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Pushing and pulling: personal mechanics influence spine loads

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This study assessed several mechanical issues related to low back loading during pushing and/or pulling tasks. Nine male participants performed two-handed pushing and pulling tasks at two handle heights with three loads, using a cable pulley system. Four of these men were professional firefighters trained in performing pushing and pulling tasks while the other five were graduate students who lacked manual work experience. The more experienced firefighters produced less spinal compression and shearing forces when compared to the less experienced students under the same conditions. The firefighters were able to create less muscle activation as compared to the students, which indicated a more efficient technique. The main contributing factors to the forces produced on the low back were the quantity of the load being pushed or pulled, handle height, experience level and the technique of the participant. Thus, attempts to set load limits for pushing and pulling tasks are difficult, since technique has such a large influence on back loading. In order to create safer working environments, education on proper pushing and pulling techniques is very important – more important than the physical variables in many cases.

Keywords: Push; Pull; Low back

1. Introduction

Manual material handling has been identified as a potentially harmful risk factor for injury (Jansen *et al*. 2002). It has been suggested that lifting and carrying tasks are being replaced via ergonomics interventions into pushing and pulling tasks (De Looze *et al*. 2000). One reason for this shift is that pushing and/or pulling an object, such as a wheeled container, will enable a person to transport heavier weights, potentially making a more efficient work setting. Currently, it is estimated that half of the manual material handling tasks performed in an industrial setting require a push and/or pull manoeuvre (Kumar 1995, van der Beek *et al*. 1999). It has also been suggested that, on average, 9–20% of low back injuries may be associated with either a pushing and/or pulling task (Kumar 1995,

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Schibye *et al*. 2001). This statistic motivated the present research, with the objective of better understanding the role of pushing/pulling techniques on back loading.

The two primary mechanisms of low back injuries are tissue overloading and incidents of spinal segment instability (Cholewicki and McGill 1996, McGill 2002). The first mechanism, damage to spinal tissues, occurs when an applied load exceeds the tolerance level of that particular tissue. To avoid tissue overloading, some authorities have recommended safety limits for acceptable shear and compression loads on the spine. The National Institute for Occupational Safety and Health (NIOSH) compression action limit is set at 3400 N and the maximal permissible limit is set at 6300 N (National Institute for Occupational Safety and Health 1981). A recommended guideline of 500 N (McGill 2002) was proposed for anterior–posterior (a/p) tissue shear forces. Snook and Ciriello (1991) also made some suggestions on maximum acceptable weights and forces for pushing and pulling tasks based on people's perception of fatigue.

The second mechanism associated with low back injuries involves incidents of spinal segment instability, which have been suggested to cause low back injuries and are thought to be the result of prior tissue damage or loss of joint stiffness (Panjabi 1992, Cholewicki and McGill 1996, McGill 2002). Lumbar column stability results primarily from the coordinated action of the surrounding musculature (Cholewicki *et al*. 2000). These two primary injury mechanisms, likelihood of instability and tissue overloading, can be predicted from the spinal models that were used in this study (Cholewicki and McGill 1996).

The purpose of this study was to quantify spine loads, muscle activation patterns and an estimate of spine stability, while expert and novice workers pushed and pulled loads. It was hypothesized that the experienced workers would perform in a way that was more protective to their backs.

2. Methods

Nine male participants were fitted with electromyographic (EMG) electrodes (to measure muscle activity), a device to measure three-dimensional (3-D) spine motion and infrared emitting diodes (IRED) to track body segment motion. Each participant then performed pushing and pulling tasks with two handle heights and three loads on a cable pulley system (figure 1). The data collected were then processed through the biomechanical models to produce estimates of compression and shearing forces, levels of muscle activation and stability indices.

2.1. *Participants*

Data were collected from ten participants but instrumentation error rendered one participant's inadmissible for study. Since the spinal/stability model is based on a 50th percentile male, participants were sought bearing a resemblance to this standard. The mean stature of the nine participants was 180 (± 6) cm and weight was 74.7 (± 14) kg (table 1). Four of the participants were employed by the city fire department and five were university students. No participant had a prior history of disabling back injury.

2.2. *Instrumentation*

Five components of data collection were needed to fulfil the requirements of biomechanical spinal stability estimation.

