Combined influence of transfer distance, pace, handled mass and box height on spine loading and posture

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Abstract

Work-related low back disorders are commonly associated with handling tasks. The objective of this study was to determine the combined influence of distance, pace, handled mass and height, on back loading and posture during free box transfer. Kinematics and kinetics of 17 handlers were recorded during a box transfer task between two pallets. Four-way repeated measures ANOVA were conducted on four lift-deposit height conditions (from lift and deposit of 0.16 or 1.16 m), three distances between pallets (1.5, 1.0 and 0.5 m), two handled masses (10 and 20 kg) and two paces (free and faster). The interaction between distance and height on back loading and posture ($P < 0.001$) showed that increasing distance to more than 1 m is not recommended to avoid unnecessary cumulative loading, but that the shorter distance of 0.5 m, which generally reduced the most spine loading, may increase it for transfers varying in height. The effect of pace to reduce spine cumulative loading and increase the peak asymmetric loading ($P < 0.05$) was accentuated by mass, height and distance. The combined factors revealed the importance of tradeoff between peak, cumulative and asymmetric loading.

Keywords: manual material handling; lifting; musculoskeletal disorder; back; speed

Highlights

- A box transfer distance of more than 1 m creates unnecessary cumulative loading.
- A transfer distance of 0.5 m generally obtained less peak and cumulative loading.
- Faster pace reduced cumulative spine loading, but induced postural asymmetry.
- Handled mass increased spine loading, but had less influence at greater heights.
- Working conditions imply a tradeoff between peak, cumulative loading and posture.

1. Introduction

The relationship between work-related low back musculoskeletal disorders and manual materials handling (MMH) is supported by epidemiological evidence (Bernard, 1997; Burdorf and Sorock, 1997). Many external conditions of MMH tasks have been investigated to determine their impact on workers' physical exposure. For instance, the height of the load, the initial distance of the load from the body, the handled mass and the speed of the lift have been related to the L5/S1 external moment or compression force (Corbeil et al., 2019; Harari et al., 2019; Hoozemans et al., 2008; Lavender et al., 2003; Plamondon et al., 2014; Plamondon et al., 2012; Plamondon et al., 2017), while transfer distance and working pace have received less attention.

As expected, handling heavier loads increases spine loading (Buseck et al., 1988; Corbeil et al., 2019; Granata et al., 1999; Hoozemans et al., 2008; Lavender et al., 2003; Lavender et al., 1999; Plamondon et al., 2012; Plamondon et al., 2017; Schipplein et al., 1995), and lifting near the floor leads to the most pronounced effect on spine loading (Corbeil et al., 2019; Harari et al., 2019; Hoozemans et al., 2008; Lavender et al., 2003; Plamondon et al., 2014; Plamondon et al., 2012). Both factors directly contribute to the external moment acting on the spine, which can be considered the most important risk factor for low back disorders (Marras, 2006). Some studies have investigated the horizontal initial position of the box, where it was determined that the further away the box, the greater the moment arm and peak moment (Faber et al., 2011; Lavender et al., 1999; Schipplein et al., 1995). The distance between lift and deposit locations was mostly studied from a posture perspective, where lumbar flexion and twisting were reduced as transfer distance increased, especially during the deposit phase (Jorgensen et al., 2005; Kim et al., 2014; Mehta et al., 2014). Faster lifting speed increased peak spine loading (Buseck et al., 1988; Bush-Joseph et al., 1988; de Looze et al., 1994; Dolan et al., 1994a; Gagnon and Gagnon, 1992; Jager and Luttmann, 1992; Lavender et al., 2003; Lavender et al., 1999) and was associated with increased sagittal, lateral and twisting acceleration (Granata et al., 1999). The estimation of spine loading at different transfer distances and working pace could improve current recommendations for workplaces.

Some authors have argued that substantial loading occurs during the transfer or carrying phase, that it may even surpass the lifting phase loading, and that literature remains sparse on the topic (Marras et al., 2010). In addition, when lift and deposit were performed as part of a combined task rather than a single task, less peak spinal loading and cumulative spinal moments were observed (Harari et al., 2019; Straker et al., 1997). This suggests that studies of single tasks such as symmetric lifting may have limited ability to predict spine loading and kinematics during a combined MMH job. Many studies have focused on symmetric lifting with fixed feet positions and on participants without experience in MMH, which hampers the representativeness of a work setting. To study a more ecological MMH job and obtain more external validity, lift and deposit tasks should be combined and assessed without restrictions on the feet position and handling technique.

Furthermore, the previously reported factors were often considered in isolation, and their combined effects were not exhaustively investigated especially with transfer distance or with pace. Interactions can help to identify work contexts that accentuate risks of injuries. The interaction between handled mass and height has been studied, showing that the greater spine loading obtained when increasing handled mass is much less pronounced at mid-body heights than near the floor (Harari et al., 2019; Hoozemans et al., 2008; Lavender et al., 2003; Marras et al., 1999; Plamondon et al., 2012). However, the other interactions have not been extensively examined such as transfer distance with height or pace with handled mass and their influence on spine loading.

Hence, the objective was to determine the combined influence of transfer distance, working pace, handled mass and lift-deposit height on spine loading and posture during free box transfer. Working pace was hypothesized to interact with handled mass, lift-deposit height and transfer distance, where the effect of the faster pace would be accentuated by mass, height and distance. It was also hypothesized that the decreased transfer distance between lift and deposit locations would exacerbate the spine asymmetric loading when combined with a heavier handled mass and a lower lift-deposit height.

