force, turning torque and other workplace factors generally produced more protective biomechanically determined risk limits than the models created for compressive spinal loading. In fact, all biomechanically determined limits were derived from A/P shear measures except for straight push exertions. It should be

Table 2. Peak hand forces and turning torques produced by the population tested, mean (SD).

Exertion		Handle height	Male (*n* = 31)	Female (*n* = 31)	Population (*n* = 62)
Resultant hand force (N) – *Straight*	1-Hand Pull	81.3 cm (32 in)	363 (105)	253 (61)	308 (102)
		101.6 cm (40 in)	260 (73)	198 (46)	230 (69)
		121.9 cm (48 in)	231 (52)	190 (44)	210 (52)
	2-Hand Pull	81.3 cm (32 in)	543 (188)	365 (104)	454 (176)
		101.6 cm (40 in)	382 (124)	248 (65)	314 (119)
		121.9 cm (48 in)	290 (78)	224 (56)	257 (76)
	2-Hand Push	81.3 cm (32 in)	289 (74)	221 (50	255 (72)
		101.6 cm (40 in)	303 (67)	216 (47)	260 (72)
		121.9 cm (48 in)	365 (112)	259 (59)	312 (104)
Resultant torque (Nm) – *Turns*	1-Hand Pull	81.3 cm (32 in)	112 (30)	76 (19)	94 (31)
		101.6 cm (40 in)	109 (30)	79 (22)	94 (30)
		121.9 cm (48 in)	110 (26)	79 (24)	95 (29)
	2-Hand Pull	81.3 cm (32 in)	134 (33)	97 (25)	116 (35)
		101.6 cm (40 in)	139 (39)	105 (30)	122 (39)
		121.9 cm (48 in)	145 (37)	105 (32)	125 (40)
	2-Hand Push	81.3 cm (32 in)	113 (33)	82 (25)	97 (33)
		101.6 cm (40 in)	124 (31)	97 (29)	111 (33)
		121.9 cm (48 in)	138 (31)	102 (33)	120 (37)

noted, however, that whereas the prior investigation by Knapik and Marras (2009) employed an earlier version of the same biomechanical model, maximum A/P shear loads were found at a lower endplate level in the present investigation (L5/S1 Superior compared to L3 and above). These differences may be attributable to changes made to the lines of action of each of the muscles in the dynamic spine model that now better approximate motions of the spine by accounting for muscle curvature during complex exertions (Hwang et al. 2016a, 2016b).

In pulling exertions, the reaction force at the hands creates a flexion moment in the torso that must be counteracted by the back extensor muscles, thereby increasing spinal loads. It is apparent that subjects are typically able to exert hand forces and turning torques past levels that might be considered risky to the low back. These results are not surprising, as individuals are unlikely to be able to sense biomechanical loading on the spine due to the lack of nociceptors in the IVD (Adams, Mcnally, and Dolan 1996). In pushing exertions, however, the reaction force at the hands creates an extension moment in the torso that is more easily counteracted by the flexion moment created by the mass and location of the torso. This likely led to the reduction in peak hand forces and spinal loads that were observed for straight pushing relative to straight pulling.

It is interesting to note, however, that the risk limits presented for straight pushing are generally lower than comparable risk limits for straight pulling. While these results contradict typical ergonomics recommendations that note pushing to be preferable to pulling in occupational environments, they can be explained partially by the fact that the 'worst-case scenario' was examined in order to develop the guidelines. Though subjects were confined to an upright posture in this study, prior push/pull studies examining other postures have shown that torso angles tend to increase (causing a flexion moment about the spine) in order to efficiently balance moment exposure from increased external hand forces (causing an extension moment about the spine) (Hoozemans et al. 2007). Likewise, allowing subjects to lean backward during

