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Differences in spinal moments, kinematics and pace during single-task and combined manual material handling jobs

Yaar Harari[a,b], Raziel Riemer[a,*], Avital Bechar[a,b]

[a] Department of Industrial Engineering and Management, Ben-Gurion University of the Negev, Beer Sheva, Israel
[b] Institute of Agricultural Engineering, Agricultural Research Organization, Bet Dagan, Israel

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ABSTRACT

This study compared the spinal moments (i.e., peak and cumulative moments acting on the L5/S1 joint), kinematics (i.e., peak trunk and knee angles) and work pace of workers, when either removing a box from a shelf or depositing a box on a shelf, under two conditions: as a single task or as part of a combined task. An experiment was conducted, in which the subjects performed the tasks and were recorded using a motion capture system. An automated program was developed to process the motion capture data. The results showed that, when the removing and depositing tasks were performed as part of a combined task (rather than as single tasks), subjects experienced smaller peak and cumulative spinal moments and they performed the tasks faster. The results suggest that investigations into the separate tasks that comprise a combination have a limited ability to predict kinematics and kinetics during the combined job.

1. Introduction

Work-related musculoskeletal disorders (MSDs) are responsible for 30% of lost injury days and result in annual costs of between $45 billion and $54 billion in the US alone (Bureau of Labor Statistics, 2015; National Academy of Sciences, 2001). The largest source of work-related claims and costs due to MSDs is manual material handling (MMH), accounting for 32% of claims and 36% of costs (Murphy et al., 1996). MMH refers to jobs which include lifting, lowering, carrying, pulling and pushing objects. In an effort to reduce work-related MSDs in MMH jobs, many studies have investigated worker biomechanics and developed task-analysis tools (Garg and Kapellusch, 2009).

However, observations of work processes within organizations suggest that risk assessment using biomechanical analysis is difficult to apply (Straker et al., 1997b). One of the reasons for this difficulty could be the assumption that the risk of a work process that includes a combination of tasks (e.g., the continuous-sequential task of removing a box from a shelf, carrying it and then depositing it on another shelf) can be evaluated by separately assessing the risk of each component task (Straker et al., 1996; Dempsey and Mathiassen, 2006). The hypothesis of the current study is that a worker's kinematics and kinetics are different when a removing or depositing task is performed as a single task, rather than as part of a combined MMH job, which could lead to differences in the risk-of-injury assessment.

To the best of our knowledge, only one study has compared the biomechanics of single-task and combined MMH jobs (Straker et al., 1997b). In this study, subjects performed a combination of tasks (i.e., pulling a box, then lifting, carrying, lowering and pushing it), and also carried out each of the component tasks as a single task. The authors found that the peak hand force and the peak spinal compression and shear forces were different during the combined MMH job than during the single tasks that comprised it.

However, the study of Straker et al. (1997b) used a 2-D biomechanical model and assumed symmetrical movement of the body, an assumption that may be less accurate for combined MMH jobs, as these include motions such as body turning. Straker et al. (1997b) attached reflective markers to only one side of the body, and when the subject's body turned the markers could no longer be seen by the cameras. In addition, the cumulative load (Kumar, 1990) was not considered. Finally, the kinematics of the workers in the combined scenario were not investigated. Understanding worker kinematics could benefit motion and task-duration prediction models (Harari et al., 2018; Qu and Nussbaum, 2009) and may also help to explain the dynamic differences between single-task and combined MMH jobs.

The objective of the current study is to compare spinal loading (i.e., peak and cumulative moments acting on the L5/S1 joint), kinematics (i.e., peak trunk and knee angles) and work pace, when a removing or depositing task is conducted as a single task and as part of a combined

* Corresponding author. Ben-Gurion University of the Negev, Department of Industrial Engineering and Management, P.O.B. 653, Beer Sheva, Israel.
E-mail address: rriemer@bgu.ac.il (R. Riemer).

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MMH job.

2. Methods

The experiment consisted of two parts. In the first part, the subjects conducted combined jobs, which comprised the continuous-sequential removing of a box from a shelf, carrying it and depositing it on another shelf. In the second part, the subjects conducted the removing and depositing tasks separately, as single-task jobs. Each subject's motion was recorded using a motion capture system, and the spinal loading, kinematics and work pace were calculated as described in Section 2.4. In order to process the motion capture data, we developed a program that identified and classified each of the tasks and calculated the associated kinematics and kinetics.