2. Methods

2.1 Subjects

Seventeen participants (2 women, 15 men, mean ± SD body mass 82 ± 15 kg, height 175 ± 8 cm, age 36 ± 10 years) completed a consent form approved by the Université Laval Ethics Committee prior to participation in the study. Inclusion criteria were a good physical capacity according to the Physical Activity Readiness Questionnaire (PAR-Q), no musculoskeletal disorder affecting work or present in the last seven days according to the Nordic questionnaire, and work experience in MMH varying between 0.5 and 5 years (mean ± SD of 2.2 ± 1.3). Exclusion criteria were a BMI over 30 and age over 60 years.

2.2 Instrumentation

Whole-body kinematics were recorded at 30 Hz with an eight-camera Optotrak Certus system (Northern Digital Inc., Waterloo, Canada). Optical markers were grouped in three to form rigid clusters and attached with straps to hands, forearms, arms, head, thighs, shanks and feet (Fig. 1). Mounting blocks were fixed on the skin with medical adhesive on top of the acromion, at the T6-T7 level and at the S1-S2 level where the scapulae, back and pelvis clusters were attached (Fig. 1). The clusters were placed over the bony surfaces of body segments, rather than on the muscle part to reduce soft tissues artefact. The markers were connected to a strober placed on a belt that transmitted the data wirelessly. Ground reaction forces were retrieved at 1000 Hz from a home-made force platform (size 190 x 130 x 18 cm) composed of six force sensors (model MC3A-6-1000; Advanced Mechanical Technology Inc., Watertown, MA, USA). Three digital cameras recorded the trials from different views. The Optotrak system sent a trigger signal to the other systems for synchronization purposes.

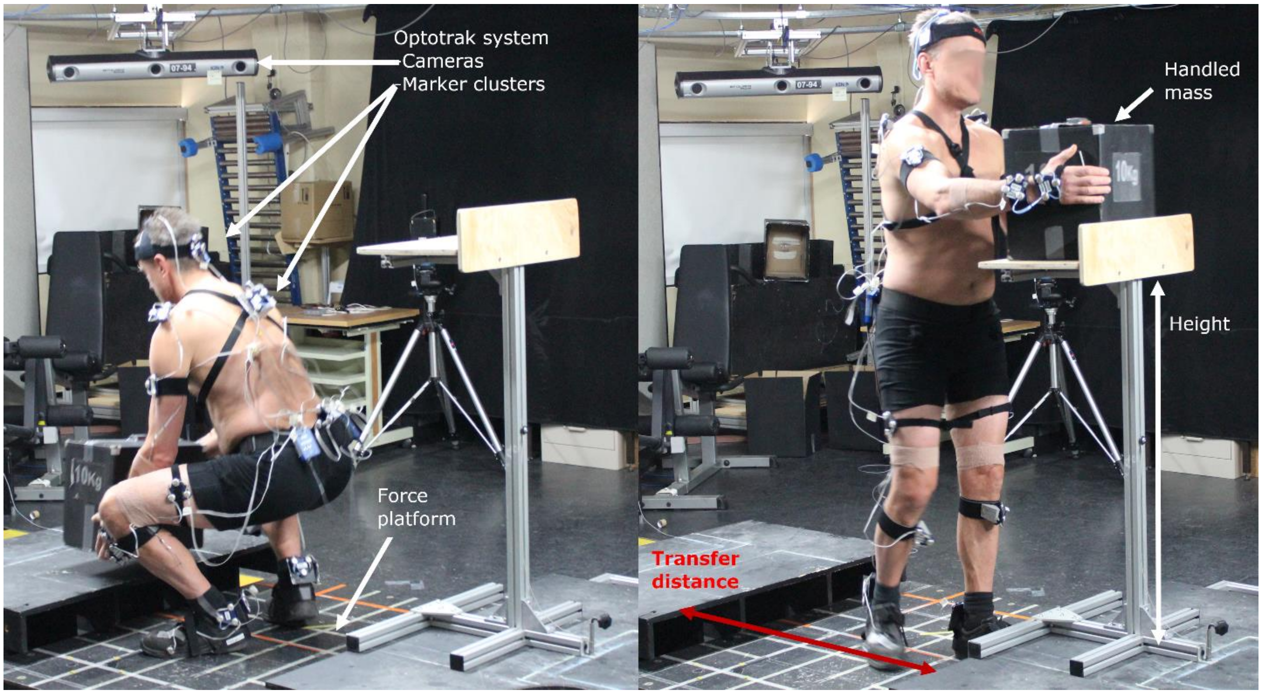

Fig. 1 Experimental setup and instrumentation of the subject.

2.3 Experimental protocol

Forty-eight anatomical landmarks complying with the International Society of Biomechanics recommendations (Wu et al., 2002; Wu et al., 2005) were identified with a probe from the Optotrak system during a static neutral posture. The task consisted in lifting a box from a pallet, carrying it and depositing it on another pallet on the opposite side of the force platform. The participant always started on the opposite side from the box facing the deposit pallet. When the start signal was given, the participant turned around, picked up the box, carried it and deposited it on the other pallet. Then the participant returned to face the pallet where the box originally was. Four repetitions of this sequence were executed for each of the 48 experimental conditions, for a total of 192 handled boxes. A few practice trials were done with a 2-kg box for approximately three minutes to familiarize the subject with the task until he felt comfortable. No further instructions were provided with regards to foot placement or handling technique; the participants were free to choose their movements or adapt them to the situation.