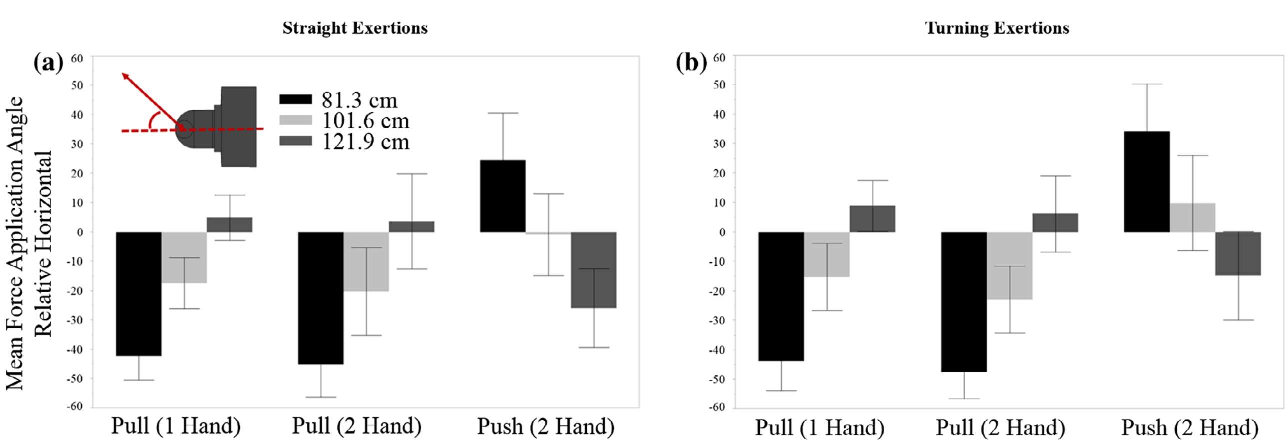

Figure 4. Mean direction of force application relative to horizontal for (a) straight exertions and (b) turning exertions by exertion type and handle height. Positive values denote a downward angle of force application (as if pushing down on the handles), while negative values denote an upward angle of force application (as if pulling up on the handles).

Table 3. Most conservative risk limits for straight and turning push/pull exertions protective of various percentages of the population tested.

			Straight exertions	Turning exertions
Exertion	Height	Percent population protected	HF limit (N)	Torque limit (Nm)
1 Hand Pull	81.3 cm (32 in)	90	212	58
		75	252	72
		50	295	87
		25	338	103
		10	378	117
	101.6 cm (40 in)	90	184	74
		75	217	88
		50	253	104
		25	289	119
		10	322	134
	121.9 cm (48 in)	90	164	75
		75	198	91
		50	235	108
		25	272	125
		10	306	141
2 Hand Pull	81.3 cm (32 in)	90	203	71
		75	282	86
		50	368	102
		25	454	118
		10	533	133
	101.6 cm (40 in)	90	260	87
		75	306	104
		50	356	124
		25	406	143
		10	452	161
	121.9 cm (48 in)	90	301	96
		75	336	113
		50	374	133
		25	412	153
		10	447	170
2 Hand Push	81.3 cm (32 in)	90	195	72
		75	243	88
		50	295	105
		25	347	122
		10	395	138
	101.6 cm (40 in)	90	217	94
		75	250	109
		50	286	126
		25	322	142
		10	355	157
	121.9 cm (48 in)	90	290	96
		75	333	114
		50	380	133
		25	427	152
		10	470	169

straight pulling is expected to load the facet joints, thereby offsetting load to the IVD slightly as well.

To help mitigate biomechanical risk associated with turning, this investigation is, to our knowledge, among the first to present turning torque limits. However, a few other laboratory studies have investigated the biomechanical risks placed onto the low back during turning exertions (Lee, Hoozemans, and van Dieen 2012; Marras, Knapik, and Ferguson 2009a; Sandfeld, Rosgaard, and Jensen 2014; Weston, Khan, and Marras 2017). It is expected that biomechanical loads placed onto the lumbar spine would be increased relative to straight pushing or pulling due to increased trunk muscle coactivity requirements during turning (Granata and Bennett 2005; Le et al. 2017). The results of this investigation in particular show significant interactions including exertion direction on spinal load measures.

As gender was noted to affect the dependent measures investigated, strength data (assessed via external hand forces and turning torques) has been provided for each gender and for the subject population as a whole. It is important to note, however, that the ultimate pushing and pulling guidelines proposed within this investigation did not differ based on gender. Ultimately, the guidelines proposed are protective of a representative population of (healthy) males and females because the gender of workers is a factor which cannot generally be controlled for in workplace design. It should be left to the practitioner to choose a risk level that he or she deems appropriate when utilising the guidelines presented based upon the gender distribution and health status of the working population. For example, working populations with a high proportion of females or workers with prior low back complaints may benefit from more protective risk limits.

