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Biomechanical and ergonomic impacts of handling in obese workers

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Sustainable Prevention and Work Environment

Studies and Research Projects

REPORT **R-825**

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Biomechanical and Ergonomic Impacts of Handling in Obese Workers

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SUMMARY

Obesity is an emerging problem that seems to be a risk factor in occupational health and safety. Musculoskeletal injuries are more frequent, and their indirect (non-medical) costs higher, in obese individuals than in workers having a healthy weight. Given that the obesity rate among Canadian workers is steadily rising, it is important to look at the issue of obesity in the workplace. The risk of back injury during work remains very high today, and the occupation that generates the most injuries is that of manual materials handler. There are few data on how obesity affects the ways in which handling tasks are carried out. The purpose of this study is to analyze the work strategies of obese handlers and compare them with those of healthy-weight handlers.

The biomechanical and ergonomic impacts in 17 obese and 20 healthy-weight handlers were evaluated in the laboratory. The task studied consisted in moving boxes from a conveyor to a hand trolley and back. The weight of the load, the lifting height and the lifting task configuration were varied so that we could study the participants' work methods. We took several biomechanical measurements—including moments acting on the back, posture and box displacement—that would enable us to judge the safety and efficiency of the handling methods observed.

The results clearly show that the anthropometric characteristics of obese handlers are linked to a significant increase (> 23%) in peak lumbar loading during lifting and lowering of boxes from and onto a hand trolley or conveyor. Due to the large variations between individuals, we observed few postural differences between the two groups. The handlers' weight explains 57% of the variation in peak extension moment on the back during lifting of a box from the ground.

These results suggest that the excess weight of an obese worker has a significant added effect on the musculoskeletal structures of the back, which exposes obese handlers to a higher risk of developing a musculoskeletal disorder (MSD) during load handling.

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1 INTRODUCTION

1.1 Occupational health and safety issue and objective

Obesity is an emerging problem that seems to amplify occupational health and safety issues. After monitoring over 10,000 workers for nearly seven years, Ostbye et al. (2007) showed that the number of work days lost because of temporary disability was five times higher for obese workers. Such disabilities are due to injuries at work, especially ***musculoskeletal disorders*** (MSDs) of the back. Given that the obesity rate among Canadian workers is steadily rising, it is important to look at the issue of obesity in the workplace. The risk of back injury during work remains very high today, and the occupation that generates the most injuries is that of manual materials handler. There are few data on how obesity affects the ways in which handling tasks are carried out.

1.2 Obesity rates in the general population and among workers

Obesity and overweight rates are rising rapidly in the Québec population. The term "epidemic" — generally reserved for contagious diseases—is used by the World Health Organization to describe the sudden, rapid weight gain of populations. This epidemic afflicts the entire Western world, including Québec. In 2003, 14% of Quebecers suffered from obesity (BMI[1] ≥ 30) and 33% were overweight (25 ≤ BMI < 30) (Mongeau et al., 2005). The incidence of excess weight and obesity in Québec adults climbed from 43% in 1990 to 56% in 2004 (Audet, 2007). What is worrisome is that people who have excess weight tend to become obese eventually. In one study, nearly a quarter of the people who had been overweight were obese eight years later (Le Petit and Berthelot, 2005).

In 2005, more than two million Canadian workers aged 18 to 64 were obese. Obesity among Canadian workers has increased, rising from 12.5% in the mid-1990s to 15.7% in 2005. After adjustment to focus on people aged 18 to 64 and holding a blue-collar job, the obesity rate was 19.2% for men and 16.1% for women. Obesity was more frequent among older workers (55 to 64): 17% in 1994-1995, 19% in 2000-2001 and 21% in 2005. In comparison with other workers, obesity was more frequent among men whose day-to-day activities or work routines included performing exhausting tasks or carrying very heavy loads. Moreover, obese men were more likely than their normal-weight co-workers to state that their work required a lot of physical effort.

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1. BMI = body mass index, a measure for human body fat. It is calculated by dividing the person's weight in kilograms by the square of his or her height in metres.

1.3 Obesity as an emerging risk factor

Manual materials handlers play a critical role in the world economy, but many of them suffer from injuries or disorders related to the physical nature of their work. In fact, there is a moderate to high correlation between manual handling and back injuries (Liira et al., 1996; Magnusson et al., 1996; Bernard, 1997; Burdorf and Sorock, 1997; Gardner et al., 1999; Kuiper et al., 1999; Hoogendoorn et al., 2000; Vingard and Nachemson, 2000; 2001). Frequent bending and twisting of the trunk, along with the lifting of heavy objects, are thought to increase the risk of back injury. The causes have not been clearly identified, but according to the National Research Council (2001), there is a clear relationship between back disorders and the physical load imposed by manual material handling. The physical load will be tolerated to the extent that the muscle tissue has sufficient capacity to withstand overloading or to adapt to continuous internal loads. If the internal loads exceed the individual's capacity or ability to adapt, there is a high risk of tissue rupture or fatigue, which could give rise to discomfort or pain and could lead to functional incapacity if the situation is not corrected (National Research Council, 2001). Craig et al. (2006) used a multivariate regression model to demonstrate a relationship between the high rate of handlers' injuries at work (n=442) and certain personal, non-occupational risk factors. Among the five risk factors identified in the multivariate analysis, low aerobic capacity and a high percentage of body fat are noteworthy. In another study of 7,690 workers at a U.S. aluminum manufacturing company, of the 2,221 employees who had sustained at least one injury, 85% were classified as overweight or obese. The authors calculated that the odds of injury in the obese group ($30 \leq BMI < 40$) were **2.21** times higher than for healthy-weight workers ($18.5 \leq BMI < 25$) (Pollack et al., 2007). In addition to this higher frequency of injury, several authors report that the indirect (non-medical) costs are higher for obese workers (Finkelstein et al., 2007; Ostbye et al., 2007; Trogdon et al., 2008). The results of a meta-analysis show that obese workers have a rate of absenteeism due to illness, injury or disability that is higher than that of non-obese workers (Trogdon et al., 2008). After monitoring 11,728 employees for nearly seven years, Ostbye et al. (2007) showed that the higher a person's BMI, the higher the medical costs. A similar link has been noted for the cost of indemnity claims (Figure 1).

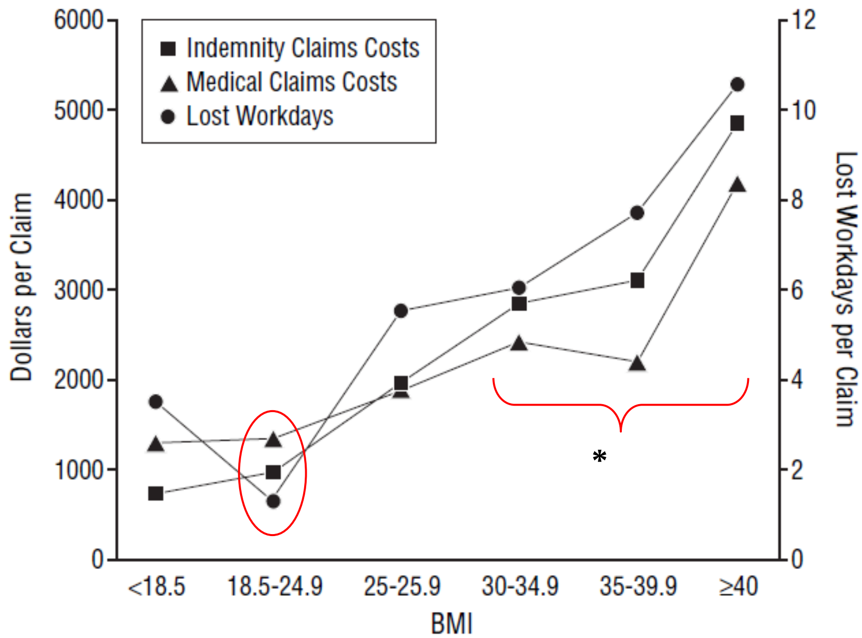


Figure 1 shows mean indemnity claims costs, medical claims costs and number of lost workdays per claim (per 100 full-time equivalents) by body mass index (BMI) category.
Costs are in U.S. dollars. Average values for recommended-weight employees are circled in red, while those for obese employees are indicated by an asterisk. From the study by Ostbye et al. (2007).

Moreover, the number of workdays lost because of temporary disability is reported to be five times higher for employees in obesity class I (30 ≤ BMI < 35) than for their recommended-weight co-workers. The ratio is 8 to 13 times higher for obese employees with a BMI exceeding 35. These disabilities were due to occupational injuries, especially MSDs affecting the back (Ostbye et al., 2007).

It should be noted that in Québec, manual materials handlers have the highest incidence of spinal disorders (n=3743). Québec has 36,650 people with the job title "material handler" (class: Trades, transport and equipment operators), and 89% of them are men (32,695) (Statistics Canada, 2008). Although the number of spinal disorders has steadily decreased—with a relative decline of 16.0% over the 2008–2011 monitoring period (Commission de la santé et de la sécurité du travail du Québec (CSST), 2012)—the average income replacement indemnity (IRI) was $4,140 in 2011, or $295 more than in 2008. For the CSST’s 2008 fiscal year, the total cost for spinal disorders was $540.5 million, compared with $425.6 million in 2000.

1.4 Hypotheses on mechanisms

As stated in a systematic literature review published in 2007, few studies have looked at the mechanisms explaining the link between obesity and the high incidence of occupational injuries (Pollack and Cheskin, 2007). The explanations are based on certain hypotheses that remain to be validated.

Sleep apnea, sleepiness and fatigue can have an impact on alertness and the ability to process information, and can thus be linked to a high risk of occupational injury. In cases of extreme obesity (BMI ≥ 40), some authors report that the subjects are "too tired" or "exhausted" to keep working for extended lengths of time (Duval et al., 2006). Another suggested mechanism is linked to the sometimes precarious health of obese individuals and the use of medication to control health problems (diabetes, heart and lung disease, etc.) (Gilmore et al., 1996).

The link could also be explained by an alteration of functional capacities due to excess weight. "Functional capacities" means our ability to perform the usual activities of everyday life. Our repertoire of daily movements depends on our mastery of basic activities, such as the ability to move around and stay balanced. Such movements are performed over and over throughout the workday. Laboratory studies comparing balance control in obese versus healthy-weight individuals show increased postural sway (as indicated by increased centre of pressure[2] path length for a specified duration), as well as increased effort deployed in performing this task (Handrigan et al., 2010a; Handrigan et al., 2010b; Handrigan et al., 2012; Corbeil et al., 2001; Hue et al., 2007). Weight loss in obese individuals leads to an immediate improvement in postural stability through reduced swaying (Teasdale et al., 2007). Greater effort to control balance also affects the ability to perform tasks requiring accurate and rapid arm movement. In comparing obese and lean subjects, Berrigan et al. (2006) showed that when asked to aim at a target located in front of them (within or beyond their grasp) from an upright standing posture, obese individuals were slower and less accurate than lean individuals. The difference was exacerbated when more precise arm movements were required but was eliminated when the subjects were in sitting position. This suggests that the additional constraints on balance imposed by excess weight could compromise the accuracy of grasping and aiming and thus result in greater error (Berrigan et al., 2006).

Locomotor capacity is also affected by excess weight: researchers observing gait have noted reduced speeds, lower cadence, shorter strides and a wider base of support in obese subjects (McGraw et al., 2000; de Souza et al., 2005). Moreover, the metabolic energy cost of walking (expressed as W/kg)—determined to a large degree by body mass—has been found to be 10% greater (per kg) for obese individuals than for normal-weight individuals. The percentage of

2. Center of pressure is the term given to the point of application of the ground reaction force vector. The ground reaction force vector represents the sum of all forces exerted by the ground on a body in contact with it.

body fat accounted for 43% of the variance in metabolic rate, while mass distribution (thigh mass/body mass) was not significantly related (Browning et al., 2006).

Lower aerobic fitness and muscle strength (Mattsson et al., 1997; Hulens et al., 2001) and reduced anaerobic performance (Lafortuna et al., 2002; Sartorio et al., 2004) have also been posited to explain the substantially lower capacity of obese individuals to work and to perform basic everyday activities (Mattsson et al., 1997). For example, one U.S. study (Tsismenakis et al., 2009) showed that excess weight in emergency responder candidates affected their tolerance for exercise, with 7% of overweight candidates and 42% of obese candidates unable to exercise at a workload of 12 METs,[3] which is the minimum criterion based on expert recommendations for safe performance of firefighter tasks (National Fire Protection Association, 2007). Higher BMI has been associated with significantly higher cardiovascular risk, reduced exercise capacity (Tsismenakis et al., 2009) and poorer balance control (Hue et al., 2007; Hue et al., 2008; Tsismenakis et al., 2009), as well as greater perceived exertion and lactate accumulation (fatigue indicators) during tests involving carrying heavy loads (Barnekow-Bergkvist et al., 2004).