Four external conditions (height, distance, mass and pace) were controlled during the experiment. Two heights—16 cm and 116 cm—were used, resulting in four height conditions for lift and deposit (low-low, low-high, high-low and high-high). Subjects were given three transfer distances between pallets: 0.5 m, 1.0 m and 1.5 m. Two boxes (26 × 33 × 34 cm) of different masses, 10 kg and 20 kg, were handled. Finally, the pace varied between a self-selected speed and a normalized faster pace. First the tasks were executed at a natural free pace. The total time taken to achieve the task was recorded for each distance without informing the subject and the average duration of a repetition was calculated. Then a 25% faster time was imposed for each distance, with sounds indicating the start and end of every repetition. The trials always started with the longer distance between the pallets and progressed towards the shorter distance. The order of the other conditions was randomized between the subjects for each distance.

Some breaks of approximately one minute were given when the operators had to modify the setup for the next trial. To avoid fatigue, subjects rated their perceived exertion level with the Borg-20 scale (Borg, 1982). When the rating of perceived exertion surpassed 11/20, a two-minute break was given. If the rating still increased after the next trial, a three-minute break was given, otherwise the subject had the usual one-minute break. The subjects were not informed of this procedure in an attempt to obtain more valid ratings of perceived exertion.

2.4 Data analysis

A segmental biomechanical model, composed of 16 rigid segments linked by 15 joints corresponding to 37 degrees of freedom, was built with CusToM, a customizable toolbox developed in Matlab enabling musculoskeletal analysis (Muller et al., 2019). The geometrical parameters were subject-specific calibrated using motion capture data and an optimization-based method (Puchaud et al., 2020). The optimization-based calibration is commonly used for the full body in biomechanics and is notably used in the OpenSim (Fregly et al., 2007) and AnyBody Technology (Reinbolt et al., 2008) softwares. Body segment inertial parameters were estimated from anthropometric tables (Dumas et al., 2007). From the positions of the 48 anatomical landmarks obtained from the positions of the rigid clusters on each segment, joint coordinates were computed in an inverse kinematics step with multibody optimization (Lu and O'Connor, 1999) and then filtered with a 4th-order Butterworth low-pass filter with a cutoff frequency of 6 Hz and no phase shift. Inverse dynamics method was used in a bottom-up approach from the ground reaction forces to estimate the L5/S1 moment.

From the three views of the digital cameras, an observer identified the lift and deposit instants. The lift was defined as the instant when the box lost contact with the pallet and the deposit when the box initiated contact with the other pallet. The transfer phase started at the lift instant and ended at the deposit instant. For every handled box, spine loading was estimated during the transfer phase.

2.5 Statistical analyses

Several dependent variables were observed separately in the statistical analyses. Peak and cumulative loading were measured as they are both related to the risk of low back injuries

(McGill, 1997). Peak values of the resultant moment at the joint L5/S1 were computed from the vector sum of the three external moment components (extension, lateral bending and torsion) and peak values of the asymmetric moment from the vector sum of the lateral bending and torsion components. The occurrence of the peak was normalized as a percentage of the transfer phase, where 0% and 100% represent the lift and deposit instants. The peak values were extracted during the lifting phase, which was from the lift instant (0%) to the middle instant between lift and deposit (50%). Cumulative loading during transfer (0% to 100%) was measured with the area under the moment curve and was computed for the resultant and asymmetric angular impulse at the L5/S1 joint. The duration of the transfer or flight time was retrieved between the lift and deposit instants. At the instant of the peak resultant moment, lumbar 3D joint angles between L5/S1 and T6 (absolute for right or left lateral bending and torsion), trunk inclination relative to the vertical axis, mean flexion of right and left knee and horizontal distance between the center of the hands and the L5/S1 joint (moment arm) were extracted.

The third repetition was deemed most representative of the worker's technique and was kept for the statistical analyses, unless there was a problem with the quality of the data, such as marker occlusion. Otherwise, either the fourth, second or first repetition was selected, in that order. Parametric tests were used, as the normality of the distribution was verified with Lilliefors tests. Separate four-way repeated measures analyses of variance were conducted on the dependent variables with the factors of height (low to low, low to high, high to low and high to high), distance (1.5 m, 1.0 m and 0.5 m), handled mass (10 kg and 20 kg) and pace (free and fast). Bonferroni post hoc tests were carried out when height or distance was significant. When sphericity was not met according to Mauchly's test, the Huynh-Feldt correction was applied. The significance level was set to $\alpha = 0.05$.

3. Results

The results focus on significant interactions; any interaction or variable not presented was not significantly different. The complete statistical results are available in the Supplementary material.

3.1 Transfer distance

Interactions between distance and height (Fig. 2) were observed on most of the dependent variables ($P \leq 0.05$, partial $\eta^2 > .150$). The main effect of distance ($P < 0.001$, partial $\eta^2 > .450$) showed substantial increases at 1.5 m in cumulated resultant and asymmetric loading for all heights reaching 28% compared to 1.0 m or 0.5 m. For transfers of the same height (low-low and high-high) at 0.5 m in comparison to 1.0 m, the resultant and asymmetric peaks decreased by approximately 8% and the cumulative resultant and asymmetric loading decreased by 15% and 43%, respectively.