2.1. Subjects

The subjects were 20 college students (10 males and 10 females) with a mean age of 26.8 years (SD = 1.1; range 24–28 years), height of 171.9 cm (SD = 8.3; range 154–185 cm), and weight of 68.2 kg (SD = 10.9; range 53–80 kg). All subjects passed a screening questionnaire to ensure that they did not suffer from a heart condition or a musculoskeletal disorder and were not sick or injured. The experimental protocol was approved by the ethics committee of the university.

2.2. Experimental design

2.2.1. The MMH jobs

The subjects performed two types of MMH job. The first was a single-task job that involved one of the following tasks: removing a box from a shelf or depositing a box onto a shelf. The second type was a combined job that consisted of continuous-sequential box conveying from one station to another, and back again. This job is common in production lines and packing houses; in the present study, it consisted of the following tasks: 1) removing a box from a shelf; 2) turning 180° and carrying the box in front of the body for a distance of 2.7 m; 3) depositing the box onto another shelf; 4) turning 180° and returning to the first shelf (Fig. 1).

The box was made of plastic and had dimensions 20 × 55 × 36 cm (height × width × depth). Handles were located on both sides of the box at a height of 15 cm from the bottom. The mass of the box was distributed evenly in terms of width and depth and was concentrated at the bottom of the box.

2.2.2. Task definition

For both the single tasks and combined task, the removing and depositing tasks had the same definition using the same criteria, as follows. The removing task refers to removing a box from a shelf. We defined the beginning of this task as the time frame in which the subject began to reach with his/her hands toward the box (i.e., his/her hands started to move toward the box), while the task was considered to end when the subject's hands (which were now holding the box) reached a steady height (i.e., the height at which the box would be carried). The depositing task refers to placing a box on a shelf. This task started when the subject began to move the box toward the shelf (i.e., when the subject's hands started to move toward the shelf) and it ended when the subject's hands returned to the sides of his/her body (i.e., when the hands reached the height that they occupied during normal walking without a box). More explanation on the task definition and the detection of these events during the experiment is detailed in Section 2.6.

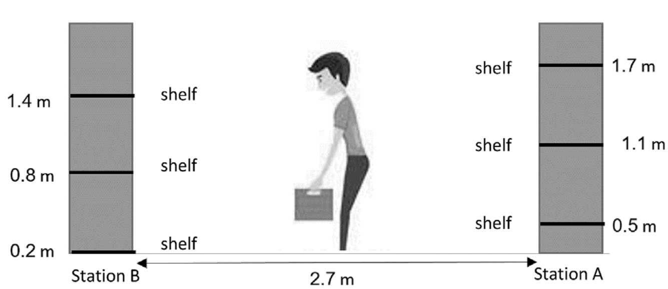

Fig. 1. The experimental layout. Stations A and B each comprise three shelves and are located a distance of 2.7 m apart. The subject walked to one of the stations, removed a box from a shelf, carried the box to the other station, deposited the box onto a shelf and returned to the initial station.

Table 1
Values of the job design characteristics.

Box masses [kg]	Shelf heights (removing) [m]	Shelf heights (depositing) [m]
2, 5, 8,12[a]	0.2, 0.5[b], 0.8, 1.1[b],1.4, 1.7[b]	0.2, 0.5[b], 0.8, 1.1[b],1.4, 1.7[b]

[a] Only males.
[b] Not measured for the single task.

2.2.3. Description of the independent variables

Three of the job's characteristics were defined as independent variables: 1) the mass of the box that was handled, 2) the height of the shelf from which it was removed, and 3) the height of the shelf upon which it was deposited. The values that these characteristics took are presented in Table 1. The subject's gender was also considered as an independent variable in the model.