There are two other mechanisms that can explain the link between injuries and obesity, and they are related to ergonomics and personal protective equipment. People with excess weight may be inclined not to use personal protective equipment (or to use it improperly and less regularly) because it is ill-suited to their body shape and causes discomfort. Workstations, too, can be ill-suited to larger body circumferences. Factors related to cognitive load and work organization can also affect the condition of obese workers.

Lastly, classical or Newtonian mechanics would indicate that the greater the weight overload on the trunk, the greater the resultant external load on the musculoskeletal system. It is possible that handlers have developed work methods to compensate for these external loads. For instance, some handlers may opt for safe work methods, i.e., protecting their backs first and foremost, while others may choose methods that will enable them to be more productive and make better stacks. The latter hypothesis was tested in this study.

1.5 Objective

The objective of this study was to compare the strategies of obese and healthy- weight handlers. The general research hypothesis was that the majority of obese handlers ($30 \leq BMI < 35$) would adopt safe handling practices, as evaluated mainly on the basis of variables defining a back load comparable to that of non-obese handlers ($18.5 \leq BMI < 25$). The data gathered in this study were compared against those compiled for the expert/novice project (099-367) with male subjects.

3. MET = Metabolic equivalent: The ratio of metabolic rate (rate of energy consumption) during physical activity to metabolic rate at rest.

2 METHODOLOGY

2.1 Participants

The study group consisted of 17 obese male handlers[4] aged 22 to 52 (height: average = 1.74 m, range = 1.60 to 1.81 m; weight: average = 95.4 kg, range = 75.8 to 107.3 kg; BMI: average = 31.4 kg/m^2, range = 29.6 to 34.6 kg/m^2) and 20 healthy-weight handlers aged 18 to 50 (height: average = 1.75 m, range = 1.62 to 1.85 m; weight: average = 67.5 kg, range = 55.2 to 81.8 kg; BMI: average 21.90 kg/m^2, range = 19.8 to 21.9 kg/m^2) (Tables 3.1 and 3.2).

The participants selected were familiar with the handling tasks in this study (boxes of reasonable size, unconstricted area, etc.). Subjects were recruited over an eight-month period through posters and placement agencies. The criteria for selection were as follows: manual materials handler (as principal task), low occurrence of injuries and no injuries in the past year, and more than one month of experience.

2.2 Setup

The external foot forces exerted during the handling tasks were recorded through an extended force platform (1.90 x 1.40 m) mounted on an AMTI 6-axis load cell (model MC3A-6-1000, Watertown, Massachusetts). The signals were gathered at a frequency of 1024 Hz and then filtered through a second-order, low-pass, zero-phase lag Butterworth filter (cutoff at 10 Hz). Two photogrammetric measurement systems were used to record the three-dimensional coordinates of markers affixed to the skin on the main body segments and to track the movement of the boxes. The first system was made up of infrared diodes (LEDs) affixed to the trunk, with the signals captured by four Optotrak columns (Northern Digital Inc., Waterloo, Ontario). The second system consisted of three video cameras and was used mainly to track the box movements. Both systems used a sampling frequency of 30 Hz. The position data were filtered by means of a quintic spline with a variance of 10, and a variance of 0.02 was selected for derivatives (speed and acceleration). A synchronized signal triggering data collection, controlled by means of an analog data acquisition card, was sent to the various devices. Because of the difference in sampling frequency between the Optotrak system and the force platform, subsampling was done on the force platform data so that it could be combined with the inverse dynamic model.

4. The data for 19 of the handlers are from a previous research study comparing expert and novice handling methods (research project 0099-3670). Of these 19 handlers, five were assigned to the obese group (four experts and one novice) and 14 to the healthy-weight group (five experts and nine novices).

2.3 Experimental protocol

For each participant, we conducted only one experimental session, which included measurement of physical capacities (Part 1) and handling tasks (Part 2).

2.3.1 Part 1: Anthropometric characteristics and physical capacities

In the first part of the session, the main objective was to measure the anthropometric characteristics and physical capacities (strength, endurance) of the participants. The participants were first given a consent form explaining the study procedure and what they had to do. Then they had to fill out the physical activity readiness questionnaire (PAR-Q), designed to screen any health problems preventing physical activity. The participants were measured and photographed for purposes of estimating their anthropometric characteristics using the Jensen method (1978). The anthropometric data were needed for the inverse dynamic model used to estimate the external loads in the second part. For the maximum isometric lifting strength test, the participant was standing, trunk and knees bent, positioned to grasp a handle at knee height (½-stoop and ½-squat; Figure 2.1). This test consisted in exerting maximum extension force against a load cell fixed to the ground (Chaffin et al., 1978; Chaffin et al., 1999). Three tests were conducted, with a two-minute break between each and a warm-up period beforehand. This part of the study was followed by a rest period of 20 minutes to prevent the effects of fatigue from contaminating the results of the second part.

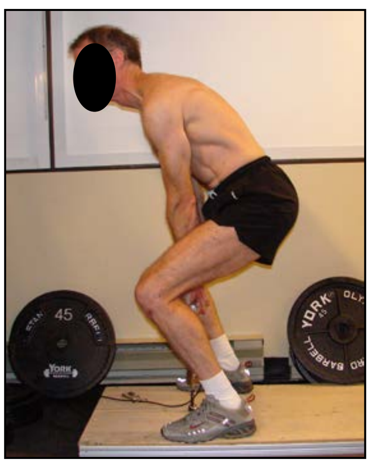


Figure 2.1 General test of maximum isometric lifting strength

2.3.2 Part 2: Handling

The task consisted in transferring boxes, starting with the box facing the subject, to a hand trolley 1.5 m away. One key aspect of our approach is that we allowed participants to proceed as they deemed fit, with no particular instructions. The experimental conditions were realistic in terms of

(1) the difficulties encountered on the job and (2) the conditions that would enable handlers to demonstrate the know-how acquired over time. Subjects were therefore free to use whatever movements they wanted to accomplish the task requested of them in a realistic, asymmetric context (three-dimensional space). Foot movement was not restricted, since a large force platform was used.

The participants were instrumented so that we could gather the measurements needed for the segment biomechanical model. This model was developed over many years of research and has been subjected to extensive validation (Gagnon and Gagnon, 1992; Plamondon et al., 1996; Desjardins et al., 1998). We had to attach 50 markers to 16 body segments: the hands, the forearms, the upper arms, the head, the upper trunk, the lower trunk, the pelvis, the thighs, the legs and the feet. Generally speaking, each segment has to have at least three markers placed on anatomical landmarks used to locate joint centres (Chaffin et al., 1999). The 3D reconstruction of these markers was done with the Optotrak system. The reconstruction error was less than 1 mm. The data were then input into the multisegment model, which was used to determine the kinematic and kinetic parameters needed to calculate the net moments at L5/S1 (extension, lateral bending and twisting moments) (Hof, 1992). The error in these moments is estimated at less than 10 Nm (for more details, see Plamondon et al., 1996). Figure 2.2 shows the box transfer situation studied. Four boxes (26 cm deep x 34 cm wide x 32 cm high) were on a conveyor positioned at the height of a pallet (approximately 15 cm from the ground). The participant had to grab the first box at the end of the conveyor, pull it to him and carry it to a hand trolley. All four boxes had to be stacked on the hand trolley. Participants were free to work at their own pace and use whatever handling techniques they wished. The boxes were as follows: one 15-kg box, one 15-kg box marked Fragile, one 15-kg box with a lateral centre-of-gravity offset and one 23-kg box. These were the same boxes used by participants in the IRSST project on experts vs. novices (Plamondon et al., 2010). The order of the boxes was arranged so that each box was presented twice at the same height. Two conveyor positions were studied: one facing the hand trolley (180°) and 1.50 m away from it, and the other at a 90° angle to the hand trolley, the same distance away (1.50 m).

Each participant performed 128 handling operations: four one way + four the other way = 8 x 2 (180° and 90°) x 4 boxes = 64 x two operations = 128 box transfers. Because a certain amount of muscular fatigue was anticipated, we planned two-minute breaks after each four-box round trip and a five-minute seated break at the halfway point (after 32 round trips).[5] On average, the full session lasted just over 90 minutes.

5. All the handlers participating in Project 099-367 said that this rest time (total of 32 x 2 min = 64 + 5 min = 69) was amply sufficient.

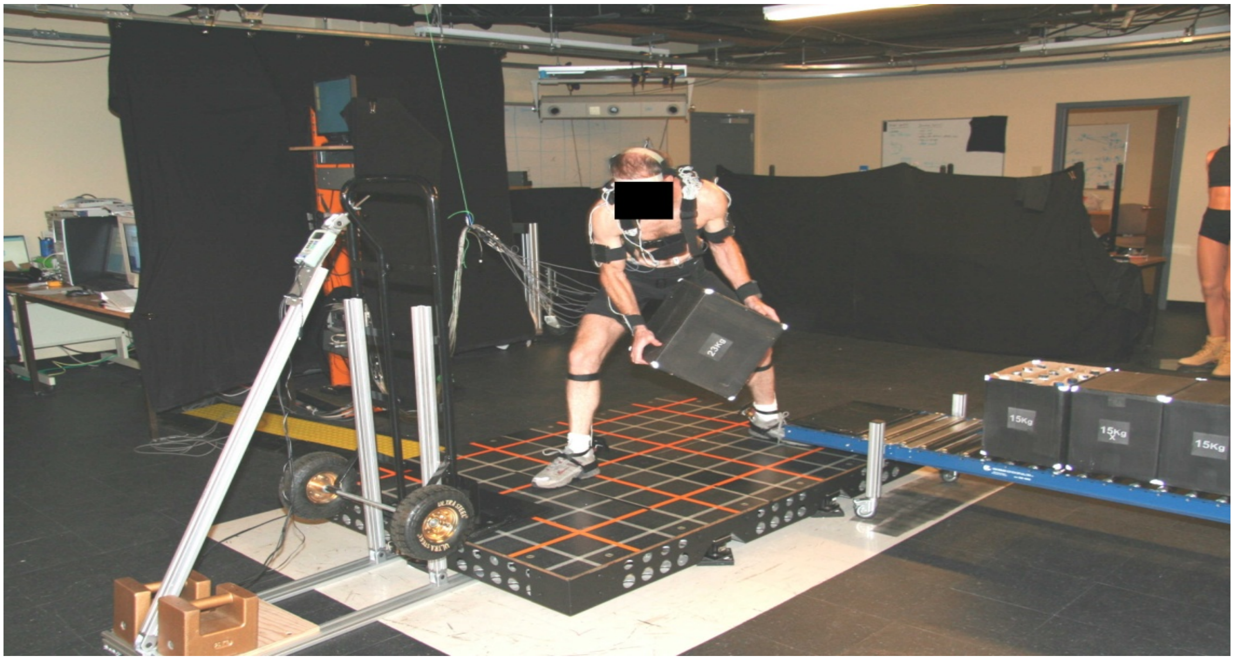


Figure 2.2 Experimental setup for the 90° condition. The subject is moving the box from the conveyor to the hand trolley.

Based on these tasks, we were able to compare the effects of

- box weight: 15 kg or 23 kg
- lifting height: from the conveyor (approximately 15 cm from the floor) to four different deposit heights (stack heights: ground level, 32 cm, 63 cm and 95 cm)
- movement type: lifting vs. lowering
- conveyor position: 90° or 180°

General fatigue perception was measured by means of the Borg CR-10 scale (Borg, 1990). After each box transfer series, the participant had to indicate his fatigue level on a scale of 0 to 10 (0 being no fatigue and 10 maximum fatigue).

2.4 Data analysis

Different work methods were noted: some were safe work methods, aimed primarily at protecting the back, while others were high-performance methods aimed at improving productivity and the quality of the stack. The safe work methods were identified mainly on the basis of back loading variables that reduce effort and promote balance. The performance methods were identified on the basis of completion time.

The kinematic and kinetic data were used as inputs for a 3D biomechanical loading model able to estimate the net moments at L5/S1 (Plamondon et al., 1996). The mechanical work done on the object (based on the displacement of its centre of mass), and on the external load were also estimated.

The main dependent variables selected as safety criteria were as follows:

- Lumbar loading:
  - resultant and asymmetric moments at L5/S1
- Constraining postures:
  - Extreme bending
  - Asymmetric postures
- Duration of handling

Lumbar loading and the various kinematic variables (duration, distance, velocity, and linear and angular accelerations) for the main segments (trunk, pelvis, thighs) and joints (knees, hips, lumbar column) were based on the multisegment biomechanical model of Plamondon et al. (1996).

For analysis purposes, each handling operation was divided into two phases, a lifting phase and a deposit phase (Figure 2.3). The lifting phase starts when the hands first touch the box and ends with the box in flight (the box is no longer in contact with anything except the hands). The deposit phase begins after the lifting phase, at the midpoint of the flight, continues as the box first touches the support surface at the final destination and ends when the handler's hands are no longer in contact with the box. The total duration of the task is the sum of the durations of the lifting phase and the deposit phase.