Duration increased progressively with distance for low-low transfers, which explains the reduction in cumulative loading. Duration remained similar between 0.5 m and 1.0 m for the other transfers. The cumulative loading reduction during high-high transfers at 0.5 m was related to the lesser peak moment obtained in this condition.

Generally, the 0.5 m distance showed the most reduction in spine loading. At closer range, subjects made more direct transfers especially for low-low transfers by delaying the occurrence of the peak moment and using more lumbar flexion and less knee flexion with a marked difference of 11° between 0.5 and 1.0 m. However, more distance proved effective to reduce the spine peak loading by up to 8% when transfers varied in height. In addition, resultant and asymmetric cumulative loadings were similar between 1.0 m and 0.5 m for transfers varying in height, while they progressively increased with distance for transfers of the same height.

An interaction between distance and mass on resultant angular impulse was observed ($P < 0.001$, partial $\eta^2 = .412$). The 20-kg box induced more peak, cumulative and asymmetric spine loading ($P < 0.001$, partial $\eta^2 > .800$), but this increase was more pronounced for longer transfer distance (27%, 30% and 32% for 0.5, 1.0 and 1.5 m, respectively).

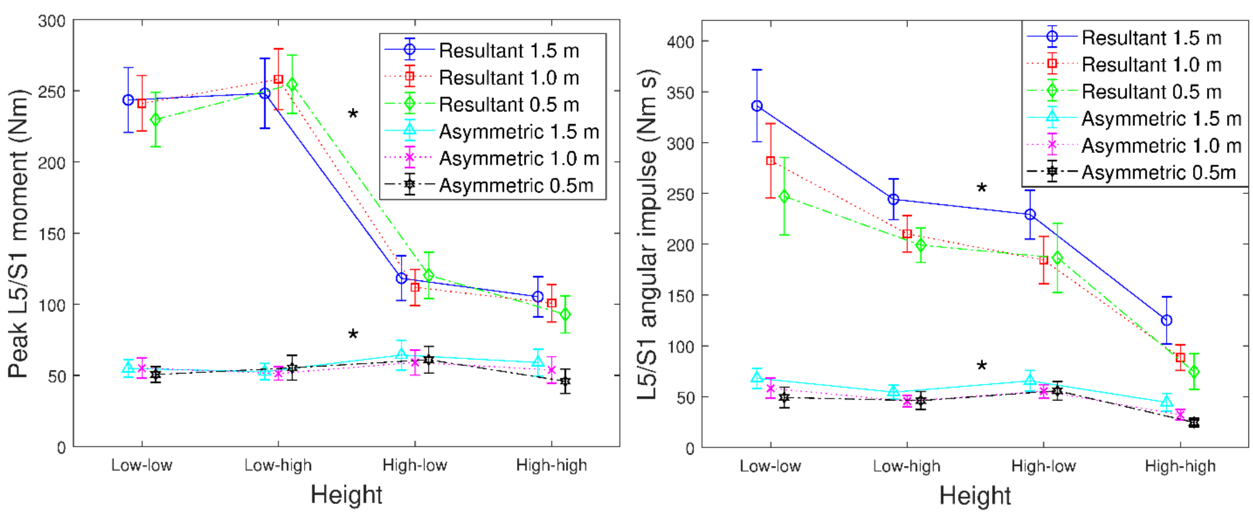

Fig.2 L5/S1 resultant and asymmetric peak moment (Nm) and angular impulse (Nm s) marginal mean ± 95% confidence intervals to emphasize the interaction between box height (low-low, low-high, high-low and high-high) and transfer distance (1.5, 1.0 and 0.5 m) where significance at $P \leq 0.05$ was identified (*).

Table 1. Marginal means of dependent variables, including L5/S1 external moments and posture for each factor and the associated P values of the main effects tested in the repeated measures four-way analysis of variance; significance is identified in bold and significant post hoc tests in superscript

Factor / Variable	Mass		Height*				Distance*			Pace	
	10 kg	20 kg	L-L	L-H	H-L	H-H	1.5 m	1.0 m	0.5 m	Free	Fast
L5/S1 resultant peak moment (Nm)	160	194	238^{a}	254^{b}	117^{c}	100^{d}	179	178	174	174	180
	<.001		**<.001**				.224			**.013**	
L5/S1 resultant angular impulse (Nm s)	170	231	288^{a}	218^{b}	200^{c}	96^{d}	234^{a}	191^{b}	177^{c}	217	183
	<.001		**<.001**				**<.001**			**<.001**	
L5/S1 resultant peak moment occurrence (%)	10	11	9^{a}	9^{ab}	19^{b}	6^{a}	10^{ab}	8^{a}	14^{b}	10	12
	.396		**.003**				**.008**			.293	
L5/S1 asymmetric peak moment (Nm)	49	62	54^{ab}	53^{ab}	61^{a}	53^{b}	58	55	53	51	59
	<.001		**.014**				.088			**<.001**	
L5/S1 asymmetric angular impulse (Nm s)	44	56	58^{a}	49^{b}	59^{a}	34^{c}	58^{a}	48^{b}	44^{b}	51	48
	<.001		**<.001**				**<.001**			.064	
L5/S1 asymmetric peak moment occurrence (%)	14	15	19^{a}	15^{ab}	15^{ab}	8^{b}	17	14	11	15	13
	.622		**.012** ^{c}				.055			.437	
Lumbar flexion (°)	26	25	44^{a}	40^{a}	12^{b}	6^{c}	24^{a}	27^{b}	27^{ab}	25	27
	.204		**<.001**				**.018**			**.026**	
Lumbar lateral bending (°)	6	6	6^{ab}	6^{ab}	7^{a}	4^{b}	5	6	6	5	6
	.669		**.029**				.195			.097	
Lumbar torsion (°)	13	13	7^{a}	11^{ab}	18^{c}	15^{bc}	12	12	14	10	15
	.889		**<.001**				.209			**.019**	
Trunk inclination (°)	46	45	76^{a}	73^{a}	21^{b}	13^{c}	43^{a}	45^{a}	49^{b}	45	47
	.183		**<.001**				**<.001**			.054	
Knee flexion (°)	39	44	60^{a}	64^{a}	22^{b}	19^{b}	45^{a}	42^{a}	37^{b}	44	39
	.027		**<.001**				**<.001**			**.004**	
Duration (s)	1.7	1.8	2.1^{a}	1.8^{b}	1.8^{b}	1.4^{c}	2.2^{a}	1.6^{b}	1.5^{c}	2.0	1.6
	.026		**<.001**				**<.001**			**<.001**	
Moment arm (cm)	45	42	52^{a}	51^{a}	35^{b}	35^{b}	43	44	43	42	44
	<.001		**<.001**				.444			**.007**	