2.3. Experimental procedure

Upon entering the lab, the subject's height and weight were measured. The subject was instructed to work at a pace that he/she could maintain for 8 h of work, and to stop the procedure if any physical difficulty occurred. Prior to the main experiment the subject practiced both the single-task and combined jobs for 5 min. The experiment was divided into two parts: one for the single-task jobs and one for the combined job. Each part was divided into three trials for females and four trials for males, one for each box mass (i.e., 2, 5 and 8 kg, and for the male subjects, an additional mass of 12 kg). During each trial in the single-task part, the subject removed the box four times from each shelf height (0.2 m, 0.8 m and 1.4 m above the floor). The three additional heights (0.5 m, 1.1 m and 1.7 m above the floor) were not measured for the single task. Each removing task began with the subject standing a distance of 1 m from the shelf, with the arms to the sides of the body. The subjects were free to move forward (all of them took at least one step toward the shelf). After each removal, the box was taken from the subject by one of the research team and placed back on the shelf, and the subject returned to the initial position in order to prepare for the next removing task. A similar procedure was performed for depositing, in which the initial position involved the subject holding the box at waist level. During each trial in the combined part, the subject completed three repetitions of the combined job for each of 18 combinations of removing and depositing heights (see Appendix 1). The order of the two parts of the experiment (i.e., single-task and combined), the order of the trials (i.e., box masses) and the order of the removing and depositing heights within each trial were randomly assigned for each subject. After each trial, the subject received a 5-min break.

2.4. Dependent variables

To test the differences in the subjects' biomechanics between the single-task and combined jobs, we calculated the task duration and each subject's spinal loading and kinematics. The spinal loading variables were the peak and cumulative joint moments acting on the joint between the L5/S1 vertebrae. The cumulative joint moment vector due to a single execution of a removing or depositing task was calculated as follows:

$$M_{cumulative} = \sum_{1}^{n} M_i \Delta t \quad (1)$$

Where n is the number of frames of motion data captured during the task, M_i is the moment for time frame i, and Δt is the time interval between successive frames. In this study we focused on the flexion/extension moments, as they were much higher than the moments along the other axes, and we used an inverse dynamics technique to calculate the net muscle joint moment. To simplify the notation, herein we refer to the output of this analysis as the "joint moment".

The kinematics variables included the peak inclination angle of the trunk, the peak bending angle of the knees, and the horizontal distance between the hands and the L5/S1 joint, in the time frame in which the subject experienced the largest spinal moment. The trunk inclination angle was defined as the angle between the trunk segment and the vertical axis of the lab, where the angle of a straight trunk was defined as 0°, and the angle for bending with the trunk parallel to the floor was 90°.

2.5. Data collection

62 reflective markers were positioned on the subject's body, creating a full body model (see Appendix 2). The model was based on the studies of Ferrari et al. (2008), Leardini et al. (2009) and Seay et al. (2008). Three additional markers were positioned on the box being handled. During the experiment, the markers' positions were captured by the Qualisys™ (GÖTEBORG, Sweden) system using 14 cameras at a sampling rate of 100 Hz.

2.6. Data processing program

During the combined part of the experiment, each trial was captured as one record. Thus, each record included 54 job cycles, where a job cycle refers to one removing task followed by one depositing task. This part of the experiment resulted in 70 records (10 subjects x 3 masses for the female participants and 10 subjects x 4 masses for the male participants). In total, 7560 tasks were performed in the combined part of the experiment, equally divided between removing and depositing tasks.

During the single-task part of the experiment, each record pertained either to a removing task or to a depositing task and included 12 job executions (3 shelf heights x 4 repetitions). This part of the experiment resulted in 140 records (10 subjects x 2 tasks × 3 masses for the female participants and 10 subjects x 2 tasks × 4 masses for the male participants). In total, 1680 tasks were performed in the single-task part of the experiment, equally divided between removing and depositing tasks.

In order to process the motion capture data for each removing or depositing task individually, an automated program was developed and implemented, which used both Visual3D™ and MATLAB™ (see Appendix 3). This program was applied to process the data from both the combined and single-task parts of the experiment. The program consisted of four stages: first, the motion capture data were imported and filtered; second, the subjects' joint angles and moments were calculated; third, the initial and final time frames of each removing (or, respectively, depositing) task were identified and the removing (depositing) task was classified according to its initial (final) height; and finally, the values of the dependent variables for each task were calculated. The following paragraphs describe each of these stages in more detail.

In the first stage of the automated program, the motion capture data were filtered using a fourth-order low-pass Butterworth filter with a 6 Hz cutoff frequency (Butterworth, 1930). In the second stage, the subject's joint angles and moments were calculated using top-down 3-D inverse dynamics (Winter 2009) in Visual3D™, where joint centers were determined using the inverse kinematics approach (Reinbolt et al., 2005). Whenever the box was not touching the shelves (i.e., for all recording frames in which the box mass affected the subject's dynamics), half of the box's mass was added to the mass of each of the subject's hands.