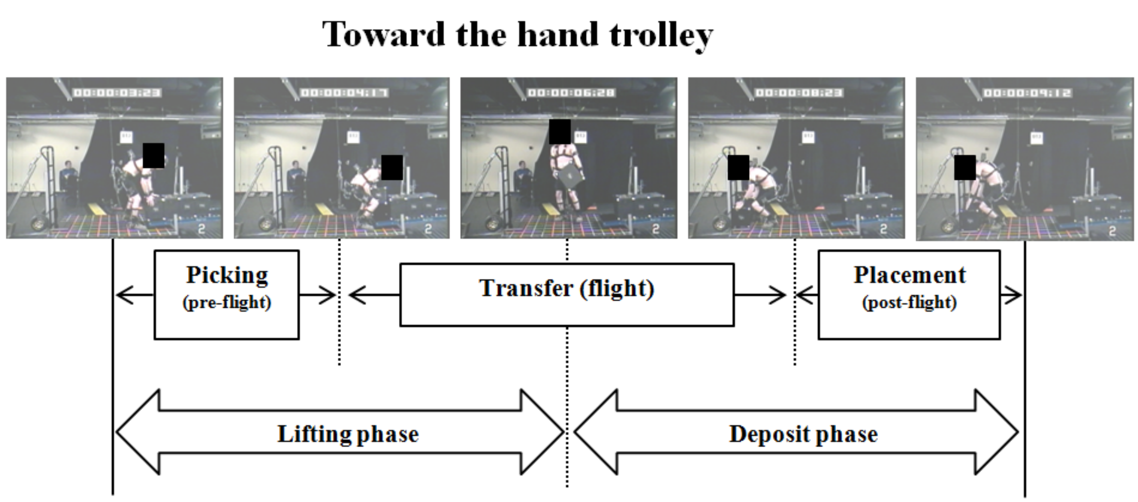


Figure 2.3 Breakdown of box handling operation – Moving boxes to the hand trolley. The same breakdown applies to the return trip (moving the boxes back to the conveyor)

Because the participants' anthropometric characteristics have a significant influence on the calculation of resultant and asymmetric moments at L5/S1, we normalized the data as follows: the moments at L5/S1 were divided by the L5/S1 moment exerted by the weight of the trunk in horizontal position (values presented in Table 3.2). These normalized moments are expressed in units of weight (weight of the trunk).[6] The kinematic and kinetic variables are fully defined in Appendix B.

2.5 Statistical analyses

The statistical analyses were performed using variance analyses with repeated measurements to determine the differences between the main factors. The principal independent variables studied are presented in Table 2.1. Load characteristics, conveyor position and lift and deposit heights were the parameters modified to try to elicit greater variation in the participants' work methods. A separate statistical analysis was done for each trip, i.e., the trip to the hand trolley and the return trip. A posteriori comparisons (Tukey HSD) were applied to locate the differences. A probability of 0.05 was used.

Simple linear regressions were performed to determine the ability of body-mass parameters to predict external loading on the back. A stepwise multiple linear regression (step-by-step method: F to enter = 3.84, F to remove = 2.71) was also done to find the elements that significantly determined peak extension moment acting on the back.

Table 2.1 Independent variables in analyses of trips from conveyor to hand trolley and back

Comparisons between subjects	Normal weight vs. obesity
Comparisons within subjects	Box weight: 15 kg and 23 kg
	Stack height: ground level, 32 cm, 63 cm and 95 cm
	Conveyor position: 90° vs. 180°

6. For example, to normalize an L5/S1 resultant moment of 150 Nm, we divided it by the subject's horizontal trunk moment, say 100 Nm, which yields a normalized moment of 1.5 times the trunk weight.

3 RESULTS

The obese handlers who participated in the study were older, on average, and had more experience than the healthy-weight handlers (Table 3.1). Thus there was a higher proportion of novices in the healthy-weight group and a higher proportion of experienced handlers in the obese group. However, the percentage of experts was similar in the two groups.

Table 3.1 Averages and standard deviations for demographics

	Healthy-weight handlers N = 20	Obese handlers N = 17
Age (years)	25.3 (± 6.9)	34.0 (± 7.2)*
Experience (years)	3.7 (± 7.8)	6.5 (± 6.6)
Novice (n)	15 (75.0%)	4 (23.5%)*
Expert (n)	5 (25.0%)	4 (23.5%)
Experienced (n)	0 (0.0%)	9 (52.9%)*

*Indicates p-value associated with independent samples t-test is less than 0.05; Novice: 1 to 12 months of experience in handling; Experienced: minimum four years of experience; Expert: minimum five years of experience, a low incidence of injuries and recommendation by the corporate hiring manager.

Table 3.2 shows that obese handlers differ from healthy-weight handlers in terms of all anthropometric data except height, which was similar. The average values for segment mass, segmental centre of gravity locations and inertia moments are shown in Appendix A, tables A.1-A.3.

Table 3.2 Averages and standard deviations for anthropometric data

	Healthy-weight handlers N = 20	Obese handlers N = 17
Height (m)	1.75 (± 0.06)	1.74 (± 0.06)
Weight (kg)	67.5 (± 6.9)	95.4 (± 9.6)*
Trunk weight (kg)	30.9 (± 3.5)	48.6 (± 5.9)*
Trunk moment at L5/S1 (Nm)	86.9 (± 7.4)	113.6 (± 14.8)*
BMI (kg/m^2)	21.9 (± 1.1)	31.4 (± 1.5)*
Width of iliac crest (m)	0.27 (± 0.03)	0.31 (± 0.05)*
A-P distance to C7 (m) †	0.11 (± 0.01)	0.14 (± 0.01)*
A-P distance to T12 (m) †	0.21 (± 0.01)	0.28 (± 0.02)*
A-P distance to S1 (m) †	0.20 (± 0.01)	0.27 (± 0.02)*

*Indicates p-value associated with independent samples t-test is less than 0.05; A-P: anterior-posterior.
† Average from three tests conducted with a GPM Caliper.

No significant difference was observed in terms of maximum isometric lifting strength (obese: 134.1 kg; healthy weight: 130.3 kg; p=0.70). When examined in relation to the subjects' weight (kg of maximum lifting strength/weight), the relative maximum strength shows a marked advantage for the healthy-weight handlers, with a relative strength of 1.93 compared to 1.41 for obese handlers ($p < 0.001$).

No difference between obese and healthy-weight handlers was observed in terms of general fatigue before (1.32 = very low vs. 0.85 = extremely low), during (3.18 = moderate vs. 2.42 = low) and after (3.88 = moderate vs. 3.24 = moderate) the handling tasks (ps > 0.18).

3.1 Conveyor to hand trolley

There was no significant difference between obese and healthy-weight handlers in terms of the total task duration for each box and pre-flight (picking) time (ps > 0.10, Table 3.3). As for flight time, the Mass x Group (MG) interaction is significant. This interaction shows that, for both groups, flight time was longer when the load rose from 15 kg to 23 kg. The increase was greater, however, for healthy-weight handlers (healthy-weight: +227 ms; obese: +108 ms). The Configuration x Group (CG) interaction indicates that the post-flight (placement) time was longer for the 180° configuration than for the 90° configuration (+151 ms) for healthy-weight handlers, while it was shorter for obese handlers (-118 ms).

Table 3.3 Average duration and standard deviation for conveyor-to-trolley phase

Variable	Obese		Healthy weight		Group effect (p)	Interaction (p)		
	A	SD	A	SD		CG	MG	HG
Total task duration	5.48	1.73	5.59	1.76	0.85	0.56	0.28	0.64
Pre-flight time	1.55	0.44	1.91	0.79	0.10	0.14	0.07	0.35
Flight time	2.45	0.70	2.35	0.73	0.66	0.80	**0.02**	0.89
Post-flight time	1.49	0.78	1.34	0.51	0.50	**0.04**	0.16	0.28

A: Average; SD: Standard deviation; CG: Configuration x Group interaction; MG: Mass of box x Group interaction; HG: Height of box x Group interaction.

3.1.1 Peak moments on the back

Lifting phase

Table 3.4 and Figure 3.1 show that when the boxes are lifted from the conveyor, the peak moments at the spine in obese handlers are 25.4 to 48.5% greater than in healthy-weight handlers. Once the moments are normalized to take into account the weight of the handler's trunk, however, there is no significant difference between the two groups. The occurrence of the peak resultant moment is not significantly different from one group to the other ($p = 0.18$).

The Configuration x Group interaction is significant for the peak extension moment (sagittal flexion). Regardless of whether the conveyor and trolley are at 90° or 180° to each other, the peak extension moment is greater for the obese group (+26.7%). However, for the healthy-weight handlers, the moment increased from 214 Nm to 221 Nm (difference of +7.5 Nm) when the angle between the conveyor and the trolley was changed from 90° to 180°, while for the obese group the peak extension moment rose from 267 Nm to 284 Nm (difference of +17.3 Nm).

In addition, when the obese handlers lifted the first box, they developed a peak extension moment that was 18.5 to 17.6% lower than that needed to lift the other three boxes from the conveyor. For the healthy-weight group, no difference was observed in this variable as the boxes were lifted (+1.1% to 6.8%). When the peak extension moment is normalized in relation to the subjects' trunk weight, the Height x Group interaction is still significant: the effect of the first box is still present for the obese handlers, but the Group effect disappears.

Deposit phase

We also observed marked and significant increases ranging from +23.0 to 36.4% in the peak moments acting on the back in obese handlers when the boxes were placed on the trolley ($ps < 0.05$; except for the peak lateral bending moment $p=0.19$; Table 3.4 and Figure 3.1). For example, when placing boxes on the trolley, the obese group had a peak resultant moment of 191 Nm, compared with 154 Nm for the healthy-weight group, i.e., a difference of 23.6% (Table 3.4). As in the lifting phase, the occurrence of the peak resultant moment is not significantly different from one group to the other ($p = 0.33$).

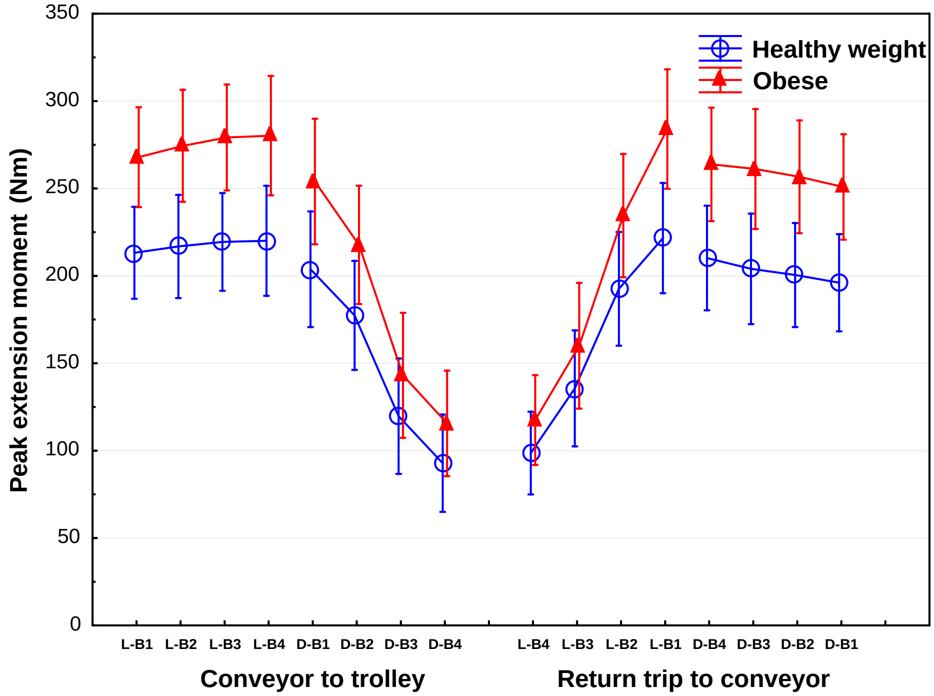
Analysis of the normalized extension moment indicates a significant interaction between the mass of the box and the handler group. The Mass x Group interaction shows that the increase in box mass (from 15 to 23 kg) is associated with an increase in moment that is greater for healthy-weight handlers than for obese handlers (healthy weight: +0.33 or from 1.51 to 1.84; obese: +0.26 or from 1.49 to 1.75).