* Different subscripted letters indicate that the pairwise comparisons are significantly different

3.2 Work pace

The interaction between distance and pace on L5/S1 resultant angular impulse and duration ($P < 0.05$, partial $\eta^2 > .150$) showed that the reduction in cumulative loading due to pace as related to the lesser duration (Table 1) was more pronounced with distance (Fig. 3). Since duration was much longer at the 1.5 m (Table 1), pace showed more influence on the spine cumulative loading in this condition. A three-way interaction between pace, height and mass was observed on resultant L5/S1 angular impulse ($P = .017$, partial $\eta^2 = .189$). The cumulative loading reduction with pace (Table 1) was also more pronounced with the heavier handled mass (Fig. 3). Similarly, lower height of lifting and depositing accentuated the cumulative loading reduction observed with pace (Fig. 4). An interaction between mass and pace (Fig. 3) was revealed on the peak asymmetrical moment ($P < 0.001$, partial $\eta^2 = .551$) indicating that the increase at the faster pace (Table 1) was more pronounced with the 20-kg box (28%) than the 10-kg box (20%). In addition, the increased spinal asymmetric peak loading due to pace was related to subjects using more lumbar torsion to achieve the task at a faster pace (Table 1). Finally, a main effect of pace showed increases in L5/S1 resultant peak loading, which was associated to a superior moment arm, more lumbar flexion and less knee flexion at the faster pace (Table 1).

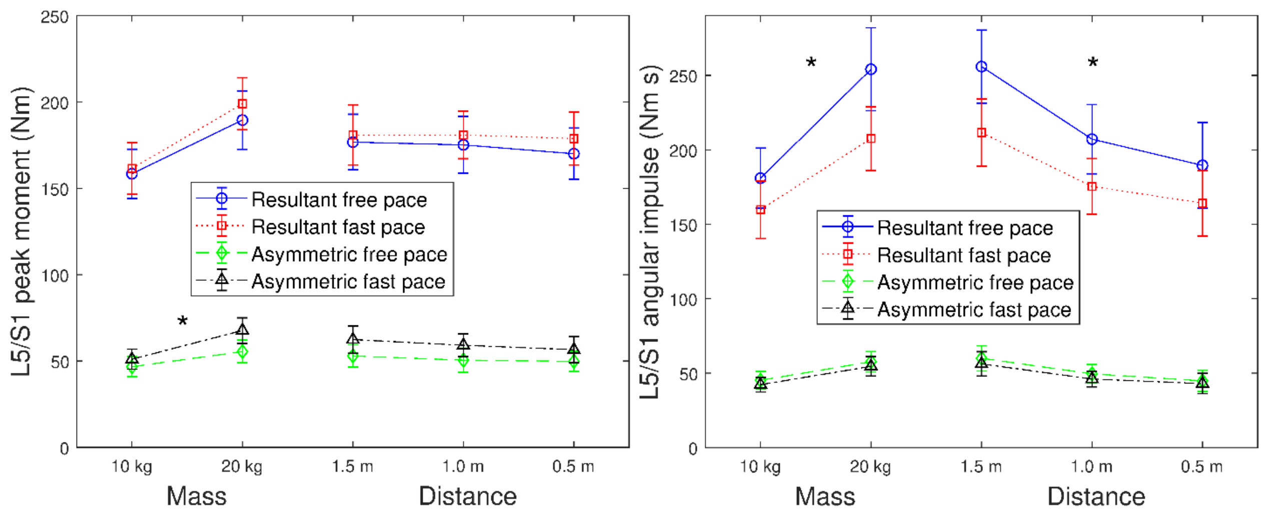

Fig.3 L5/S1 resultant and asymmetric peak moment (Nm) and angular impulse (Nm s) marginal mean ± 95% confidence intervals to emphasize the interaction between pace (free and fast) and handled mass (10 kg and 20 kg) and the interaction between pace (free and fast) and transfer distance (1.5, 1.0 and 0.5 m) where significance at $P \leq 0.05$ was identified (*).