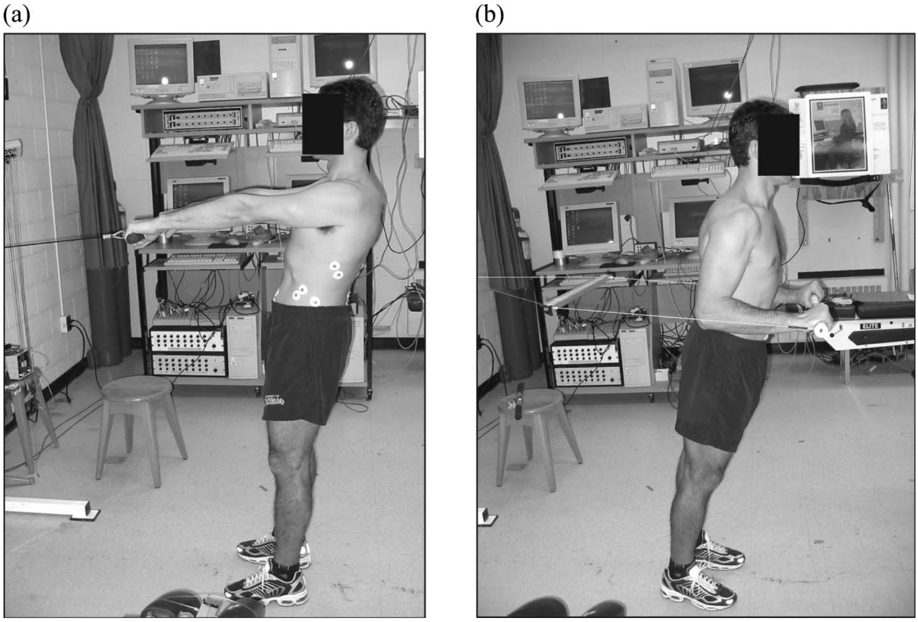


Figure 1. Represents (a) pulling posture with the handle at shoulder height; (b) pushing posture with the handle at waist height.

Table 1. Stature and weight measures for firefighters and students.

Firefighters	Stature (cm)	Weight (kg)
	180.0	80.1
	177.8	75.0
	172.0	70.9
	187.9	93.9
Mean	179.4	80.0
SD	6.58097	10.02806
Students		
	178.5	89.7
	176.0	65.0
	192.0	79.1
	178.0	92.7
	180.0	77.3
Mean	180.9	80.8
SD	6.4	11.0

2.3. *Electromyography*

Data from 14 channels of EMG were collected. The electrodes were placed over the bellies of seven muscles bilaterally: rectus abdominis; external oblique; internal oblique; latissimus dorsi; upper erector spinae T9; lower erector spinae L3; and the erectors at L5 (McGill 2002). The signals were amplified using differential amplifiers (frequency response of 10–1000 Hz, input impedance of 10 Mohms, common mode rejection of 115 dB at 60 Hz). The raw EMG was full wave rectified, filtered using a second order

Butterworth filter (with a cutoff frequency of 2.5 Hz) and normalized to a maximum voluntary contraction (MVC) for each particular muscle (Kavcic *et al.* 2004). These signals were A/D converted at a frequency of 1024 Hz.

2.4. *Kinematics*

2.4.1. Three dimensional spinal movements. A 3 Space Isotrak (Polhemus Inc, Colchester, VT.) electromagnetic tracking device was worn to measure the three rotational axes of lumbar spine motion where the transmitter was adhered over the sacrum, and the receiver was adhered to the 12th thoracic vertebrae.

2.4.2. Three-dimensional kinematic and kinetic analysis. An Optotrak (Northern Digital Inc., Waterloo, Ontario) was used to detect and record 3-D motion of the head, arms, hands, trunk, pelvis and lower limbs. IRED were placed on the lateral side of each of these segments (19 were attached to the body and four on the push/pull handle apparatus). Specifically, 16 of the IRED were placed bilaterally on the metatarsals, ankles, knees, hips, hands, wrists, elbows and shoulders. The final three body markers were placed on the chin, over L4/L5 and C7/T1 intervertebral joints. Four IRED were placed on the handle apparatus, the first two were extending from both sides of the hands and the last two were placed further along the cable. The handle markers were used to determine the line of action of the hand force. Two MLP load cells (Transducer Techniques, Temecula, CA) were placed on the cables attached to both sides of the pushing and pulling handle and provided the magnitude of force generated by each hand. This procedure resulted in a 15-segment link model of the body, where 3D moments at the L4/L5 joint were calculated and then used as an input into the lumbar spine model.

The distribution–moment muscle model of Zahalak (1986) was used to estimate muscle force and convert the force to stiffness to estimate stability. Spine stability analysis was performed using the model developed by Cholewicki and McGill (1996). A global stability index for the entire lumbar spine was output as well as a measure of the critical stiffness at each instant in time.

2.5. *Tasks*

Following the MVC for EMG normalization, the actual test protocol consisted of two different tasks: pushing and pulling. The tasks were performed with a double handed push or pull, followed by walking three steps while sustaining the push or pull force. The pulling trials were performed while walking backwards and pushing tasks by walking forwards. The order of pushing and pulling tasks was randomized among the participants. Push and pull cable resistance was created by a pulley weight stack to eliminate the rolling resistance, for example, that might be created by carts.

Twelve different conditions in total were tested (two tasks, two handle heights and three applied loads). The two handle heights were set at the participants' shoulder and waist height. The participants were instructed to hold the handle at the same height as the cable, keeping the cable parallel to the ground. The three loads that were applied were: 1) 44.5 N; 2) 222.4 N; 3) 400.5 N. A 222.5 N (50 lb) weight was chosen, based on the recommended psychophysical studies of Snook and Ciriello (1991), to further investigate the acceptable safe limits for pushing and pulling tasks. The other two loads were chosen to bracket above and below the suggested acceptable limit.

2.6. *Pushing and pulling task analysis*

For all pushing and pulling tasks the data were collected for 10 s, prepared and processed through the spinal and stability models (Cholewicki and McGill 1996). The model outputs or hand force, lumbar moments, compression and a/p shear force, degree of trunk flexion, stability index and muscle activation profiles were further analysed. A $2 \times 2 \times 3$ repeated measures ANOVA was performed using SAS (SAS Institute, Cary, NC, USA) to determine if there were any significant differences between the different tasks (pushing and pulling), the handle height (shoulder and waist) and the three loads (45.5 N, 222.5 N and 400.5 N) for the entire group and between the two populations (experienced firefighters and the inexperienced students). The dependant variables observed for differences were peak compression, peak a/p shear and lumbar moments.