Table 3.4 Average and standard deviation of peak spine moments – Conveyor to trolley

Variable	Obese		Healthy		Group effect (p)	Interaction (p)		
	Average	SD	Average	SD		CG	MG	HG
Lifting phase								
Peak resultant moment (Nm)	278.3	34.3	219.6	30.2	**< 0.001**	**0.03**	0.75	0.36
Peak extension moment	275.4	32.5	217.4	30.1	**<0.001**	**0.01**	0.63	0.36
Peak twisting moment	20.8	8.1	15.4	3.7	**0.01**	0.66	0.20	**<0.01**
Minimum twisting moment	-36.0	11.4	-28.7	9.9	0.05	0.10	0.30	0.60
Peak lateral bending moment	43.5	13.5	29.3	11.2	**<0.01**	0.37	0.26	0.48
Minimum lateral bending moment	-58.6	20.4	-43.1	13.6	**<0.01**	0.89	0.22	0.94
Normalized peak extension moment	2.44	0.32	2.44	0.39	0.98	0.06	0.08	0.84
Normalized peak twisting moment	0.19	0.08	0.17	0.05	0.48	0.63	0.40	**<0.01**
Normalized minimum twisting moment	-0.32	0.09	-0.32	0.11	0.87	0.11	0.07	0.41
Normalized peak lateral bending moment	0.39	0.13	0.32	0.12	0.12	0.53	0.60	0.59
Normalized minimum lateral bending moment	-0.51	0.15	-0.48	0.15	0.53	0.77	0.06	1.00
Deposit phase								
Peak resultant moment (Nm)	190.6	32.5	154.2	26.7	**<0.01**	0.12	0.97	0.07
Peak extension moment	182.6	30.9	148.4	26.7	**<0.01**	0.19	0.31	0.17
Peak twisting moment	16.4	5.2	12.2	6.3	**0.03**	0.88	0.39	0.57
Minimum twisting moment	-30.8	7.8	-24.2	7.1	**0.01**	0.64	0.84	0.83
Peak lateral bending moment	44.7	22.2	35.7	17.3	0.19	0.53	0.83	0.19
Minimum lateral bending moment	-55.8	24.2	-40.9	21.7	**0.05**	0.53	0.90	0.49
Normalized peak extension moment	1.62	0.29	1.67	0.36	0.63	0.30	**0.02**	0.92
Normalized peak twisting moment	0.15	0.05	0.13	0.07	0.55	0.89	0.89	0.98
Normalized minimum twisting moment	-0.27	0.06	-0.27	0.09	0.91	0.55	0.57	0.23
Normalized peak lateral bending moment	0.40	0.18	0.41	0.21	0.88	0.64	0.53	0.30
Normalized minimum lateral bending moment	-0.50	0.20	-0.45	0.24	0.57	0.53	0.40	0.66

A: Average; SD: Standard deviation; CG: Configuration x Group interaction; MG: Box mass x Group interaction; HG: Box height x Group interaction.

A



B

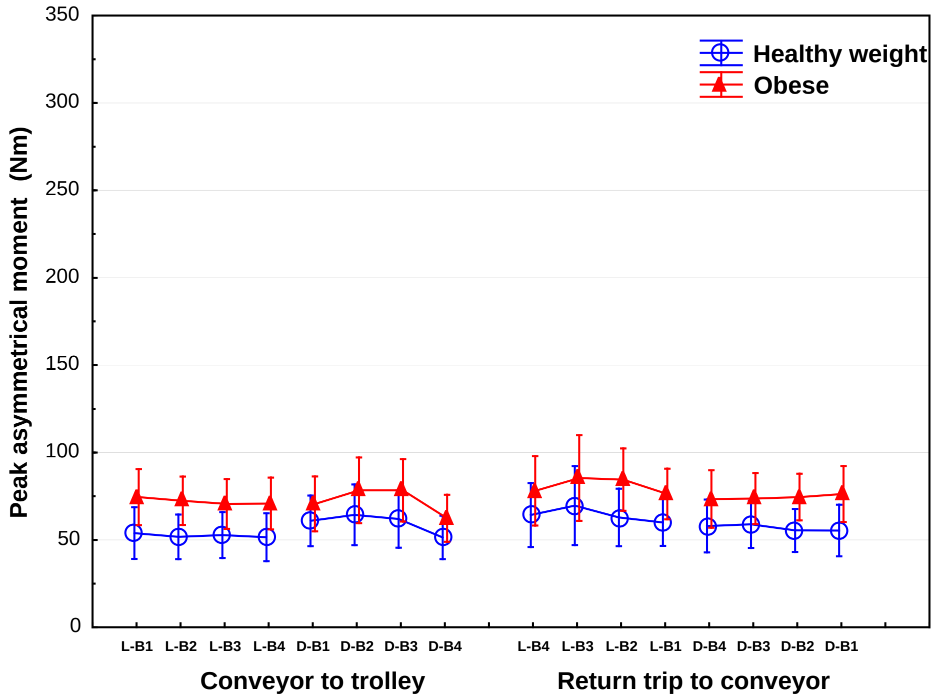


Figure 3.1 Average (95% confidence interval) peak extension moment (A) and peak asymmetrical moment (B) observed under different handling conditions

Lifting phase (L); Deposit phase (D); Four boxes: B1 to B4.

3.1.2 Angles at instant of peak resultant moment

Little difference between the groups was noted during lifting and deposit in terms of the angles calculated at the instant of peak resultant moment (Figure 3.2 and Table 3.5). However, there was significant inter-individual variability in the knee and back angles when the box was lifted from the conveyor or deposited close to the ground (from the conveyor or on the trolley in D-B1). For both groups, the standard deviation is greater than 15.7° for the lumbar flexion angle and greater than 25.0° for the angle of the right knee. This variation indicates that not all individuals in either group adopt the same strategy for lifting or depositing.

Lifting phase

For the lumbar flexion angle, a significant Height x Group interaction was noted. A breakdown of this interaction indicates that the flexion angle at the time the first box is lifted from the conveyor is less than the flexion angle observed for lifting of the other three boxes from the conveyor for the obese group ($ps < 0.001$) and of the two middle boxes for the healthy-weight group ($ps < 0.05$). No difference was detected between the groups for each of the boxes ($ps > 0.99$). However, a significant Configuration x Group interaction was observed for the lumbar lateral bending angle. This interaction indicates that the lateral bending angle tended to increase between the 90° configuration and the 180° configuration for the healthy-weight group (0.52 to 1.35°), whereas it tended to decrease for the obese group (-0.22 to -0.89°).

Deposit phase

Trunk flexion angle at C7 is not significantly different between the two groups, but the Mass x Group and Height x Group interactions are. Obese handlers decreased their trunk flexion at C7 by about 1.5° (from 46.8° to 45.1°) when the box mass rose from 15 kg to 23 kg, while the healthy-weight group increased it by less than one degree (from 49.9° to 50.3°). The interaction between Height and Group showed no difference in behaviour between the two groups. In both cases, the trunk flexion angle at C7 decreased as the stack on the trolley grew (obese: 1st box = 75.0°, 2nd box = 63.0°, 3rd box = 32.8°, 4th box = 13.1°; healthy weight: 1st box = 74.3°, 2nd box = 66.0°, 3rd box = 39.6°, 4th box = 20.7°).

A

B

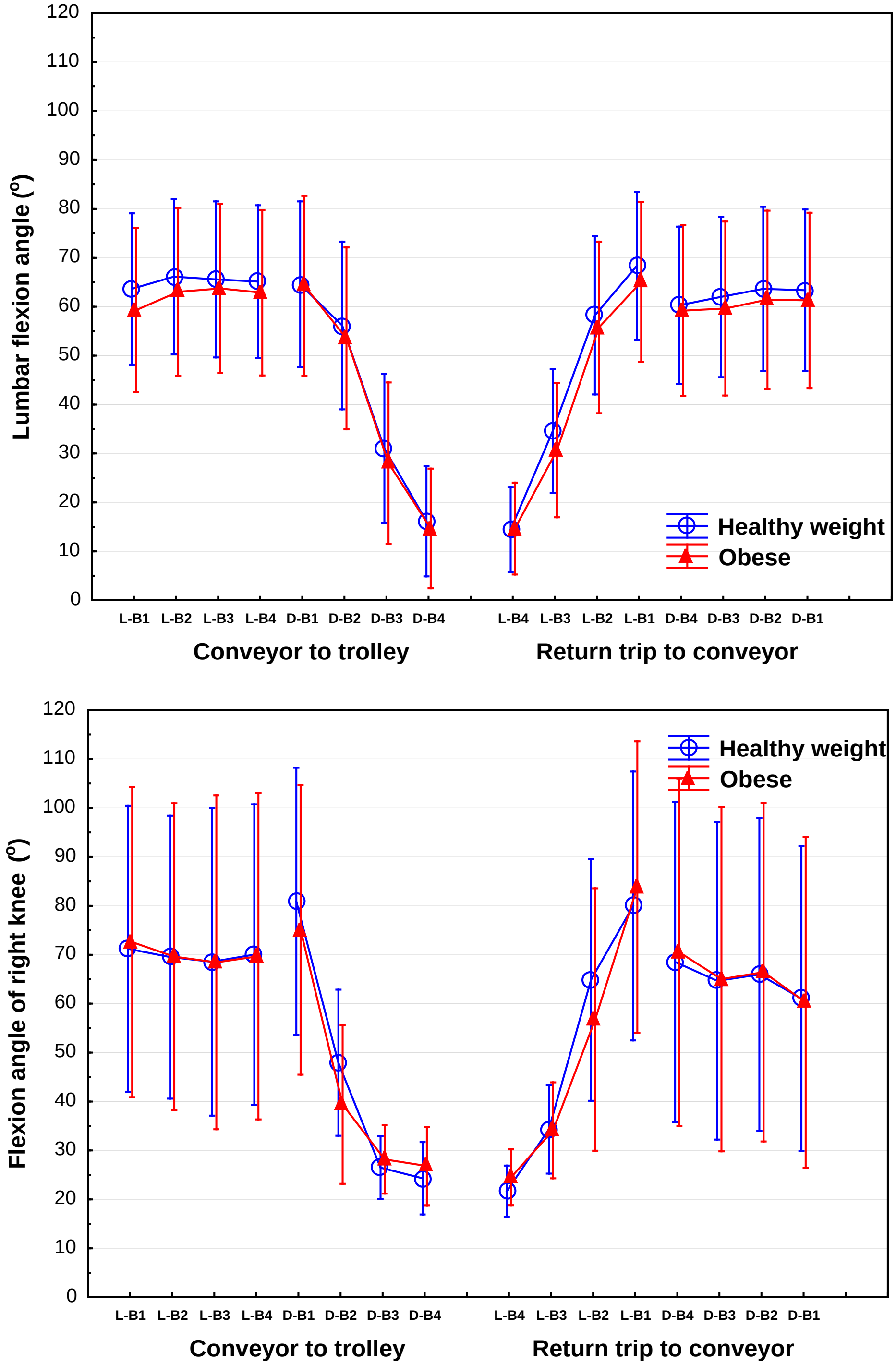


Figure 3.2 Average (95% confidence interval) lumbar flexion angle (A) and flexion angle of right knee (B) at instant of peak resultant moment observed under different handling conditions

Lifting phase (L); Deposit phase (D); Four boxes: B1 to B4.

Table 3.5 Average and standard deviation of angles observed at instant of peak resultant moment – Conveyor to trolley

Variable	Obese		Healthy		Group effect (p)	Interaction (p)		
	Average	SD	Average	SD		CG	MG	HG
Lifting phase								
Lumbar flexion angle (°)	62.2	15.7	65.1	18.4	0.61	0.25	0.76	**0.03**
Lumbar lateral bending angle (°)	-0.6	4.0	0.9	3.8	0.25	**0.04**	0.30	0.88
Lumbar twisting angle	3.3	3.4	2.1	5.3	0.42	0.27	0.23	0.95
Trunk inclination from the vertical at C7 (°)	68.4	15.8	73.7	21.3	0.41	0.27	0.31	0.29
Trunk inclination from the vertical at T12 (°)	73.9	18.2	78.1	24.8	0.57	0.44	0.38	0.29
Angle of right knee (°)	70.1	25.0	69.8	38.0	0.98	0.64	0.55	0.93
Angle of left knee (°)	73.0	21.0	71.8	35.9	0.87	0.60	0.46	0.78
Deposit phase								
Lumbar flexion angle (°)	40.1	13.2	42.0	16.1	0.95	0.85	0.34	0.54
Lateral lumbar flexion angle (°)	-1.0	4.6	-1.0	3.5	0.66	0.55	0.12	0.06
Lumbar twisting angle	0.6	3.6	1.5	4.4	0.49	0.60	0.22	0.10
Trunk inclination from the vertical at C7 (°)	46.0	10.2	50.1	14.5	0.22	0.78	**0.04**	**0.02**
Trunk inclination from the vertical at T12 (°)	47.2	12.8	49.2	17.6	0.58	0.76	0.59	0.18
Angle of right knee (°)	42.4	12.2	44.9	12.3	0.34	0.37	0.31	0.32
Angle of left knee (°)	42.1	11.8	43.4	14.3	0.78	0.72	0.85	0.73

A: Average; SD: Standard deviation; CG: Configuration x Group interaction; MG: Box mass x Group interaction; HG: Box height x Group interaction.