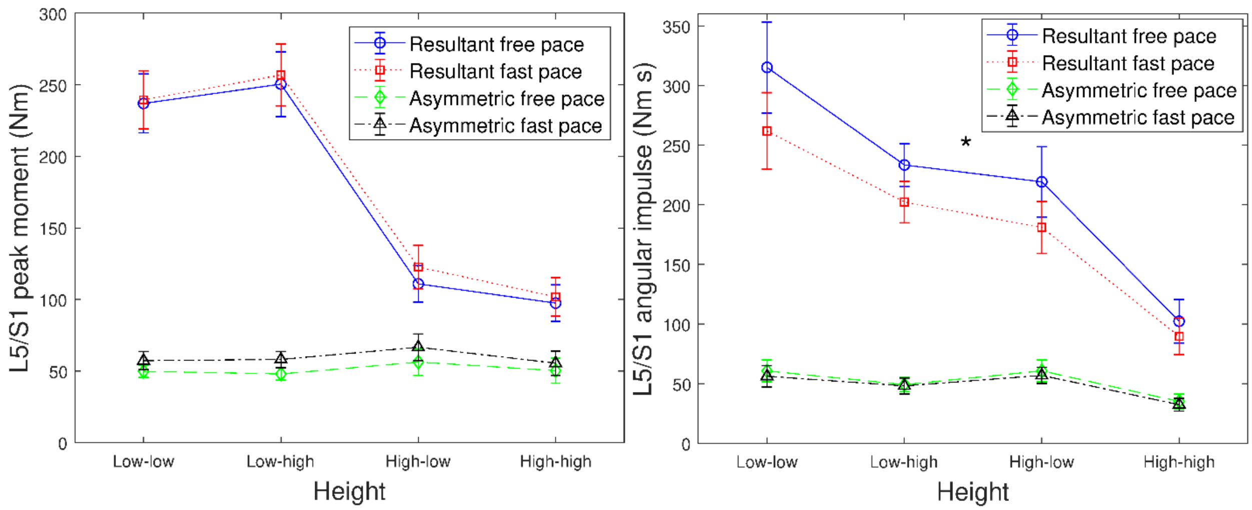

Fig.4 L5/S1 resultant and asymmetric peak moment (Nm) and angular impulse (Nm s) marginal mean ± 95% confidence intervals to emphasize the interaction between pace (free and fast) and box height (low-low, low-high, high-low and high-high) where significance at $P \leq 0.05$ was identified (*).

3.3 Box height and handled mass

Interactions between mass and height (Fig. 5) were observed on the spine resultant peak moment and angular impulse, asymmetric angular impulse, flexion and lateral bending lumbar angles, and duration ($P \leq 0.01$, partial $\eta^2 > .200$). The main effects of mass (Table 1) showed that the heavier box increased all loading variables, duration, knee flexion and decreased moment arm. The main effects of height were observed on all dependent variables (Table 1) showing that lifting from a lower location increased spine loading, joint angles, duration and moment arm. The combined effect of mass and height showed an exacerbation of spine loading and duration when lifting the 20-kg box from a lower location, but a decrease in lumbar flexion.

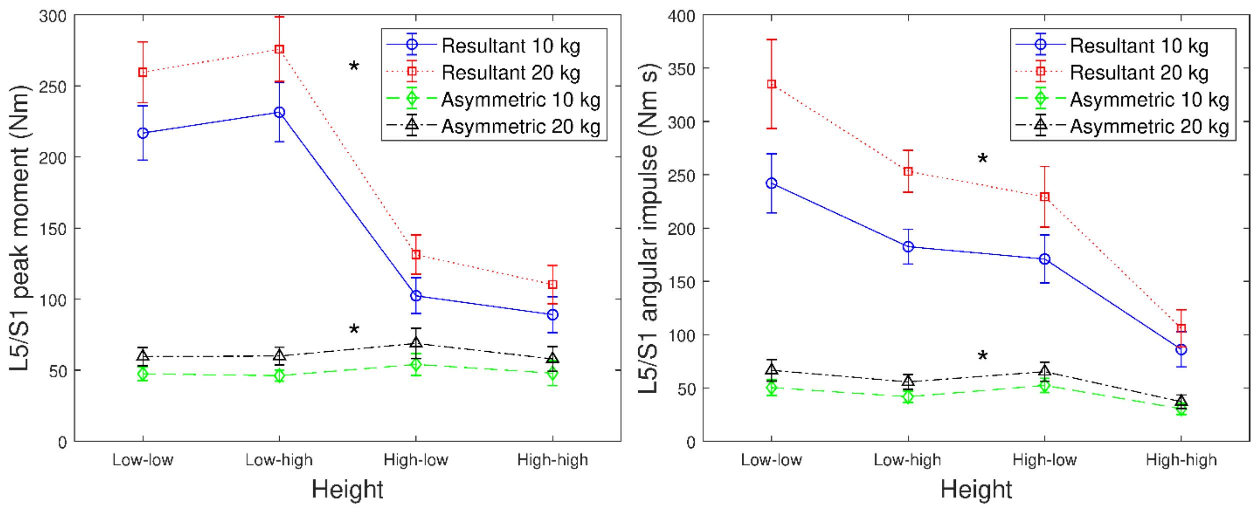

Fig.5 L5/S1 resultant and asymmetric peak moment (Nm) and angular impulse (Nm s) marginal mean ± 95% confidence intervals to emphasize the interaction between box height (low-low, low-high, high-low and high-high) and handled mass (10 kg and 20 kg) where significance at $P \leq 0.05$ was identified (*).