In the third stage, a program that identifies each task from the motion capture data was used. This program was built on our previous experience in writing this type of algorithm (Gimmon et al., 2015; Kalantarov et al., 2018). It used the hands' position and velocity signals, as well as the box position and velocity, in all three axes, in order to identify the start and end frames of each task (based on the task definitions in Section 2.2.2). For both the single and combined tasks, the same signals, criteria and thresholds were used to identify the start and end frames of a task.

The start of the removing task was defined by the event where the subject began reaching with their hands toward the box. To detect the relevant time frame, we first detected when the box started to move using box velocity signals in the Y axis, which is the direction of walking from station to station, with a threshold for box movement of Box_Velocity(Y) $>$ 0.05 m/s. Then, using the time frame where the box started to move, the hand markers' positions in the Z axis (height) were analyzed backwards (i.e., by looking at the time frames that preceded the beginning of box motion), to find the beginning of the reaching movement. Since hand height followed a *cyclic* motion during walking, while the hand motion when reaching for the box consisted of *continuous* movement (i.e., towards the box), the algorithm identified the start of reaching for shelves below (above) 1.1 m by finding the last local maximum (minimum) of the hand height before box movement. The removing task was considered to end when the subject held the box at the steady height at which it would be carried. To detect this event, we used the box velocity in the Z axis, with a threshold of Box_Velocity (Z) $<$ 0.05 m/s.

The depositing task starts when the subject's hands (now holding the box) begin to reach toward the shelf for depositing. To detect this event, we first used the box velocity signals in the Y axis and detected the time frame in which the box was deposited, with a threshold of Box_Velocity (Y) $<$ 0.05 m/s. We then analyzed the hand movement signal backwards, to detect the beginning of the reaching movement toward the shelf. The threshold for shelves below (above) 1.1 m was identified by finding the last hand height maximum (minimum) before the box was deposited. The depositing task ends when the subject's hands (now without the box after depositing it) return to the sides of the body. To detect this event, we used the hand marker velocity in the Z axis, with a threshold of Hand_Velocity(Z) $<$ 0.05 m/s.

To evaluate the performance of our program in detecting these events, 300 motion files (corresponding to two different subjects, all box masses, and all shelf heights) were visually inspected by an expert who marked the time stamps of the events (with a resolution of 1/100 s). We later compared these times with the automated program and the maximum error was ± 2 time frames (20 ms).

Finally, in the fourth stage of the program, the processed data were exported from Visual3D™ to MATLAB™, within which the dependent variables (see Section 2.4) for each task were calculated automatically. This yielded a final dataset that was subjected to statistical analyses.

2.7. Statistical analyses

In order to compare the two task types (single-task and combined), the linear mixed model (LMM) method was applied. Separate models were fitted for the removing and the depositing tasks, and for each dependent variable. The fixed effects in the LMM model were the task type (single or combined), the box's mass, the shelf height and the subject's gender. The random effect in the LMM was the subject's identification number (each subject received a different number between 1 and 20). The temporal dependent variable was the task duration. A difference in duration for the two task types might explain any difference in the cumulative spinal moments. The spinal loading dependent variables were the peak and cumulative moments acting on the L5/S1 joints. These variables are related to a worker's risk of injury. The kinematic dependent variables were the peak trunk and knee bending angles and the horizontal distance between the box and the L5/S1 joint at the time of the peak spinal moments. These variables might be affected by the working technique, which may differ between single-task and combined MMH jobs. The kinematic variables may also explain differences in the worker's spinal loadings.

In addition to examining the influence of job type (i.e., single-task vs. combined) on the dependent variables, we also investigated the interactions between job type and the job parameters, i.e., the box mass, removing height (for the removing task), and depositing height (for the depositing task). Whenever a significant interaction was found, we carried out a series of t-tests to examine the significance of the difference in the dependent variable for the two job types at each possible value of the job parameter in question. We also tested whether the order of the conditions performed by each subject (i.e., the order of masses handled and the removing/depositing heights) affected the results. The statistical analyses were performed using the R Studio environment (R Core Team, 2017). For all statistical tests, a significance level of $p < 0.05$ was set.