Additionally, numerous pushing and pulling studies report horizontal hand forces only (Chaffin, Andres, and Garg 1983; Chow and Dickerson 2016; MacKinnon 1998; Warwick et al. 1980) in order to allow for more direct comparisons between experimental conditions and to allow for

Table 4. Comparison of biomechanically determined push pull limits to psychophysically determined equivalents.

		Biomechanically determined hand force limit (N)	Adjusted Biomechanically determined hand force limit (N)	Snook and Ciriello (1991) hand force limit (N)	
Exertion	Percent of Population Protected	*Resultant hand force*	*Horizontal Component of force*	*Horizontal Component of force*	Percent Change (%)
Straight 2 Hand Push, 101.6 cm (40 in)	90	217	217	239	−9.1
	75	250	250	300	−16.6
	50	286	286	371	−22.9
	25	322	322	437	−26.3
	10	355	355	503	−29.5
Straight 2 Hand Pull, 101.6 cm (40 in)	90	260	245	240	+1.9
	75	306	288	285	+0.9
	50	356	335	341	−1.9
	25	406	382	391	−2.4
	10	452	424	442	−4.0

more simple hand forces measures to be recorded in the field. However, as has been shown in prior laboratory studies related to pushing and pulling (Knapik and Marras 2009; de Looze et al. 2000; Schibye et al. 2001), hand forces are rarely actually generated horizontally. It is not surprising that when correlating hand forces and turning torques to spinal load measures as was performed in this study, spinal load measures were shown to be more closely associated with resultant hand forces than horizontal hand forces. The choice to analyse resultant hand forces as opposed to horizontal hand forces creates limitations for the practitioner, however, such that knowledge of the mean pushing or pulling angles relative to horizontal (Figure 4) will also need to be considered by practitioners prior to use of the guidelines presented for all straight pushes and pulls; this could be achieved, for example, via use of a rope attached to a hand dynamometer in pulling or smartphone applications measuring inclination angles. Likewise, for turning, the practitioner will need to calculate turning torque as the product of a horizontally applied push force and its moment arm (likely half the handle width). Though these suggestions add a small amount of complexity when measuring pushing and pulling exposures in the field, the authors of this work feel it is an important aspect to consider.

Several differences are worth noting when comparing the biomechanically determined guidelines presented herein compared to the widely used psychophysically derived pushing and pulling guidelines from Snook and Ciriello (1991). In relation to the study populations, Snook and Ciriello (1991) developed their guidelines utilising data across multiple studies with no more than 22 subjects in any study. Pushing and pulling exposures also varied widely in pushing and pulling distance, handle height, or pushing or pulling frequency across these studies. On the contrary, the population-based risk limits presented herein are based upon data obtained from 62 subjects that performed all of the experimental conditions for which risk limits are presented. The subjects recruited for this investigation also varied across a wide range of subject anthropometries (combinations of gender, stature, mass); as such, the population utilised in this investigation is expected to be more representative of a normally distributed working population than the populations recruited when creating guidelines using the psychophysical approach. In contrast, it is important to note that participants recruited in the present investigation were mainly college-aged, and whether each subject tested had prior experience with manual materials handling operations was not investigated. Snook and Ciriello (1991) utilised older, experienced workers in their psychophysical studies. However, our population is likely representative of the current inexperienced workers often seen in industry.

In relation to the risk limits presented for biomechanical and psychophysical approaches, it was determined that the prior psychophysically derived limits are less conservative than the risk limits presented herein, particularly in pushing where the biomechanically determined risk limits presented within this investigation are up to 30% lower than the limits reported previously. However, the biomechanically determined guidelines derived here do represent a 'worst-case' in terms of biomechanical load. Hand forces and spinal loads may be reduced slightly in practice, where workers can lean to balance moment exposure onto the spine resulting from increased external hand forces (Hoozemans et al. 2007).

Finally, the results of this study and the guidelines presented herein have implications in workplace design related to manual materials handling. It is clear from the biomechanically determined guidelines presented that higher handle heights should be preferred for both straight pushing and for all turning exertions regardless of exertion type. In straight pulling, the biomechanically determined guidelines presented appear to show an opposite trend, with generally higher force limits at lower handle heights; it is important to consider, however, that more vertically applied hand forces were observed at lower handle heights in straight pulling. Thus, in terms of horizontally applied force magnitudes in pulling, higher handle heights may also be preferred. Additionally, two-handed exertions (such as manoeuvring a cart) are preferable to one-handed exertions (such as manoeuvring a pallet jack).