4. Discussion

4.1 Transfer distance

Reducing the transfer distance represents a proper intervention to decrease cumulative spine loading. Moreover, for transfers of the same height, reducing the distance led to inferior peak spine loading. At close range without height differences between the pallets, many subjects opted for a more direct handling technique. For the close low-low box transfers, handlers showed more trunk inclination and lumbar flexion, and less knee flexion and handling duration, which agrees with previous studies (Kim et al., 2014; Mehta et al., 2014). This handling technique maintained the box lower to decrease handling time and cumulative loading and to minimize the vertical displacement of the box during the lifting phase, which lowered the peak loading. On the other hand, these postural differences indicate that the subjects were changing towards a stoop technique (although not using the stoop technique per se). The stoop technique—compared to other techniques such as squat— showed similar peak spine loading but may increase the strain on the passive structures of the spine (Bazrgari and Shirazi-Adl, 2007; Bazrgari et al., 2007; Dolan et al., 1994b; Kingma et al., 2004; Kingma et al., 2006). For low-low transfers at 1.0 m or more, handlers opted for less direct transfers where they lifted the box and then lowered it towards the deposit location, most likely because steps where required, which resulted in more spine loading. Similarly, for close high-high transfers, the box was maintained at 1.16 m during the transfer to allow a direct handling technique reducing peak and cumulative spine loading.

Whereas for further distances, subjects carried the box at a comfortable mid-body height, which created vertical displacement of the box increasing both peak and cumulative loading.

However, the interaction of height and distance indicated that box transfers differing in height (vertical distance greater than 0 m) had more impact on spine loading for closer distance. When box transfers differed in height between pallets (low-high and high-low), this created more maximal spine loading (3% to 8%) for the shortest distance than the other two distances. Even cumulative loading, which usually increased with distance, showed decreases (2%) from 0.5 m to 1.0 m for high-low transfers. These results indicate that 0.5 m may in some conditions be considered a space restriction, which limits the handler's possible motor control strategies of achieving the task. When the box has to cover more vertical displacement, it reduces the likelihood of a direct transfer technique as described for transfers of the same height. In these conditions, it appears that the combination of short distance and height difference of the task reduced the handling technique possibilities. The distance reduction can become more constraining than helpful when it reaches a certain point, as some movements to turn around are restricted by the available space. It seems that the handlers can benefit from distance to adapt their handling technique and footstep strategies when the task is more complex.

These combined results suggest that a transfer distance between 0.5 m and 1.0 m may be best suited to reduce overall spine loading. In comparison, 1.5 m was too far, which significantly increased cumulative loading without reducing peak loading. While 0.5 m generally reduced the most spine loading especially for box transfers of the same height, it was less appropriate for box transfers varying in height where the L5/S1 peak loading was more pronounced and cumulative loading was similar to 1.0 m. It would be relevant to test a 0.75 m distance between lifting and deposit location with a similar experimental protocol, since it would potentially be optimal to reduce spine loading when box transfers vary in height. This recommendation of a transfer distance between 0.5 m and 1.0 m based on back loading and posture is smaller than previous recommendations between 1.0 m and 1.25 m based on posture (Kim et al., 2014; Mehta et al., 2014). It could help handlers in their work organization decisions such as placement of the pallet truck, cart or hand trolley approximately 0.75 m from the product location. This distance can also serve as a guideline in the engineering of workplace design.

4.2 Work pace

The effect of a faster pace to reduce resultant angular impulse by 34 Nm s (17%) was accentuated by distance, height and mass as hypothesized. Lower box height, heavier handled mass and longer distance combined with the faster pace allow to further decrease spine cumulative loading. These latter conditions with longer durations have more potential for a reduction of cumulative loading by achieving the task faster. It indicates that adopting a faster work pace was more beneficial to reduce risks of injuries when the conditions present high cumulative loading. In counterparts, a faster pace could increase the physiological cost and induce superior lower limb loading. In addition, the faster pace increased the peak moment especially in asymmetry by 8 Nm

(15%) and the heavier handled mass exacerbated this effect. At the faster pace, handlers used 5 º more of lumbar torsion, which had more impact on the peak asymmetric loading with the 20-kg box. Hence, caution with postural asymmetry is warranted when combining a faster pace and heavier handled masses. A tradeoff is usually present with lifting speed increasing peak and decreasing cumulative spine loading; for this reason, determination of the optimal speed or pace remains difficult (Bernard et al., 1999).

As in previous studies on lifting, speed significantly increased the L5/S1 peak resultant moment. However, the magnitude of the increase (3%) during the faster transfer task was much smaller than during lifting (approximately 10 to 37%) (Bernard et al., 1999; Bush-Joseph et al., 1988; de Looze et al., 1994; Gagnon and Gagnon, 1992; Lavender et al., 2003; Lavender et al., 1999). This difference suggests that the subjects could have lifted at relatively similar speeds but had carried the box towards the deposit location with more speed at the faster pace. Hence, the lifting speed was calculated at the instant of resultant peak moment with the midpoint trajectory of the two hands, which was assumed to be the box position. The mean lifting speed was even slightly faster for the free pace at 0.8 m/s compared to 0.7 m/s for the fast pace. This indicates that the increase in resultant peak is mostly attributed to the increase in asymmetric components and postural adaptation with greater moment arm.