3.1.3 Box distance and path and height of centre of gravity

Lifting phase

The trip and distance variables shown in Table 3.6 do not differ significantly between the two groups. The horizontal distance between the box and L5/S1 at the instant of peak resultant moment seems to be slightly greater (2.8 cm) for obese handlers (p=0.07; Table 3.6; Figure 3.3). Moreover, the Mass x Group interaction shows that when the box mass rose from 15 kg to 23 kg, healthy-weight handlers drew the box significantly closer to their bodies during the lift, whereas the obese group made no change in that regard. Healthy-weight handlers pulled the box 1.8 cm closer, from 41.5 cm to 39.7 cm (obese group: 43.5 and 43.2 cm for the 15-kg and 23-kg boxes, respectively).

Deposit phase

The Mass x Group interaction in terms of horizontal distance from box to L5/S1 was also observed for the deposit phase (Table 3.6; Figure 3.3). Healthy-weight handlers held the box closer when depositing a heavier box, while no significant difference was observed for the other group. For the healthy-weight handlers, the distance decreased from 38.9 cm to 36.2, i.e., a decrease of 2.7 cm (obese group: 40.0 and 38.9 cm for the 15-kg and 23-kg boxes, respectively).

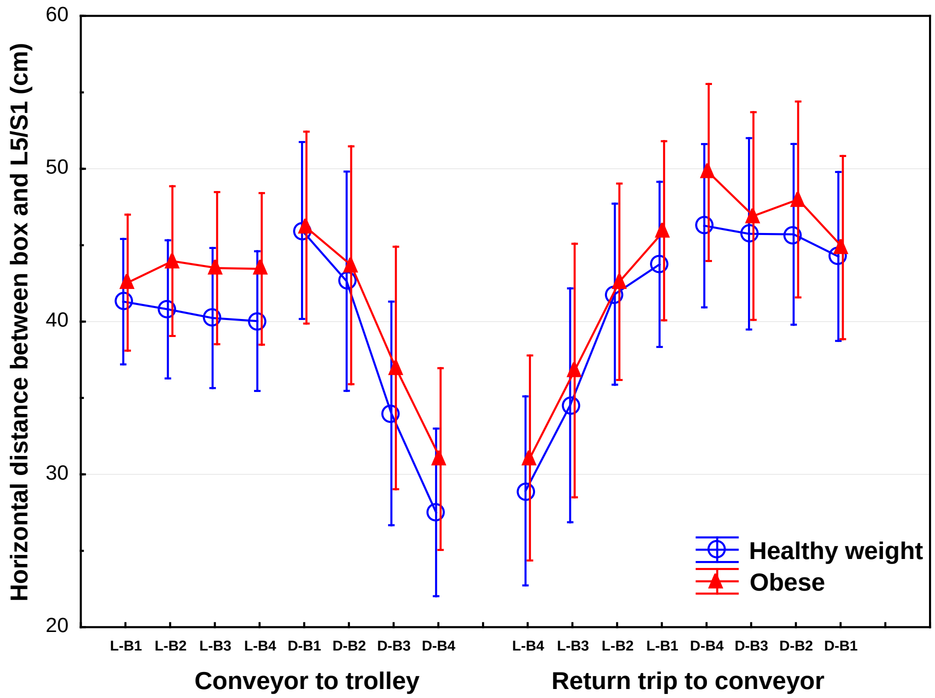


Figure 3.3 Average (95% confidence interval) horizontal distance between box and L5/S1 at instant of peak resultant moment observed under different handling conditions

Lifting phase (L); Deposit phase (D); Four boxes: B1 to B4.

Table 3.6 Average and standard deviation of box distance and path, and height of centre of gravity (COG) – Conveyor to trolley

Variable	Obese		Healthy		Group effect (p)	Interaction (p)		
	Average	SD	Average	SD		CG	MG	HG
Lifting phase								
Horizontal distance from box to L5/S1 (cm)†	43.4	5.1	40.6	4.1	0.07	0.88	**0.03**	0.11
Maximum box height	98.5	6.3	96.0	11.6	0.61	0.64	0.76	0.92
Minimum box height	40.9	4.8	39.4	6.0	0.53	0.99	0.24	0.71
Box height, 50th percentile	86.0	9.0	83.5	14.1	0.62	0.15	0.36	0.28
Maximum height of COG	93.6	4.2	93.4	5.0	0.97	1.00	0.94	0.51
Minimum height of COG	64.6	8.4	64.1	9.6	0.84	0.98	0.60	0.88
Deposit phase								
Horizontal distance from box to L5/S1 (cm)†	39.5	6.4	37.5	6.8	0.38	0.87	**0.02**	0.09
Maximum box height	102.6	4.3	101.4	7.8	0.46	0.85	0.29	0.49
Minimum box height	72.4	3.1	71.4	4.7	0.52	0.78	0.06	0.98
Box height, 50th percentile	90.6	4.3	90.8	6.3	0.91	0.52	0.74	0.91
Maximum height of COG	93.8	4.0	94.1	3.8	0.82	0.60	0.10	0.24
Minimum height of COG	81.4	4.4	81.2	3.8	0.90	0.82	0.59	0.73

†Horizontal distance at the instant of peak resultant moment; A: Average; SD: Standard deviation; CG: Configuration x Group interaction; MG: Box mass x Group interaction; HG: Box height x Group interaction.

3.2 Return trip to conveyor

No difference was observed between the two groups with respect to temporal variables (Table 3.7). The average duration of each trip from the trolley to the conveyor was just over five seconds for both groups.

Table 3.7 Average duration and standard deviation for return trip (trolley to conveyor)

Variable	Obese		Healthy		Group effect (p)	Interaction (p)		
	M	SD	M	SD		CG	MG	HG
Total task duration	5.14	1.37	5.36	1.67	0.66	0.39	0.22	0.09
Pre-flight time	1.22	0.38	1.42	0.50	0.17	0.45	0.46	0.24
Flight time	2.64	0.72	2.40	0.72	0.31	0.09	0.40	0.27
Post-flight time	1.28	0.58	1.54	0.73	0.23	0.60	0.12	0.71

A: Average; SD: Standard deviation; CG: Configuration x Group interaction; MG: Box mass x Group interaction; HG: Box height x Group interaction.

3.2.1 Peak moments on the back

Lifting phase

External loading during lifting from the trolley was 22.2% to 51.8% greater for obese handlers than for healthy-weight handlers (Table 3.8, Figure 3.1). The instant at which the resultant moment reached its peak was the same for the two groups (p = 0.18).

The Height x Group interaction for the peak resultant and extension moments indicates an exacerbation of the differences between the groups when the two boxes closest to the ground were lifted. Compared to the healthy-weight group, obese handlers had to exert an extension moment that was 19.1% and 18.0% greater to lift the top two boxes from the trolley (L-B4 and L-B3), and 21.8% and 28.2% greater to lift the bottom two boxes (L-B2 and L-B1; ps < 0.01; Figure 3.1).

Once normalized to take into account the participants' trunk weight, the peak extension moment varied differently depending on the box mass and the handler group. The Mass x Group interaction shows that the increase in box mass (from 15 kg to 23 kg) is associated with an increase in moment that is greater for healthy-weight handlers than for obese handlers (healthy weight: +0.30 or from 1.67 to 1.97; obese: +0.22 or from 1.67 to 1.88).

A Height x Group interaction is also observed with regard to the normalized peak twisting moment (p=0.02). A breakdown of this interaction indicates that the normalized twisting moment increased significantly according to box height for the healthy-weight group only. For this group, the normalized moment rose from 0.10 for box L-B4 to 0.20 for the box closest to the ground (L-B1). For the obese group, the normalized moment rose from 0.17 to 0.20 under the same conditions. Lastly, a Configuration x Group interaction shows that changing from a 90° configuration to a 180° configuration is associated with a decrease in the minimum normalized twisting moment for the healthy-weight group (Δ = -0.01) whereas a slight increase was observed for the obese group (Δ = 0.01).

Deposit phase

The absolute external loads during deposit onto the conveyor were 13.3 to 59.0% greater for obese handlers than for healthy-weight handlers (Table 3.8, Figure 3.1). The instant at which the resultant moment reaches its peak depends on the trolley position in relation to the conveyor and on the group (Configuration x Group: p = 0.04). A breakdown of this interaction indicates that the instant of peak resultant moment during the deposit onto the conveyor (90° configuration) occurred sooner in the handling cycle for the healthy-weight group than for the obese group (91.7 vs. 96.4%, p = 0.01), while no difference was detected for the 180° configuration (94.7 vs. 95.8%, p = 0.88).

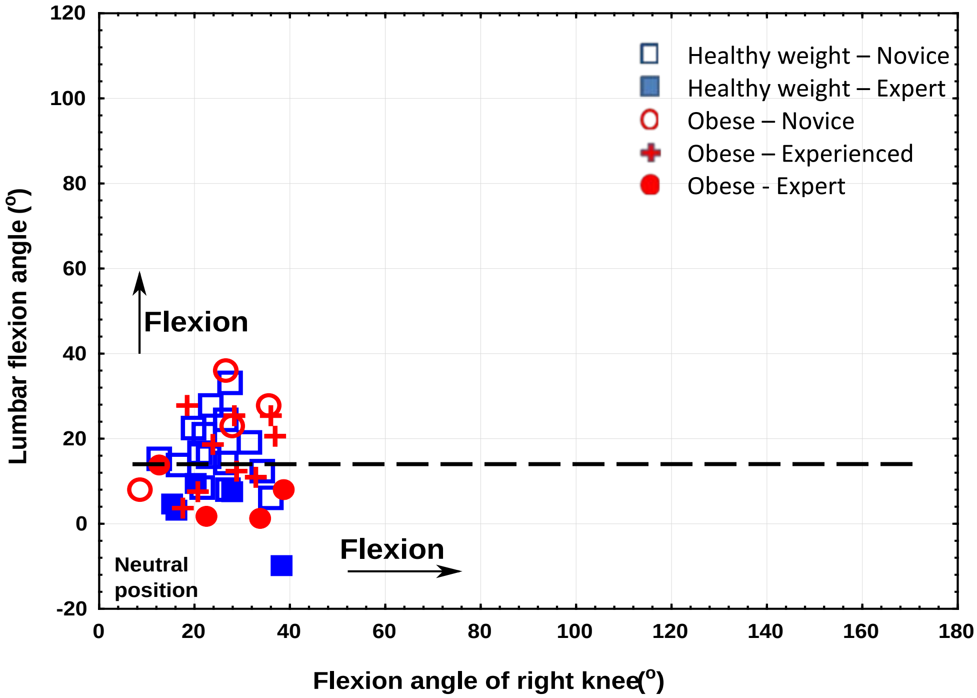
Table 3.8 indicates a significant Mass x Group interaction for the normalized peak extension moment. A breakdown of this interaction indicates that increased box mass is associated with a slight increase in the normalized extension moment for the healthy-weight group ($\Delta = 0.20$) but did not lead to any change for the obese group ($\Delta = 0.02$).

3.2.2 Angles at the instant of peak resultant moment

There was little difference between the groups in terms of the angles calculated (Figure 3.2 and Table 3.9). As stated earlier for the conveyor-to-trolley tests, and as shown in figures 3.2 and 3.5, handlers in both groups adopted extremely varied postures when lifting or depositing boxes close to the ground (i.e., from or onto the trolley, L-B1 and D-B1). Figure 3.4 illustrates two specific conditions: (A) lifting the highest box from the trolley (L-B4); (B) lifting the lowest box from the trolley (L-B1).

The variations in angles between the two groups for condition L-B1 were very large, for both the knee angle (healthy weight: min = 31.7°, max = 148.8°, Δ_{knee} = 117.1°; obese: min = 33.3°; max = 114.4, Δ_{knee} = 81.1°) and the lumbar flexion angle (healthy weight: min = 40.9°, max = 107.3°, Δ_{back} = 66.4°; obese: min = 40.2°; max: 96.9°; Δ_{back} = 56.7°). The variations are much smaller for condition L-B4 (healthy weight: Δ_{knee} = 25.3 °; Δ_{back} = 42.7°; obese: Δ_{knee} = 30.1°; Δ_{back} = 34.6°). Note that it does not appear possible to distinguish the postural strategies of the four obese expert handlers (solid red circle) from the five healthy-weight expert handlers (solid blue square). However, these nine expert handlers are differentiated from most of the novices and experienced handlers by a lumbar flexion of less than 63°. The knee angle varied enormously among all subjects, regardless of level of expertise. None of the obese handlers used a knee angle greater than 120°.