3. Results

The major finding was that pushing and pulling techniques influenced virtually all mechanical parameters of the spine. The results are organized to reflect this common finding together with push and pull differences and with novice and expert differences. Hand forces were similar while all other spine parameters were different.

3.1. *Pushing and pulling forces*

The external hand forces measured during the pushing and pulling tasks did not match the load set on the weight stack (table 2). The load placed on the weight stack was similar to the external hand force when load 'a', 44.5 N, was applied for pushing, 46.4 N and pulling, 43.3 N, tasks. Loads 'b', 222.5 N, and 'c', 400.5 N, were both less than the applied loads in all conditions. The external hand forces during the pushing tasks were greater than the hand forces during the pulling tasks for all loads. When the two populations were compared (figure 2) the forces obtained for all situations were very similar.

3.2. *Peak lumbar moments*

As expected, the peak lumbar moments significantly increased as the load increased for all trials (figure 3). Specifically, the pulling task moments were different for the two handle heights, shoulder and waist ($F = 17.73$; $p = 0.004$). The mean peak moments for the entire population at shoulder height were 74.8 Nm for load 'a', 122.1 Nm for load 'b' and 165 Nm for load 'c'. Whereas at hip height the moments were less at 54.4 Nm for

Table 2. Comparison of the load placed on the weight stack and the actual measured peak hand forces during pushing and pulling tasks.

Load	Load on weight stack (N)	Peak hand force while pushing (N)	Peak hand force while pulling (N)
A	44.5	46.4	43.3
B	222.5	154.2	146.2
C	400.5	267.9	254.5

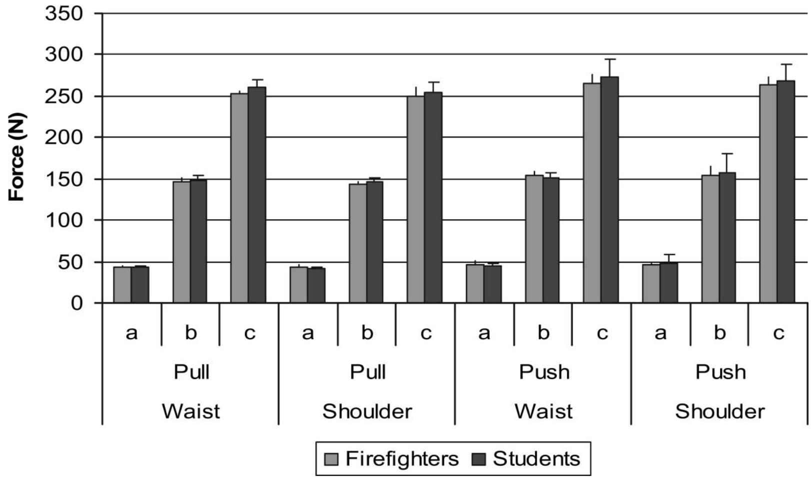


Figure 2. Peak measured initiating forces for pushing and pulling tasks, comparison between the firefighter and student populations. The handle was placed at shoulder and waist height and the weight stack was loaded with loads: a = 45.5 N; b = 222.5 N; c = 400.5 N.

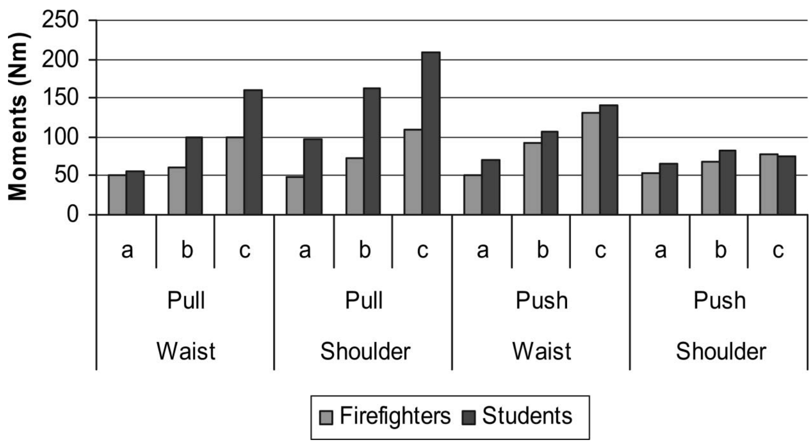


Figure 3. Peak lumbar moments comparing the firefighter and student populations. The handle was placed at shoulder and waist height and the weight stack was loaded with loads: a = 45.5 N; b = 222.5 N; c = 400.5 N.

load 'a', 81.2 Nm for load 'b' and 132.7 Nm for load 'c'. There was also a significant difference in the lumbar moments between the two populations with the handle at shoulder vs. waist height ($F = 9.19$; $p = 0.019$). Figure 3 demonstrates the students having greater peak lumbar moments for the pulling trials. The lumbar moments were also significantly different for the three loads placed on the weight stack during pulling tasks ($F = 54.54$; $p < 0.0001$) and between groups at the different loads ($F = 5.10$; $p = 0.0217$).