3. Results

A significant difference between single-task and combined jobs was found in the following dependent variables: peak and cumulative moments acting on the L5/S1 vertebrae joint, task duration, trunk and knee peak angle, and the horizontal distance between the box and the L5/S1 vertebrae joint at the time of the peak spinal moment (detailed results of the LMM are presented in tabulated form in Appendix 4). Specifically, when the removing and depositing tasks were conducted as part of the combined jobs, the peak and cumulative moments acting on the L5/S1 joint were smaller, the task duration was shorter, and the horizontal distance was smaller. Subject gender was found to affect all dependent variables except task duration. However, for the spinal loading variables, the difference between single and combined tasks was not affected by the subject's gender (i.e., the interaction between task type and gender was not significant). For the kinematic variables, the difference between single and combined tasks was affected by subject gender. Still, even for the kinematic variables, the task type had the same effect for both males and females (e.g., for both genders the horizontal distance was smaller during the combined task). Gender affected only the magnitude of the difference between single and combined tasks, and only for the kinematics. Finally, the order of the conditions (i.e., the order of the masses handled and the removing/depositing heights) did not affect the dependent variables ($p > 0.05$).

3.1. Task duration

The task duration during the combined jobs was shorter ($p < 0.05$) than during the single-task jobs by an average of 30.7% and 16.4% for removing and depositing respectively (Fig. 2). A removing or depositing height of 1.4 m resulted in the longest task time, and a height of 0.8 m resulted in the shortest time. The task duration was not significantly affected by the box mass ($p < 0.05$).

3.2. Moments acting on the L5/S1 vertebrae joint

3.2.1. Peak moments

The peak L5/S1 moment measured during the combined job was found to be smaller ($p > 0.05$) than during the single-task job, for both removing and depositing, by an average of 13% (Fig. 3). A possible explanation for this difference is that the two job types involve a

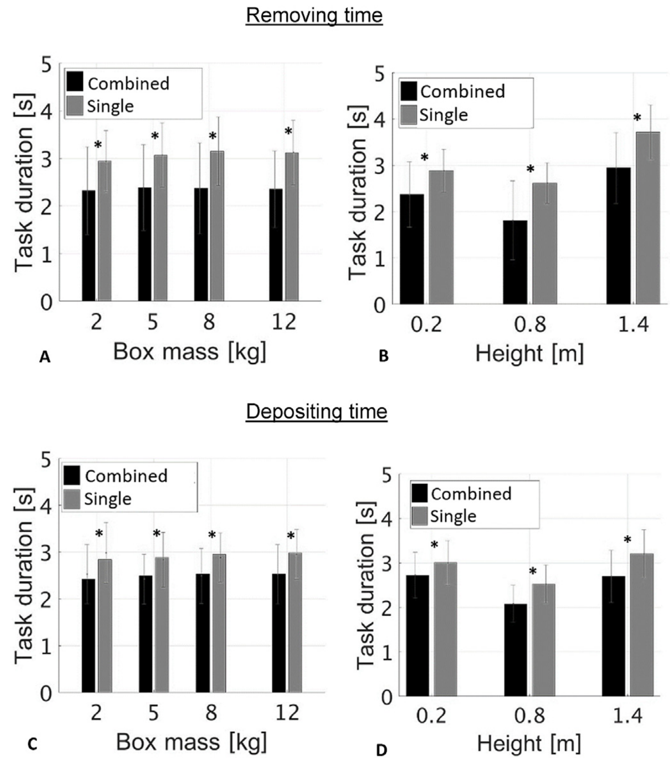

Fig. 2. Mean task duration during the single-task and combined jobs. A) Removing task, different box masses; B) Removing task, different removing heights; C) Depositing task, different box masses; D) Depositing task, different depositing heights. * indicates a significant difference between the single and combined types ($p > 0.05$). Error bars = 1 standard deviation.