A



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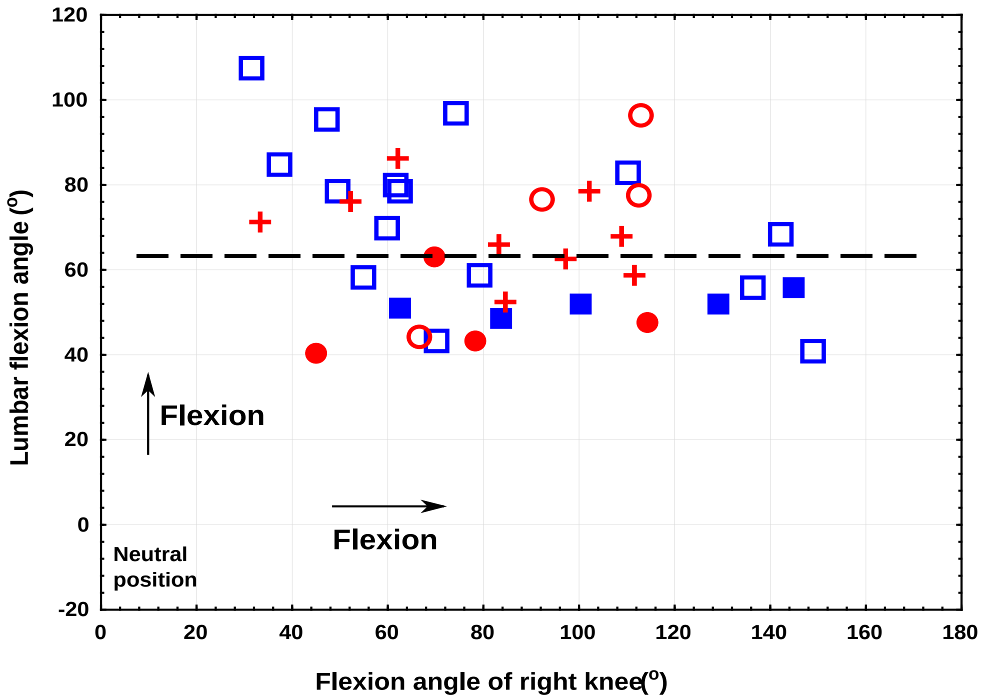

Figure 3.4 Lumbar flexion angle and knee flexion angle at the instant of peak resultant moment observed during lifting of the highest 23-kg box from the trolley (L-B4, 'A') and lifting of the lowest 23-kg box from the trolley (L-B1, 'B') – Return trip to conveyor

The subjects' level of expertise is indicated. Values shown are the average for the two tests conducted with the 180° configuration. The dotted line indicates the greatest lumbar flexion observed among the expert handlers.

Table 3.8 Average and standard deviation of peak moments at the back – Return trip to conveyor

Variable	Obese		Healthy		Group effect (p)	Interaction (p)		
	Average	SD	Average	SD		CG	MG	HG
Lifting phase								
Peak resultant moment (Nm)	207.6	34.8	169.9	32.8	**<0.01**	0.51	0.21	**<0.001**
Peak extension moment	199.0	31.2	162.1	30.5	**<0.001**	0.80	0.24	**<0.001**
Peak twisting moment	20.8	6.0	13.7	6.1	**<0.01**	0.74	0.88	0.08
Minimum twisting moment	-31.6	9.4	-23.4	6.1	**<0.01**	0.06	0.62	0.70
Peak lateral bending moment	66.2	25.7	52.0	21.6	0.08	0.19	0.23	0.31
Minimum lateral bending moment	-47.9	19.0	-35.3	14.7	**0.03**	0.57	0.75	0.90
Normalized peak extension moment	1.77	0.32	1.82	0.36	0.67	0.98	**<0.01**	0.33
Normalized peak twisting moment	0.19	0.06	0.15	0.07	0.14	0.60	0.70	**0.02**
Normalized minimum twisting moment	-0.28	0.08	-0.27	0.08	0.63	**0.05**	0.74	0.57
Normalized peak lateral bending moment	0.59	0.23	0.59	0.26	0.99	0.23	0.08	0.34
Normalized minimum lateral bending moment	-0.42	0.15	-0.39	0.17	0.61	0.50	0.39	0.90
Deposit phase								
Peak resultant moment (Nm)	261.0	32.2	206.2	32.8	**<0.001**	0.13	0.55	0.82
Peak extension moment	258.1	31.7	202.7	32.2	**<0.001**	0.08	0.52	0.83
Peak twisting moment	20.8	7.0	16.4	6.0	**0.05**	0.86	0.86	0.09
Minimum twisting moment	-33.8	10.8	-26.9	7.5	**0.03**	0.57	0.68	0.30
Peak lateral bending moment	55.8	19.4	35.1	19.7	**<0.01**	0.34	0.56	0.11
Minimum lateral bending moment	-49.5	21.1	-43.7	17.5	0.37	0.85	0.28	0.40
Normalized peak extension moment	2.23	0.27	2.24	0.42	0.99	0.05	**<0.01**	0.44
Normalized peak twisting moment	0.19	0.07	0.18	0.07	0.84	0.34	0.70	0.34
Normalized minimum twisting moment	-0.30	0.09	-0.30	0.08	0.88	0.99	0.25	0.32
Normalized peak lateral bending moment	0.50	0.18	0.39	0.23	0.12	0.39	0.98	0.21
Normalized minimum lateral bending moment	-0.43	0.15	-0.49	0.20	0.33	0.96	0.11	0.26

A: Average; SD: Standard deviation; CG: Configuration x Group interaction; MG: Box mass x Group interaction; HG: Box height x Group interaction.

Lifting phase

A significant Configuration x Group interaction was observed for the lumbar flexion angle and the lumbar flexibility index. This interaction indicates that the lumbar flexion angle decreases slightly between the 90° configuration and the 180° configuration for the healthy-weight group (44.6 to 43.2°) but increases slightly for the obese group (41.0 to 42.0°).

Deposit phase

No difference between the two groups was observed.

Table 3.9 Average and standard deviation of angles observed at the instant of peak resultant moment – Return trip to conveyor

Variable	Obese		Healthy		Group effect (p)	Interaction (p)		
	Average	SD	Average	SD		CG	MG	HG
Lifting phase								
Lumbar flexion angle (°)	41.5	12.7	43.9	14.1	0.60	**0.03**	0.08	0.63
Lateral lumbar flexion angle (°)	-1.8	4.1	-1.2	5.0	0.71	0.89	0.40	0.06
Lumbar twisting angle	-0.5	3.8	0.8	4.7	0.35	0.28	0.94	0.37
Trunk inclination from the vertical at C7 (°)	46.1	12.7	52.0	15.7	0.22	0.11	0.08	0.59
Trunk inclination from the vertical at T12 (°)	47.7	14.2	52.7	17.7	0.36	0.20	0.09	0.82
Angle of right knee (°)	49.8	13.8	50.2	17.2	0.89	0.15	0.53	0.40
Angle of left knee (°)	49.3	14.1	45.7	22.0	0.63	0.48	0.64	0.55
Deposit phase								
Lumbar flexion angle (°)	60.4	16.3	62.3	19.3	0.75	0.98	0.67	0.66
Lateral lumbar flexion angle (°)	1.1	4.8	3.0	6.1	0.32	0.35	0.52	0.32
Lumbar twisting angle	2.3	4.5	1.3	4.6	0.52	0.35	0.94	0.27
Trunk inclination from the vertical at C7 (°)	70.7	17.6	73.2	20.5	0.69	0.39	0.49	0.89
Trunk inclination from the vertical at T12 (°)	74.2	19.4	75.1	24.8	0.92	0.34	0.65	0.97
Angle of right knee (°)	65.6	32.2	65.0	36.9	0.96	0.65	0.44	0.84
Angle of left knee (°)	63.7	25.7	68.1	28.9	0.63	0.40	0.27	0.67

A: Average; SD: Standard deviation; CG:
Configuration x Group interaction; MG: Box mass x Group interaction; HG: Box height x Group interaction.

3.2.3 Distance and path of box and height of centre of gravity

Lifting phase

A Configuration x Group interaction was observed with regard to the minimum height of the subjects' centre of gravity during lifting (Table 3.10). This interaction indicates that changing from the 90° configuration to the 180° configuration is associated with a change in the minimum height of the subject's centre of gravity: an increase of 1.1 cm for obese handlers and a decrease of 0.3 cm for healthy-weight handlers.

Deposit phase

No difference between the groups was observed for the deposit back onto the conveyor (Table 3.10).

Table 3.10 Average and standard deviation of box distance and path, and height of centre of gravity (COG) – Return trip to conveyor

Variable	Obese		Healthy		Group effect (p)	Interaction (p)		
	Average	SD	Average	SD		CG	MG	HG
Lifting phase								
Horizontal distance from box to L5/S1 (cm)[†]	39.1	5.1	37.2	7.4	0.39	0.87	0.47	0.69
Maximum box height	101.6	5.1	98.7	8.8	0.23	0.57	0.65	0.39
Minimum box height	70.6	3.3	68.7	4.3	0.15	0.26	0.20	0.84
Box height, 50th percentile	96.3	5.4	93.3	8.6	0.22	0.92	0.77	0.31
Maximum height of COG	94.1	3.6	94.0	3.9	0.91	0.76	0.68	0.11
Minimum height of COG	78.9	5.4	78.4	5.0	0.81	**0.05**	0.34	0.30
Deposit phase								
Horizontal distance from box to L5/S1 (cm)[†]	47.4	5.4	45.5	6.2	0.34	0.08	0.13	0.14
Maximum box height	96.8	5.6	93.0	11.1	0.22	0.75	0.98	0.70
Minimum box height	43.1	4.8	42.1	5.5	0.55	0.24	0.68	0.66
Box height, 50th percentile	77.8	8.3	75.4	10.7	0.46	0.86	0.52	0.60
Maximum height of COG	92.9	3.6	92.4	4.6	0.67	0.73	0.92	0.94
Minimum height of COG	67.5	8.3	66.6	8.9	0.77	0.69	0.47	0.77

[†]Horizontal distance at the instant of peak resultant moment; A: Average; SD: Standard deviation; CG: Configuration x Group interaction; MG: Box mass x Group interaction; HG: Box height x Group interaction.

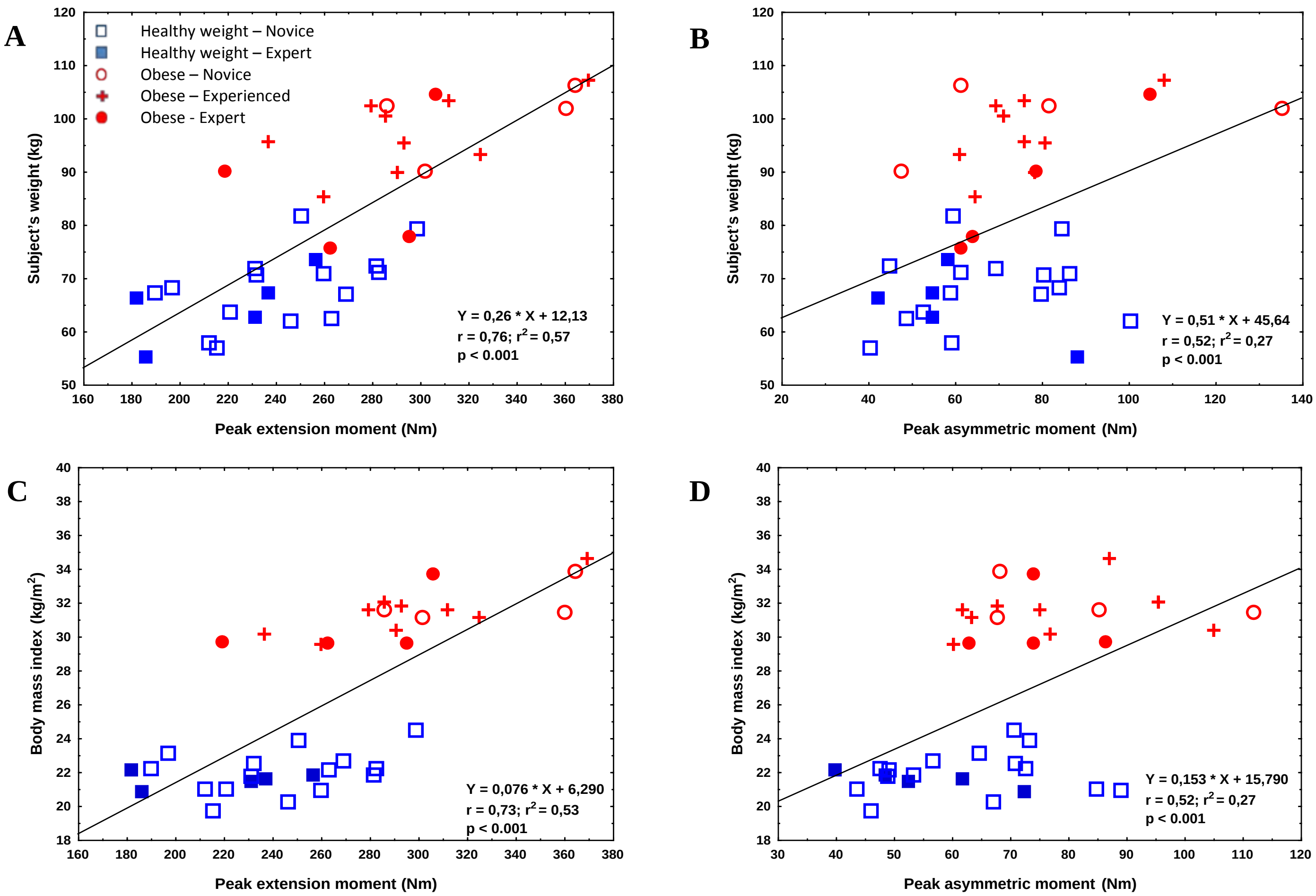

Figure 3.5 Linear regression between body weight and peak extension moment (A); body weight and peak asymmetrical moment (B); BMI and peak extension moment(C); and BMI and peak asymmetrical moment (D)

The peak moment values are averages observed for each subject during lifting of the 23-kg box from position L-B1 on the trolley (close to the ground) in the 180° configuration.