For the pushing tasks, similar differences were observed. There were significant differences in the moments with the two different handle locations, shoulder and waist

(F = 9.23; $p = 0.0288$). The average peak moments for the entire population at shoulder height were 59.9 Nm for load 'a', 73.5 Nm for load 'b' and 76.3 Nm for load 'c'. Whereas at waist height the moments were greater at 61 Nm for load 'a', 99.9 Nm for load 'b' and 136.7 Nm for load 'c'. There was no significant difference between the two groups, students and firefighters, for the different handle heights. There were significant differences in the lumbar moments for the three loads placed on the weight stack (F = 23.66; $p = 0.0001$).

3.3. *Peak compression and anterior–posterior shearing force*

3.3.1. Entire population. Peak compression (F = 14.5; $p = 0.0004$) and peak a/p shearing forces (F = 23.2; $p \leq 0.0001$) increased as the load increased (figures 4 and 5) in all pushing and pulling conditions, reflecting a similar trend as seen in the lumbar moment data. The greatest a/p shearing force occurred in the posterior direction for all pushing and pulling trials. All of the pushing trials produced greater peak compression and peak posterior shearing forces than the pulling trials of the same conditions (F = 15.1; $p = 0.008$). For the entire participant population the condition that produced the greatest peak compression and peak posterior shearing was pushing load 'c' with the handle at waist height. The peak compression force was 3865.9 ± 443.2 N and the peak posterior shearing force was 679.4 ± 154.4 N. Both values exceed the recommended action limits of 3400 N of compression and 500 N of a/p shearing force.

3.3.2. Firefighter vs. student population. When comparing the two populations (firefighters and students), the students produced higher peak compressions and peak posterior shearing forces in almost all conditions (figures 6 and 7). The peak compression values did not have any significant differences between the two populations. The posterior shearing forces did have significant differences between the two populations for the pushing vs. pulling tasks (F = 13.14; $p = 0.01$).

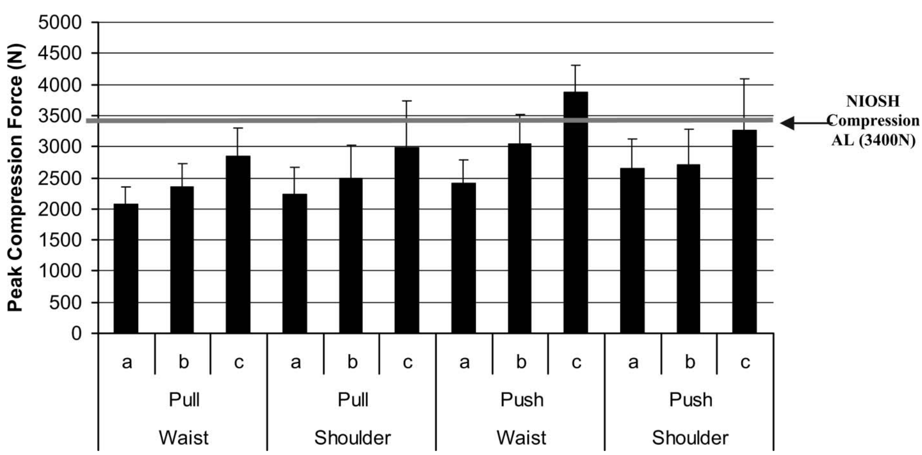


Figure 4. Peak compression forces on L4/L5 intervertebral joint for entire population for all conditions. The handle was placed at shoulder and waist height and the weight stack was loaded with loads: a = 45.5 N; b = 222.5 N; c = 400.5 N. NIOSH = National Institute for Occupational Safety and Health; AL = action limit.

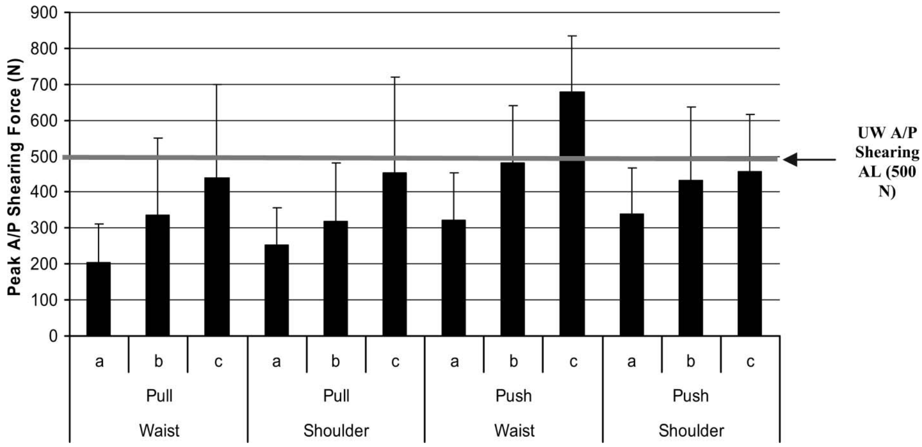


Figure 5. Peak posterior shearing forces on L4/L5 intervertebral joint for entire population for all conditions. The handle was placed at shoulder and waist height and the weight stack was loaded with loads: a = 45.5 N; b = 222.5 N; c = 400.5 N. UW = University of Waterloo Action Unit; A/P = anterior–posterior; AL = action limit.