4.1. Limitations

It is important to place the results of this study in context with its limitations. First, the study was run under laboratory conditions. Participants were mainly college-aged, and whether each subject tested had prior experience with manual materials handling operations was not investigated. The external validity of the results presented within this study may be affected by the recruitment of this subject population, as it is expected that experienced workers would display slightly different muscle activation profiles compared to a less experienced population during pushing and pulling (Lett and McGill 2006). However, use of a novice population are expected to be representative of current workers and, thus, could also allow for the derivation of more protective hand force limits, as novice subjects have not optimised neuromuscular recruitment patterns for the task.

Second, there were a few limitations related to the experimental design to note. As subjects exerted up to their max in each trial, it is possible that the results of this investigation, particularly in regard to subject strength assessed via hand force and turning torque, were subject to sincerity of effort or potential fatigue effects. It is important to note, however, that potential effects of subject fatigue were mitigated by the randomisation structure within the experimental design and via rest provided to subjects between trials; spinal loads also generally crossed tissue tolerance values below the maximum voluntary exertion levels, so it is not expected that fatigue affected the risk limits presented. Additionally, although subjects were instructed to remain upright throughout each trial to increase moment exposure to the spine, it is possible that trials with extensive torso flexion were included incidentally within the final data-set. Subjects also performed each exertion on an anti-fatigue mat to prevent slipping. Body kinematics and the direction of force application at the hands are expected to differ in an industrial environment depending on the shoe–floor interface (Boocock et al. 2006; Grieve 1983; Lavender et al. 1998; Lee, Chaffin, and Parks 1992).

Third, biomechanically determined guidelines for spinal loading were developed based upon risk thresholds for spinal loading that are neither gender nor age dependent and are dependent on force rather than stress. It is possible that biomechanical risk imposed onto the lumbar spine during occupational pushing and pulling is higher for females and higher for older individuals than might be predicted under the current methods. After all, prior research suggests decreased compressive strength in the lumbar spine for females and with age (Jäger, Luttmann, and Laurig 1991).

Fourth, the biomechanically determined guidelines developed from this work do not include a frequency component as do the psychophysical guidelines presented by Snook and Ciriello (1991). The guidelines presented herein focus on work intensity only, but it is also recognised that maximum acceptable work load is subject to interactions with both task frequency and duration (Winkel and Mathiassen 1994). Given that work duration has been noted to affect coactivation patterns and increase peak spinal loads throughout the workday (Marras et al. 2006), practitioners should account for task frequency and duration when selecting an appropriate risk level for the population.

Finally, the risk limits presented were designed to be protective of LBDs, which remain the most prevalent and costly of all work-related musculoskeletal disorders. However, mitigating risk to the shoulder joint during pushing and pulling may also be of concern to practitioners, as an array of epidemiological studies have found an association between pushing and pulling exposures and shoulder complaints among male and female workers (Hoozemans et al. 2002a, 2002b, 2014). While biomechanically determined hand force and turning torque limits could be established for the low back using tissue tolerance values reported in the literature (Gallagher and Marras 2012; NIOSH 1981), limitations exist regarding the shoulder joint in that it lacks commonly accepted tissue tolerance values to directly estimate risk in a similar fashion. This is likely because the shoulder joint encounters a large range of motion, and the strength of the joint varies greatly based on hand position and the mechanical advantage of the arm in different postures (NASA 1978). Moreover, the anatomical structures that are loaded as a result of pushing and pulling are expected to vary based on exertion type (Hoozemans et al. 2014).

5. Conclusion

Collectively, this study presents pushing and pulling risk limits using an objective (as opposed to subjective) biomechanical modelling approach and represents one of the first attempts to also prescribe risk limits during turning pushes and pulls. Biomechanically determined risk limits presented for the varied pushing and pulling exposures tested (combinations of exertion type, handle height, straight vs. turn) are up to 30% lower than comparable psychophysically determined guidelines. Thus, the results of this study suggest that current psychophysically derived pushing and pulling risk limits can underestimate biomechanical risk to the low back. Practitioners should consider implementing these biomechanically determined risk limits moving forward.

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