Another study examined the effect of transfer distance on posture; however, since work pace was controlled with lifts per minute, the subjects were moving faster for longer distances, which led to more lumbar amplitude, velocity and acceleration than the closer transfers (Jorgensen et al., 2005). Conversely, the present study controlled the task speed with the duration, but not lifts per minute (i.e. for longer distances, the same task speed was achieved, but fewer lifts per minute were made). Hence, the greater lumbar flexion and torsion observed at faster speed agrees with the previous study (Jorgensen et al., 2005). The handlers using more lumbar torsion and flexion and less knee flexion at the faster pace indicate that the whole body posture was adapted. Potential explanations are that the subjects had less time to position themselves for the lifting phase or that they adopted a posture allowing a more direct transfer.

The main findings suggest that increasing the work pace may not increase lifting speed to the same magnitude, but still impacts postural asymmetry. To determine the optimal work pace, more variations should be tested. If a faster pace had been tested where the participants had to adopt a faster lifting speed, the peak loading would most likely increase at greater extent. Taken together, the results indicate that maintaining a relatively low lifting speed and adopting a fast transition technique may be beneficial to reduce cumulative spine loading, while maintaining similar levels of resultant maximal loading. However, it must be remembered that the peak asymmetric L5/S1 moment and postural symmetry are still affected by the faster pace especially in combination with a heavier handled mass. In addition, a faster pace will also influence the physiological cost and could hasten fatigue.

4.3 Handled mass and box height

Reducing the handled mass and raising boxes from the floor level remain relevant interventions to reduce spine loading, especially for the peak moment. However, when the mass of 42.7-kg bags of masonry was halved, peak spinal loading decreased by 25%, but cumulative loading increased by 40% (Davis et al., 2010). Similarly, our results indicate that handling two 10-kg boxes leads to 47% more cumulative loading than handling one 20-kg box, which increased the peak loading by 21%. The interaction with height further showed that this effect was more pronounced at greater lifting height. The optimal mass for handled objects implies a tradeoff between risks of overexertion (peak) and fatigue failure (cumulative). Both aspects are important to maintain a margin of safety between the applied load and the failure tolerance of human structures, which lowers after cumulated lifts at work (McGill, 1997). Packaging products in many boxes of smaller masses may not be the best approach, as it will induce more trunk dynamics and repetitive loadings due to the mass of the trunk when bending. Nevertheless, as the interaction between mass and height indicated, the mass has a lesser influence at a height of 1.16 m, so situating the lifting location for heavier objects at mid-body height according to the deposit location remains an interesting approach in terms of musculoskeletal disorders prevention (Corbeil et al., 2019; Harari et al., 2019; Lavender et al., 2003; Plamondon et al., 2012).

Posture differences were mostly related to bending for lower boxes. Interestingly, the low-high and high-low tasks were executed in approximately the same duration, but the high-low condition obtained more cumulative asymmetric loading by 19% and less cumulative resultant loading by 9%. For the high-low condition, the handler can use gravity to release the box or guide it towards the deposit location (Denis et al., 2013), which reduced trunk inclination and resultant spinal moment. On the other hand, this technique accentuated asymmetry with 19% more asymmetric cumulative loading and 7º more lumbar torsion.

A novel result regarding height is the influence of the deposit location on back loading and posture during the lifting phase contrary to a previous study showing no effect (Harari et al., 2019). This discrepancy could be attributed to a combination of differences in handled mass, distance, height, handles and handling experience of the subjects. The peak moment from the same lifting location increased by 12% when the deposit was achieved at a different height, which indicates that the handler adapts his lifting technique according to the deposit location. The high-low compared to the high-high condition delayed the occurrence of the peak moment and increased lumbar flexion and lateral bending, and trunk inclination, which contributed to peak moment increase. The low-high condition obtained the most peak resultant moment, but the low-low condition obtained 28% more cumulative loading. For low-high box transfers, the work performed for lifting was used to make a faster transition towards the deposit location, which reduced handling duration and cumulative loading, but increased peak loading probably due to more lifting velocity.

4.4 Limitations

Many external work factors were considered, but the initial horizontal distance of the box on the pallet and the type of handled boxes were not considered. Personal factors such as gender, age, physical capacity, expertise, lifting technique and footstep strategies were not investigated. The biomechanical model measured spinal moments, but an internal model providing forces on the intervertebral disk and muscles forces and coactivation could provide more insight to this study. Given the sample size and number of factors, a modest statistical power can be expected. The selection of one repetition could introduce a few outliers, but trials were inspected to ensure that a representative technique was analyzed. Finally, it would be relevant to verify the same factors directly in the workplace with portable magnetic and inertial measurement units (Robert-Lachaine et al., 2020a; Robert-Lachaine et al., 2020b), although the same control of experimental conditions would be difficult.

5 Conclusion

As hypothesized, the 1.5 m distance between pallets induced more spine cumulative loading that could be avoided. Amongst the tested experimental conditions, 0.5 m most reduced the risk of injury in terms of spine loading. However, more distance showed benefits for the spine loading during transfers varying in height. Reducing handled mass and lifting height remain relevant interventions for decreasing spine loading during box transfers. A faster working pace reduced cumulative and increased peak asymmetric loading, which was accentuated by mass, height and distance as hypothesized. A faster transition technique appears appropriate to reduce cumulative spine loading when lifting speed remains similar, but asymmetric loading and posture were increased especially with heavier handled mass. The tested working conditions revealed the importance of tradeoff between low back peak, cumulative and asymmetric loading. Handlers adapted their working technique according to height, mass, distance and pace in an attempt to reduce their effort and overall risk of musculoskeletal disorders.

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