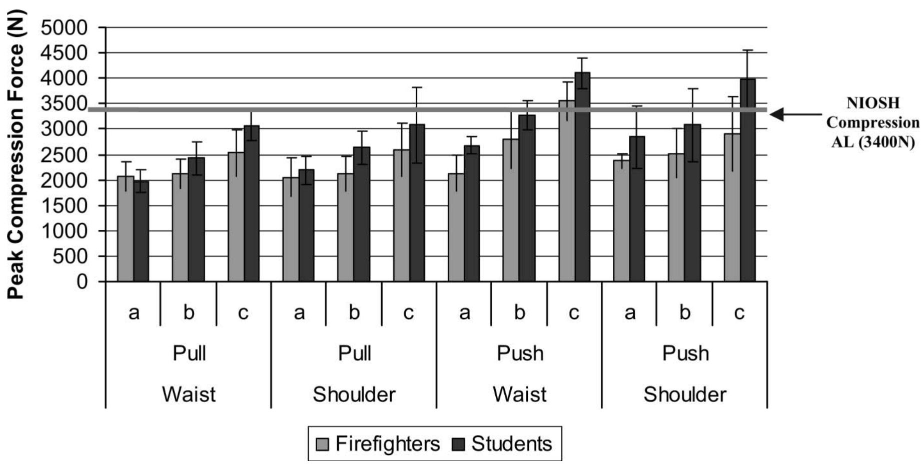


Figure 6. Peak compression forces on L4/L5 intervertebral joint comparing firefighter and student populations. The handle was placed at shoulder and waist height and the weight stack was loaded with loads: a = 45.5 N; b = 222.5 N; c = 400.5 N. NIOSH = National Institute for Occupational Safety and Health; AL = action limit.

The group mean display peak compression and posterior shearing forces exceeded the recommended action limits. The firefighters did not produce any values above the recommended action limits for either peak compression or a/p shear under all pulling conditions. Students also did not generate any compression values exceeding the recommended action limit; however, they did have two conditions that exceeded the peak a/p shearing action limit. Both handle conditions (waist and shoulder height) pulling load 'c' did exceed the limit at 578.9 $\pm$ 328.5 N and 557.7 $\pm$ 275.6 N of peak posterior shearing

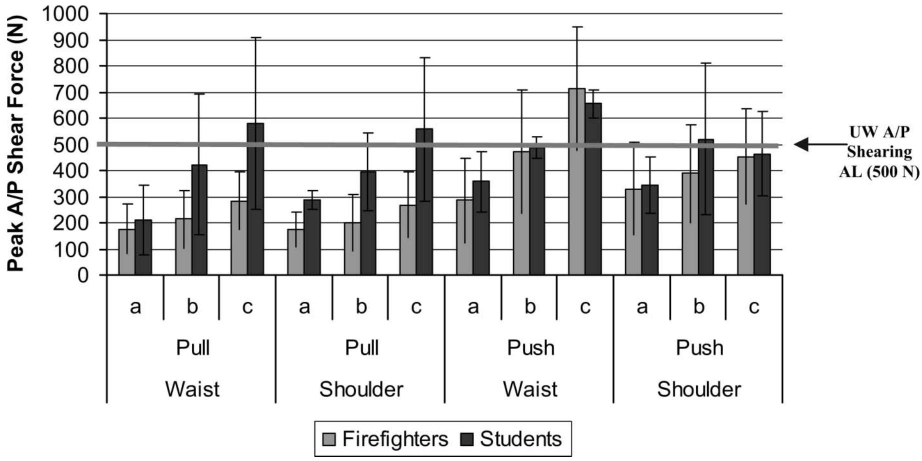


Figure 7. Peak posterior shearing forces on L4/L5 intervertebral joint comparing firefighter and student populations. The handle was placed at shoulder and waist height and the weight stack was loaded with loads: a = 45.5 N; b = 222.5 N; c = 400.5 N. UW = University of Waterloo Action Unit; A/P = anterior–posterior; AL = action limit.

force, respectively. For the pushing trials, both populations had tasks that exceeded the recommended action limits for both peak compressions and peak a/p shearing forces. Pushing load 'c' with the handle at waist height produced exceeding limits for both populations in both spinal loads. The firefighters produced 3552.3 $\pm$ 380.8 N peak compression force and the students produced 4101.1 $\pm$ 300.8 N. The a/p shearing forces were 713.2 $\pm$ 234.4 N for the firefighters and 654.1 $\pm$ 53.5 N for the students, both in the posterior direction. The last trial that exceeded the action limit was the students pushing load 'b' with the handle at shoulder height. The force posterior shearing force was 519.9 $\pm$ 290.9 N.

3.4. *Lumbar curvature and torso angle*

It should be recalled that lumbar curve is specific to the lumbar spine, whilst torso angle is the 'lean' of the torso relative to the hips. In all trials, all participants had some lumbar flexion (compared to a standing posture) and the degree of lumbar curvature increased as the load increased (figures 8 and 9). There was a significant difference for lumbar curvatures between the two samples when comparing pushing and pulling tasks (F = 13.2; $p = 0.008$). The lumbar angle was also significantly different for the load being pushed or pulled (F = 71.5; $p < 0.0001$). The interesting comparison is between torso and lumbar curvature for a given condition. For example, for pulling at waist height the experienced pullers (firefighters) used less spine flexion but more torso flexion as they created the force using hip drive.