3.3 Linear regressions

3.3.1 Simple linear regression

A significant positive linear association was found between body mass (weight and BMI) variables and external back loading. Body weight explains 57% and 27% of the variance in the peak extension and asymmetrical moments observed during lifting of the 23-kg box from the ground (L-B1) (figures 3.5A and B). BMI explains 53% and 27% of the variance in the peak extension and asymmetrical moments, respectively (figures 3.5C and D). The subject's height and number of years of experience are not significantly associated with the variations in peak moments (ps > 0.14).

3.3.2 Multiple linear regression

Multiple regression analysis was used to determine a four-variable model that could explain the variations in peak extension moments acting on the back during lifting of a 23-kg box close to the ground from the trolley (Table 3.11). The proportion of variance explained by the model is 81% and the standard error of the estimate is 22.3.

Table 3.11 Multiple regression model used to predict variability of peak extension moment at the back during lifting

Variable	Stage	R	R^2	Change in R^2	F value	p value	Beta
A-P distance from T12	1	0.776	0.602	0.602	52.90	< 0.001	0.381
Hor. distance from box to L5/S1	2	0.859	0.738	0.136	17.68	< 0.001	0.383
Weight of upper trunk	3	0.885	0.784	0.046	6.95	0.01	0.414
Lumbar flexion angle	4	0.898	0.807	0.023	3.84	0.06	0.170

4 DISCUSSION

The results clearly show that the strategies adopted by obese handlers induce a high level of maximum lumbar loading during pickup and deposit of boxes from or onto a hand trolley or conveyor. Though they varied from one individual to the next, the postural strategies (i.e., bending of the knees and back) of the obese group and the normal-weight group were similar on the whole. With regard to the duration of handling operations or the level of fatigue induced, no differences between the two groups were noted. The 22% to 59% increases in external back loading observed in obese handlers (compared with normal-weight handlers) are largely attributable to the anthropometric traits of obesity and to the handlers' individual work methods.

In our discussion, we will look first at the differences between the two groups in terms of anthropometrics and physical capacity, as well as the biomechanical consequences measured during the handling operation, including moments on the back, posture and box displacement. Lastly we will look at the factors that make it possible to predict the external extension moment on the back.

4.1 Anthropometrics and physical capacity

As expected, the obese handlers and the healthy-weight handlers were very different in terms of anthropometrics. The two groups were formed on the basis of their BMI, so it is not surprising to find differences in the properties of the various body segments. These parameters have a direct influence on the external loads to which the body is subjected during laboratory-simulated handling operations. The obese subjects had a body mass 41.4% greater than the healthy-weight handlers. The maximum physical strength (maximum isometric lifting strength) was no different in absolute terms, but it was significantly lower in relative value (-26.9%) for the obese handlers. This result concurs with the findings in recent literature. When the force and power measurements are adjusted for body mass, total lean mass or other allometric approaches, obese individuals underperform healthy-weight individuals in terms of maximum isometric strength (6 to 16%), trunk extension strength (~10%), knee extension strength (~20%) and handgrip strength (~10%) (Kitagawa and Miyashita, 1978; Blimkie et al., 1990; Miyatake et al., 2000; Hulens et al., 2001). It is recognized that this relative lack of muscle strength in obese individuals can limit or even obstruct the accomplishment of daily tasks and expose them to a higher risk of fatigue and musculoskeletal injuries (Syed and Davis, 2000; Wearing et al., 2006).

It is important to emphasize that none of our subjects had any musculoskeletal problems that could affect their normal work, and all were able to perform the task with a minimum of fatigue. No difference in general fatigue was noted between the two groups. A steady increase in fatigue, from very low at the outset to moderate at the end of the session (3 to 4 on the Borg scale) was observed in both groups. It should be remembered that regular two-minute breaks were allowed after each round trip of the four boxes to reduce the effects of fatigue, and that the handlers were free to work at their own pace. No difference between experts and novices in the performance of the same task has been reported (Plamondon et al., 2010; Plamondon et al., 2011). The results are thus representative of a work context in which physical fatigue is minimal.

Obesity is often linked to reduced aerobic capacity (Mattsson et al., 1997; Hulens et al., 2001) and anaerobic capacity (Lafortuna et al., 2002; Sartorio et al., 2004), which can substantially diminish the capacity for physical work (Mattsson et al., 1997). Obese individuals must constantly deal with their excess weight in various aspects of work (for example, locomotion, staying balanced for extended lengths of time, repetitive movements, etc.). If examined over a longer period and in a real work context, it is possible that obesity may have a more serious impact on work strategies. Problems of fatigue and reduced work capacity could be attenuated through an alternating work/rest schedule better adapted to the physical condition of obese persons. Further research will be needed to better understand the impact of dynamic work on the strategies of workers who are obese or in poor physical condition.

4.2 Back loading

The result that stands out the most in this study is the considerable increase in back extension moments and in asymmetrical moments during lifting and deposit of boxes at different heights. The closer the box was to the ground, the more the external load on the back was exacerbated by obesity. It should be remembered that the handlers' obesity was characterized by greater mass and inertia of the upper body, greater trunk circumference and reduced flexibility of the trunk.

After normalizing the moments of force to adjust for the moment generated by the weight of the trunk when horizontal, we find that the values for the two groups are identical. The normalization makes it possible to appreciate the efficacy of the work method by eliminating the contribution of excess weight to external loading. Clearly, obese handlers do not have better or worse technique than healthy-weight handlers. Nonetheless, it is the musculoskeletal structures, in the end, that bear the external loading imposed by the work method and by the individual anthropometric characteristics of each worker. According to Marras et al. (2006), the biggest factor in occupational back injury is the external moment (load) on the spine.

In this sense, the results of our study are alarming: obese handlers had resultant moments at the back (mainly due to the back extension moment) that were at least 23% greater than those of healthy-weight handlers. When lifting a 23-kg box from the hand trolley at ground level, 7 out of 17 obese handlers (41%) exceeded 300 Nm in L5-S1 peak external loading, while none of the healthy-weight handlers exceeded that threshold. Moreover, only two handlers—both of them obese—exerted peak lateral extension moments of over 100 Nm. As for biomechanical twisting load on the back, more than 76% of the obese handlers and 45% of the healthy-weight handlers exerted twisting moments greater than 30 Nm. Note that these biomechanical loading levels, which affect some obese handlers, are slightly higher than those reported for handlers moving loads with fixed foot placement: twisting moments of 57 Nm and lateral bending moments of 101 Nm (Kingma et al., 1998). Lavender et al. (2007) reported that handlers who limited their twisting moments to 30 Nm were less liable to experience back problems than those who had twisting moments greater than 30 Nm. These results show that the external loads on the back definitely increase physical exposure and therefore the risk of injury in obese handlers. Excess weight must therefore be considered a determining factor in increased exposure to MSDs.

Consequently, the safety margin for dealing with an unforeseen event, or even for meeting a need to work faster, seems to diminish for obese handlers—and that's without even taking into account the dynamic reality of the workplace. One study showed that about 15% of handling involves trunk twisting, and that trunk twisting is involved in nearly 50% of handling operations (Baril-Gingras and Lortie, 1995). Actual handling operations and the impact of obesity need to be studied in the workplace with instruments capable of measuring postural asymmetry and other parameters.

Singh et al. (2009) report that obese subjects (BMI $\geq$ 35 kg/m^2) selected maximum acceptable weights of lift (MAWL)[7] equivalent to those of a non-obese group. This was surprising, given the biomechanical and physiological costs linked to the subjects' excess weight. The authors hypothesize that the obese subjects may have used a handling technique enabling them to offset their excess weight. Based on our results, however, this seems improbable. They also hypothesize that obese people have a psychophysical detection threshold (perception) different from that of healthy-weight individuals or that they perceive physical effort differently because they are always exposed to greater loads. In both cases, the MAWL would be overestimated and would be a risk for the obese handler.

4.3 Moment arm

Minimizing moment arm, i.e., the distance between the load and the trunk, is one of the handling principles that has been most studied (McGill, 2002; Graveling et al., 2003; Marras, 2006; 2008) and is most widely applied by expert and experienced handlers (Baril-Gingras and Lortie, 1995; Authier et al., 1996). For obese handlers, this option may not always be practical given their trunk dimensions. The distance between the box and L5/S1 was slightly greater for obese handlers, but only the healthy-weight handlers were able to bring the load closer to minimize the moment arm effect on lumbar loading. Studies report that expert handlers try to reduce the

7. The maximum acceptable weight of lifts or MAWL was adjusted over a 25-minute period during which the subjects were told that the loads should correspond to an acceptable effort over an eight-hour work period.

load/body distance either by bringing the load closer or by positioning themselves closer to it by tilting the box so as to raise its centre of gravity (Authier et al., 1995; 1996; Plamondon et al., 2010). Bringing the load closer enabled the healthy-weight handlers to reduce the peak resultant moment at L5/S1 imposed by the heaviest box. Based on the data gathered, it is not possible to know whether obese handlers could have adopted this strategy or whether their physical circumference would have physically prevented them from doing so. This latter possibility illustrates the negative impact of obesity on the operating flexibility of obese handlers. Tilting the box allows the handler to bend the knees less during the lift; it reduces lifting height while ensuring better stability of the knees. According to our results, box-tilting—measured indirectly by lifting height—does not seem influenced by obesity.

It must be kept in mind that the length of the moment arm does not of itself explain the external back loading. For example, a 1.4-cm difference in load-body distance between two healthy-weight handlers yields a 73-Nm difference in maximum moment, while a 1.2-cm difference between two obese experts yields a difference of 31 Nm. Other factors come into play, such as box acceleration, tilt and angular trunk acceleration. Future research should focus on better defining the strategies of bringing the box closer to the body, more specifically in relation to the morphological measurements of the participants.

4.4 Posture

We observed little difference between the handler groups in terms of phase duration and postures adopted. On average, the obese handlers adopted a strategy similar to that of the healthy-weight handlers during the lifting and deposit of boxes from and to different heights. Similarly, Xu et al. (2008) failed to find any difference between obese subjects (BMI $\geq$ 30 kg/m^2) and normal-weight subjects in terms of back angle during load lifting in the sagittal plane with fixed foot placement. The load mass lifted corresponded to 10% (~ 6 kg) and 25% (~ 15 kg) of the subjects' capacity. The authors nonetheless did note that the obese subjects showed higher trunk sagittal plane and transverse plane (twisting) velocity and acceleration. They offer little in the way of explanation, but on the basis of their results and given the relatively small sample (n = 6 per group), these increases in trunk kinematics could be linked to slightly higher peak back loading in obese participants (171.6 Nm vs. 191.8 Nm; p=0.15). The differences between obese and non-obese participants reported by Xu et al. (2008) were not observed in our study. It should, however, be mentioned that the handling conditions in our study differed considerably from those of Xu et al. (2008) in terms of foot constraints, lifting task configuration, the mass and number of loads handled and, especially, the number of subjects.

Our results indicate that for the 'average' obese or healthy-weight handler, the closer the box to be lifted or deposited was to the ground, the more the back and knees were bent. Nevertheless, the ‘average’ strategies are subject to wide variation from one individual to the next, for both obese and healthy-weight handlers.

This variation is striking when one looks at the subgroups divided according to expertise. In particular, the knee position during lifting of boxes close to the ground in the return trip to the conveyor seemed, at first glance, to be as variable for the experts as for the novices. But when we analyzed this result according to the height of the participants, we noticed that the three shorter experts (< 1.68 m) adopted a strategy of moderate lumbar flexion (< 65°) and slight knee bending (< 72°), while the six taller experts had moderate lumber flexion and greater bending at the knee. This correlation between height and knee bending when lifting the box closest to the ground has not been observed before in novice and expert handlers. Plamondon et al. (2010) emphasized that the difference between experts and novices lay as much in knee bending as in lumbar flexion; i.e., that most experts will increase knee bending but will limit back bending during maximum lifting effort. In analyzing the nine experts in our study, we observed the same tendencies, especially with regard to lumbar flexion, with most experts limiting their flexion to less than 65° during maximum lifting effort. That said, a great many novice and experienced handlers (9/28 or 32%) kept their lumbar flexion below this level (moderate, i.e., < 65°). This shows that some novice (or experienced) handlers can adopt safe postures.