3.5. *Stability index*

The stability index increased as the load and the compression force at L4/L5 intervertebral joint increased (figure 10). All the pushing trials created a higher stability index as compared to the pulling trials with the same condition.

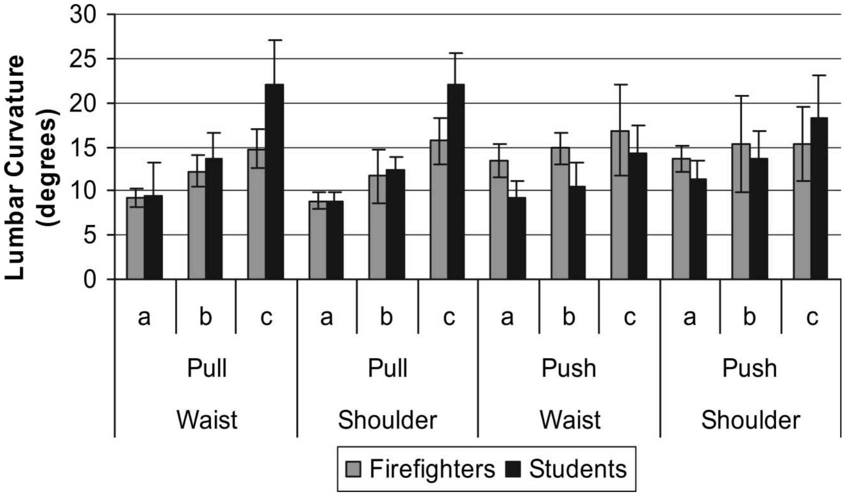


Figure 8. Peak lumbar flexion curvature during all pushing and pulling tasks, comparing between the firefighter and student populations. All values were positive. The handle was placed at shoulder and waist height and the weight stack was loaded with loads: a = 45.5 N; b = 222.5 N; c = 400.5 N.

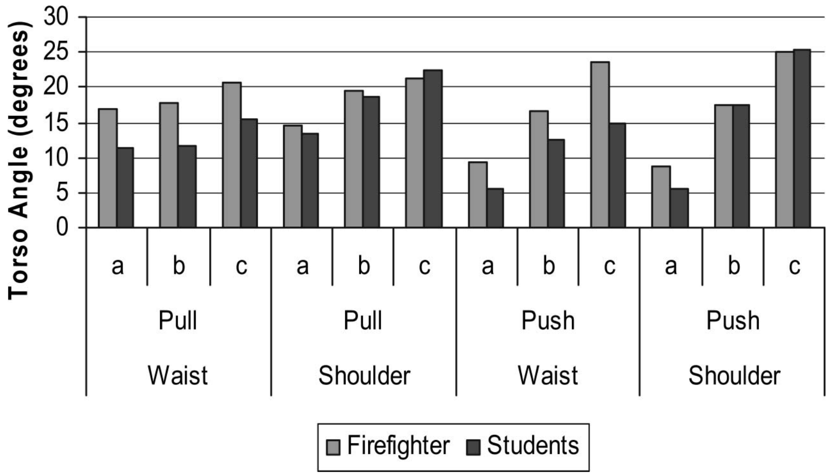


Figure 9. Peak torso angle during all pushing and pulling tasks, comparing between the firefighter and student populations. The handle was placed at shoulder and waist height and the weight stack was loaded with loads: a = 45.5 N; b = 222.5 N; c = 400.5 N.

3.6. *Muscle activation profiles*

In all but one of the trials, muscle activation increased as the load increased (figures 11 and 12). The rectus abdominis, internal obliques and external obliques tend to create the most force while pushing with the handle at shoulder height. The trial in which the participants were pushing load ‘c’ with the handle at shoulder height produced the largest muscular activation. The right internal obliques produced the highest activation amongst

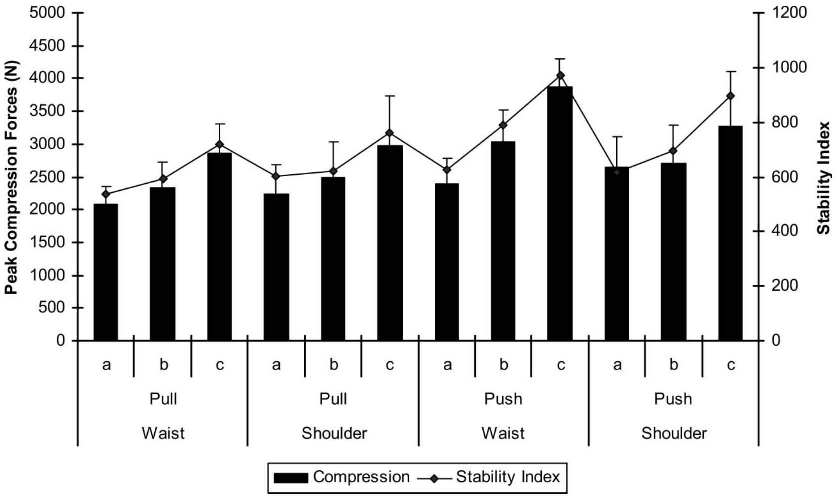


Figure 10. Peak compression and stability index for all pushing and pulling trials. The handle was placed at shoulder and waist height and the weight stack was loaded with loads: a = 45.5 N; b = 222.5 N; c = 400.5 N.

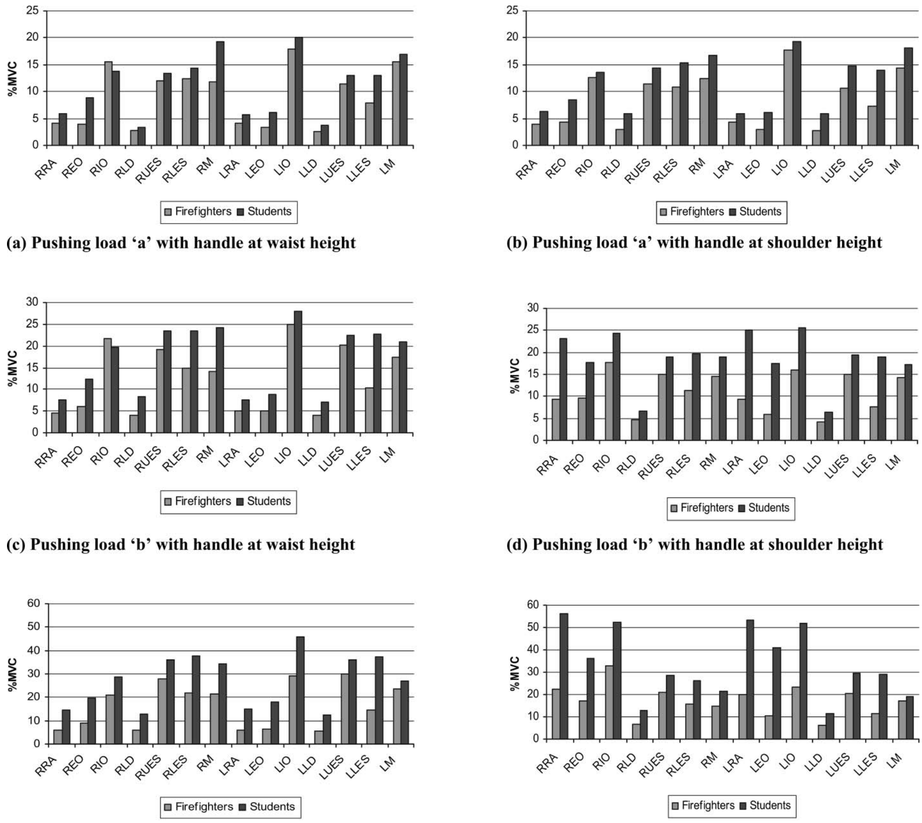
all trials at 43.8 ± 19.9% of MVC. When the participants where pushing with the handle at waist height, the internal obliques were still highly activated especially in the higher loads. The back muscles had increased activation when the handle was placed at waist height, as compared to the handle at shoulder height. When averaged between the right and left sides, the 'L5', the upper and lower erector spinae were activated to 19.5, 21.4 and 18.4% of MVC respectively for load 'b'. For load 'c' the muscle activation was increased to 7.0, 32.9 and 28.8% MVC, respectively.

For the pulling trials a different trend was observed (figure 12). The back muscles tended to play a larger role in the pulling activities, creating higher levels of activation. The left latissimus dorsi had the highest activation level when pulling load 'c' with the handle at waist height at 37.8 ± 24% MVC.

Examining the trends between the two groups based on experience, firefighters and students illustrated overwhelmingly that the firefighters generated lower levels of muscle activity to perform the same tasks.

4. Discussion

The main findings of this study were: as the pushed/pulled load increased, so did the spinal loads; spine stability increased as the load increased; the optimal handle height for pushing is at shoulder level and at waist height for pulling; pulling creates smaller spinal forces than pushing under the same conditions; the experienced population (firefighters) had lower spinal compression forces and muscle activation profiles compared to the less experienced population (students) performing the same task. The firefighters exemplified pulling skill by directing the transmissible hand force vector through their lower lumbar spine to reduce the reaction moment and to optimize hip drive and lumbar curvature. This implies that work technique is a dominant contributing factor to spinal loading and, by default, risk of injury.