However, none of the obese handlers showed knee bending of more than 120°, whereas five healthy-weight handlers (including two experts) did so at the time of maximum effort when lifting a box from the ground. This may be explained by leg flexibility and/or the muscular effort needed to extend the knees from a crouched position.

4.5 Prediction model

This study has enabled us to present a preliminary statistical model for predicting peak extension moment when lifting a load from the ground. Attention should not be focused on the model itself but rather on the four factors that were identified in the multiple regression analysis and that explain over 80% of the variation observed. These factors are associated with certain basic principles recognized in the scientific literature and discussed above, and with two other factors linked to the worker’s anthropometry. Load/body distance and lumbar flexion are the main factors connected to the work methods attributed to expert handlers. The factors linked to anthropometry are parameters sensitive to obesity. Upper trunk weight (estimated by Jensen’s volumetric technique, 1978) is part of the mass that must be supported by the lower spine. Upper trunk weight is necessarily linked to the individual’s BMI and overall weight. The other anthropometric factor is the thickness of the trunk as measured at T12. This variable, too, is linked to BMI and weight, in addition to having a direct influence on the load position in relation to the body. Obesity therefore influences three of these four factors, and that would account for obesity’s negative impact on external back loading.

4.6 Limitations of the study

As in the study comparing expert and novice handlers, in our study there was an age difference: the obese handlers were older and more experienced. Recruitment took place over and eight-month period, and was not simple; in particular, it was difficult to persuade obese handlers to participate. We had to change our selection criteria to include not only novices (our starting criterion) but also handlers with more than one year of experience (our final criterion). We also adjusted our samples to ensure an equal number of experts in each group.

We were not able to completely dissociate the effects of obesity from those of worker experience. Nevertheless, we have shown that the BMI and weight factors related to obesity have a significant influence on external back loading, whereas age and experience do not. We also noted that the behaviour of obese experts seemed similar to that of healthy-weight experts. Our study results highlight the fact that an uneven distribution of obese participants in groups of handlers can influence certain data, including external moments.

Several sources of error are associated with the biomechanical model. The imprecision of measuring instruments, the misidentification of anatomical landmark positions and the displacement of skin markers relative to landmarks, especially in obese participants, can cause measurement errors in kinematic and kinetic data. However, steps were taken to diminish these errors: for example, the instruments were calibrated and the lab assistants were given strict instructions on how to affix the devices to the participants. The data were also visually checked to ensure accuracy. Consequently, we believe that these errors did not significantly affect our results.

Steps were also taken to limit the constraints inherent in laboratory simulations, but we cannot claim that the handlers reproduced their usual work methods down to the last detail. In any case, these constraints affected both the obese and healthy-weight participants to the same extent.

4.7 Conclusion

In conclusion, there can be no doubt that the excess weight of an obese worker has a deleterious effect on the external loading of the musculoskeletal structures of the back. The morphology of the obese handler also limits the possibility of bringing the load closer, which reduces his margin of manoeuvre. These biomechanical factors therefore expose obese handlers to greater risks of developing an MSD from manual materials handling than healthy-weight handlers.

There are few differences between the work methods of obese handlers and healthy-weight handlers, whether expert or not, in experimental conditions where fatigue is minimal. However, the results could be very different if the handlers had been subjected to more intense work conditions, given the reduced aerobic and anaerobic capacities of obese individuals. Further studies are needed to understand why this know-how (and perhaps other techniques) develops and how it changes as a worker gains experience. These results have great importance because they underline the need to take the obesity factor into account in manual materials handling.

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APPENDICES

Appendix A: Body Segment Parameters

Tables A.1, A.2 and A.3 below list average values for body segment parameters requires for the 3D biomechanical model used to estimate net moments at the L5/S1 joint (Plamondon et al., 1996).

Table A.1 – Average and standard deviation of mass of each segment

	Healthy-weight handlers N = 20	Obese handlers N = 17
Sacrum	9.3 (± 1.7)	16.2 (± 2.8) *
Right thigh	8.0 (± 1.1)	10.2 (± 1.7) *
Left thigh	8.0 (± 1.1)	10.2 (± 1.7) *
Right shank	3.5 (± 0.4)	4.5 (± 0.7) *
Left shank	3.5 (± 0.4)	4.5 (± 0.7) *
Right foot	2.0 (± 0.4)	2.5 (± 0.4) *
Left foot	2.0 (± 0.4)	2.5 (± 0.4) *
T12	8.0 (± 1.4)	13.7 (± 2.6) *
C7	13.5 (± 1.8)	18.7 (± 3.2) *
Head	5.7 (± 0.6)	6.5 (± 0.7) *
Right upper arm	2.0 (± 0.3)	2.6 (± 0.5) *
Left upper arm	2.0 (± 0.3)	2.6 (± 0.5) *
Right forearm	1.6 (± 0.3)	2.1 (± 0.3) *
Left forearm	1.6 (± 0.3)	2.1 (± 0.3) *

*Indicates p-value associated with independent samples t-test is less than 0.05.

Table A.2 – Average and standard deviation of centres of gravity in x, y and z axes for each segment

	Centre of gravity in x axis		Centre of gravity in y axis		Centre of gravity in z axis	
	Healthy weight	Obese	Healthy weight	Obese	Healthy weight	Obese
Sacrum	-0.1 (±0.01)	-0.1 (0.02)*	-0.01 (±0.01)	0.01 (±0.01)	-0.0002 (±0.006)	-0.004 (±0.008)
Right thigh	-0.2 (±0.02)	-0.2 (±0.02)*	-0.01 (±0.01)	-0.005 (±0.01)	0.006 (±0.007)	0.008 (±0.008)
Left thigh	-0.2 (±0.02)	-0.2 (±0.02)*	-0.01 (±0.01)	-0.004 (±0.01)	-0.008 (±0.007)	-0.01 (±0.07)
Right shank	-0.2 (±0.02)	-0.2 (± 0.02)	-0.02 (±0.01)	-0.02 (±0.01)	0.01 (±0.006)	0.009 (±0.01)
Left shank	-0.2 (±0.02)	-0.2 (± 0.02)	-0.02 (±0.01)	-0.02 (±0.01)	-0.004 (±0.009)	-0.001 (±0.01)
Right foot	-0.1 (±0.01)	-0.1 (± 0.02)	-0.005 (±0.01)	-0.007 (±0.01)	0.004 (±0.006)	0.002 (±0.005)
Left foot	-0.1 (±0.01)	-0.1 (± 0.02)	-0.003 (±0.01)	-0.006 (±0.01)	-0.001 (±0.007)	-0.003 (±0.006)
T12	-0.1 (±0.01)	-0.1 (± 0.02)	0.02 (±0.02)	0.07 (±0.02)*	-0.002 (±0.009)	0.0005 (±0.01)
C7	-0.2 (±0.01)	-0.2 (± 0.02)	0.02 (±0.02)	0.03 (±0.02)*	0.0004 (±0.01)	-0.0002 (±0.009)
Head	-0.1 (±0.01)	-0.1 (± 0.01)	0.06 (±0.02)	0.06 (±0.02)	-0.003 (±0.007)	-0.001 (±0.005)
Right upper arm	-0.2 (±0.01)	-0.1 (±0.01)*	-0.0002 (±0.01)	-0.001 (±0.02)	-0.01 (±0.009)	-0.006 (±0.01)
Left upper arm	-0.2 (± 0.01)	-0.1 (±0.01)*	0.005 (±0.02)	-0.001 (±0.02)	0.01 (±0.01)	0.007 (±0.02)
Right forearm	-0.1 (± 0.01)	-0.1 (± 0.02)	0.002 (±0.007)	0.002 (±0.01)	-0.004 (±0.01)	0.006 (±0.02)*
Left forearm	-0.1 (±0.01)	-0.1 (±0.02)	-0.0002 (±0.01)	-0.0005 (±0.01)	0.005 (±0.01)	-0.007 (±0.02)*

*Indicates p-value associated with independent samples t-test is less than 0.05.

Table A.3 – Average and standard deviation of moments of inertia of each segment

	Moment of inertia about the sagittal axis		Moment of inertia about the transverse axis		Moment of inertia about the longitudinal axis	
	Healthy-weight	Obese	Healthy weight	Obese	Healthy weight	Obese
Sacrum	0.07 (±0.02)	0.2 (±0.04)*	0.05 (±0.02)	0.1 (±0.04)*	0.08 (±0.02)	0.2 (±0.05)*
Right thigh	0.1 (±0.03)	0.1 (±0.03)*	0.1 (±0.03)	0.1 (±0.03)*	0.03 (±0.007)	0.05 (±0.01)*
Left thigh	0.1 (±0.03)	0.1 (±0.03)*	0.1 (±0.03)	0.1 (±0.03)*	0.03 (±0.007)	0.05 (±0.01)*
Right shank	0.05 (±0.01)	0.06 (±0.01)*	0.05 (±0.01)	0.06 (±0.01)*	0.005 (±0.001)	0.009 (±0.002)*
Left shank	0.05 (±0.01)	0.06 (±0.01)*	0.05 (±0.01)	0.06 (±0.01)*	0.005 (±0.001)	0.009 (±0.002)*
Right foot	0.007 (±0.003)	0.008 (±0.002)	0.009 (±0.003)	0.01 (±0.003)*	0.004 (±0.001)	0.006 (±0.002)*
Left foot	0.007 (±0.003)	0.009 (±0.003)	0.009 (±0.003)	0.01 (±0.003)	0.004 (±0.001)	0.006 (±0.002)*
T12	0.06 (±0.01)	0.1 (±0.04)	0.04 (±0.01)	0.1 (±0.04)*	0.07 (±0.02)	0.2 (±0.06)*
C7	0.2 (±0.04)	0.3 (±0.09)*	0.1 (±0.03)	0.2 (±0.07)*	0.1 (±0.03)	0.2 (±0.07)*
Head	0.03 (±0.004)	0.04 (±0.007)	0.03 (±0.005)	0.04 (±0.008)*	0.02 (±0.004)	0.03 (±0.006)*
Right upper arm	0.02 (±0.004)	0.02 (±0.006)	0.02 (±0.004)	0.02 (±0.006)	0.002 (±0.0006)	0.004 (±0.001)*
Left upper arm	0.02 (±0.006)	0.03 (±0.006)*	0.02 (±0.004)	0.02 (±0.006)	0.002 (±0.0006)	0.004 (±0.001)*
Right forearm	0.02 (±0.006)	0.03 (±0.006)*	0.02 (±0.006)	0.03 (±0.006)	0.001 (±0.0004)	0.002 (±0.0007)*
Left forearm	0.02 (±0.006)	0.03 (±0.006)*	0.02 (±0.006)	0.03 (±0.006)	0.001 (±0.0005)	0.002 (±0.0007)*

*Indicates p-value associated with independent samples t-test is less than 0.05.

Appendix B: Definitions

Table B.1: Definitions of kinetic and kinematic variables

Variable	Description
Peak resultant moment at L5/S1 (Nm)	Highest value for resultant moment (m) at L5/ S1. Resultant moment = $\sqrt{m_{extension}^2 + m_{lateral\ bending}^2 + m_{twisting}^2}$
Occurrence (%)	Occurrence of resultant moment: negative value = pre-flight; 0 to 50% = flight in lifting phase; 51 to 100% = flight in deposit phase; 100% = post-flight; lifting phase -200% to 50%; deposit phase 51% to 200%; 0% to 100% = flight
Lumbar flexion angle (°)	Flexion angle of the lumbar region (°) calculated using the Grood and Suntay (1983) sequence
Lateral bending angle (°)	Lumbar lateral bending angle (°) calculated using the Grood and Suntay (1983) sequence
Lumbar twisting angle (°)	Lumbar twisting angle (°) calculated using the Grood and Suntay (1983) sequence
Trunk inclination (at T11) from the vertical (°)	Angle of flexion of the trunk from the vertical at T11 (°)
Horizontal distance of box from L5/S1 (m)	Horizontal distance (m) of the box from the L5/S1 joint
Right knee flexion (°)	Angle of flexion of the right knee (°)
Left knee flexion (°)	Angle of flexion of the left knee (°)
Lumbar flexion angular velocity (°/s)	Angle of velocity of the lumbar area along the transverse axis of the trunk (°/s).
Peak asymmetrical moment at L5/S1 (Nm)	Highest value for asymmetrical moment (Nm) at L5/S1 Resultant moment = $\sqrt{m_{lateral\ bending}^2 + m_{twisting}^2}$
Cumulative resultant moment at L5/S1 (Nms)	The sum of the resultant moments at L5/S1 during the flight of the box