(a) Pushing load 'a' with handle at waist height

(b) Pushing load 'a' with handle at shoulder height

(c) Pushing load 'b' with handle at waist height

(d) Pushing load 'b' with handle at shoulder height

(e) Pushing load 'c' with handle at waist height

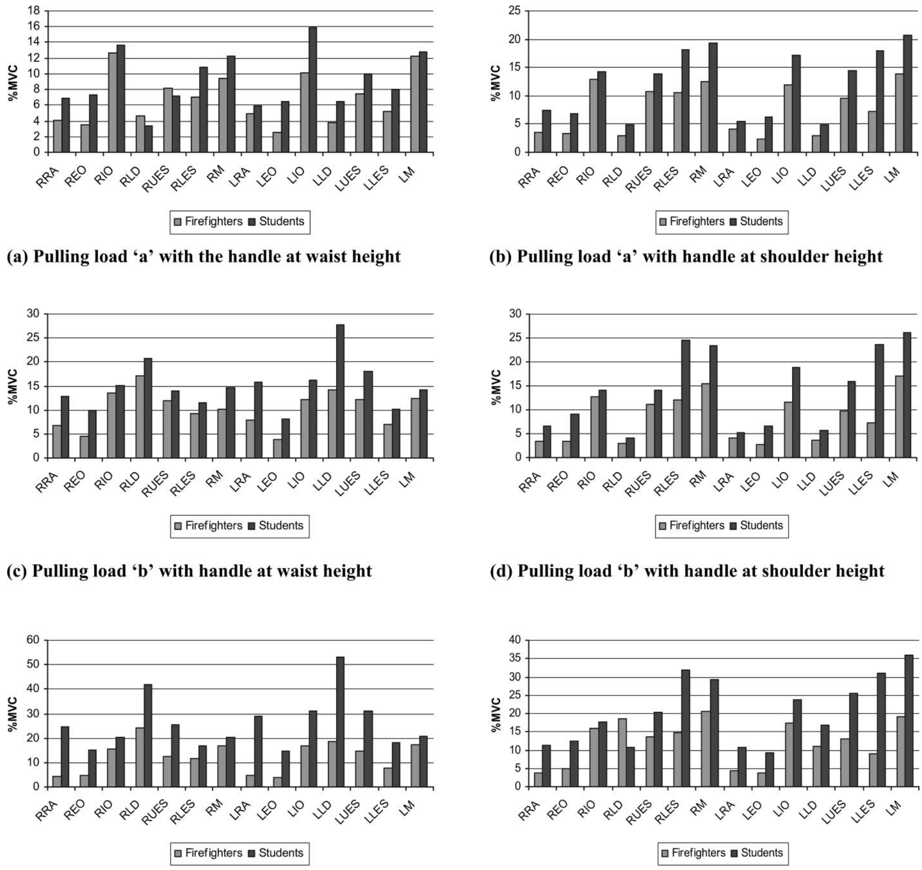
(f) Pushing load 'c' with handle at shoulder height

Figure 11. Represents the muscle activation profiles for the student and firefighter populations during the all pushing trials. Load applied to the weight stack: a = 45.5 N; b = 222.5 N; c = 400.5 N. MVC = maximum voluntary contraction.

It was found that the optimal handle height for reducing low back forces during pushing tasks was at shoulder height. This height allows individuals to increase lumbar flexion curvature and use body weight to assist with push, minimizing the muscle activation. In this way, the centre of mass of the upper body lies in front of the base of support creating a forward hinge torque to assist with the push and reducing the reliance on muscular activation.

Based on the findings of this study it would be very difficult to determine acceptable pushing and pulling limits that would fit an entire population. This study used the previously determined psychophysical push/pull guidelines (Snook and Ciriello 1991) for testing spinal loads. With these loads, some individuals exceeded the recommended compression and shear values and some stayed below it. This observation lends more evidence to the claim of Snook and Ciriello that the loads were acceptable for 50% of the population. Interestingly, their psychophysical approach produced strikingly similar results to the NIOSH biomechanical compressive load recommendation and the Waterloo shear load recommendation.

Is there a 'proper' pushing and pulling technique to spare backs from risky loading? The data here suggest that a 'proper' technique for pushing would be for the individual to



(a) Pulling load 'a' with the handle at waist height

(b) Pulling load 'a' with handle at shoulder height

(c) Pulling load 'b' with handle at waist height

(d) Pulling load 'b' with handle at shoulder height

(e) Pulling load 'c' with handle at waist height

(f) Pulling load 'c' with handle at shoulder height

Figure 12. Represent the muscle activation profiles for the student and firefighter populations during the all pulling trials. Load applied to the weight stack: a = 45.5 N; b = 222.5 N; c = 400.5 N. MVC = maximum voluntary contraction.

create a hinge torque by leaning into the load so that the upper body centre of mass is in front of the feet (base of support). In order to maximize the individual's ability to create this hinge torque, the handle should be adjusted closer to shoulder height. The proper technique for pulling would be to create a hinge torque with upper body centre of mass behind the base of support. Additionally, the line of action of the hand force should be directed through the lumbar spine to reduce the moments, subsequent extensor muscle activity and compressive spine loads. It would appear that the handle should be adjusted to waist height, to optimize the technique displayed by the expert firefighters.

The major limitation of this work was the small sample size. The major strength was the amount of data collected and processed to render these in-depth variables – particularly stability. While statistical analysis was compromised, the graphically displayed trends for variables, such as EMG amplitudes, were meaningful. The biomechanical modelling approach used here also had several limitations. For example, some muscles were not monitored, such as transverse abdominis and the small spinal rotators. This may have caused some inaccuracy of the load estimations together with an underestimation of the overall stability index (Cholewicki and McGill 1996). However, the activation of these muscles was predicted from movement synergists (McGill *et al.* 1996). Finally, the push/pull tasks were produced on a cable that did not support vertical loads. The advantage of this setup was that the push/pull forces were 'pure'. The disadvantage was that pushing a cart, for example, has an inertial rolling mass that would be different and would also support some vertical forces. Nonetheless, it was the intent of this study to document 'pure' push/pull mechanics.

In conclusion, this limited study suggests that technique expertise assists in reducing back loads during pushing and pulling, and that some previously suggested psychophysical guidelines are in agreement with biomechanical load guidelines.

Acknowledgement

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