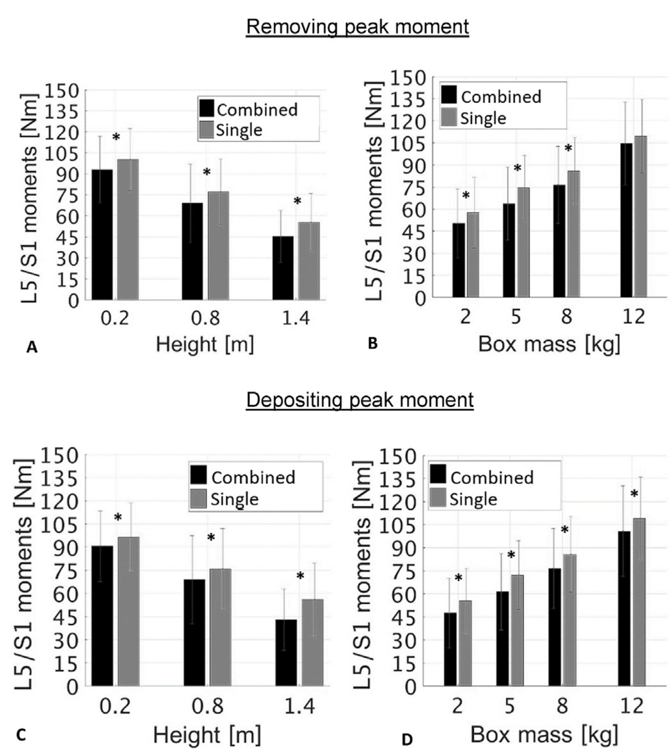

Fig. 3. Peak L5/S1 moments during the single-task and combined jobs. A) Removing task, different removing heights; B) Removing task, different box masses; C) Depositing task, different depositing heights; D) Depositing task, different box masses. * indicates a significant difference between the single and combined moments ($p < 0.05$). Error bars = 1 standard deviation.

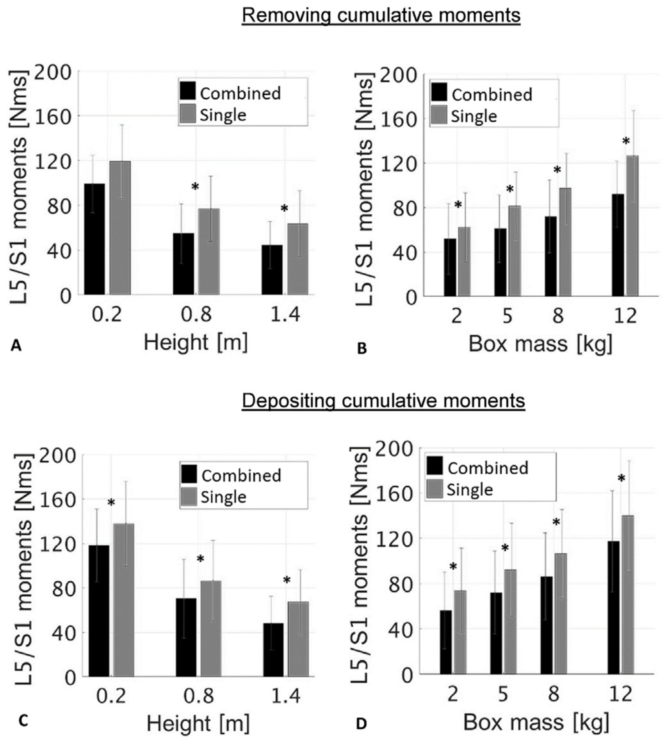

Fig. 4. Cumulative L5/S1 moments during the single-task and combined jobs. A) Removing task, different removing heights; B) Removing task, different box masses; C) Depositing task, different depositing heights; D) Depositing task, different box masses. * indicates a significant difference between the single and combined moments ($p < 0.05$). Error bars = 1 standard deviation.

different technique, as mentioned in Section 3.3. The peak moments decreased as the removing and depositing heights increased, and increased as the box mass increased ($p > 0.05$).

3.2.2. Cumulative moments

The cumulative moment on the L5/S1 joint during combined jobs was found to be smaller ($p < 0.05$) than during single-task jobs, by an average of 32.8% and 25.3% for removing and depositing respectively (Fig. 4). This result was expected, since we already found that during combined jobs, the peak moments were smaller and the task duration shorter, which would also result in smaller cumulative moments. The cumulative moments decreased as the removing and depositing heights increased, and increased as the box mass increased ($p > 0.05$).

3.3. Kinematic differences

3.3.1. Horizontal distance at peak spinal moment

The horizontal distance between the box and the L5/S1 joint at the time of the peak spinal moment was smaller during combined jobs ($p < 0.05$) than during single-task jobs, by an average of 8.6% and 8.8% for removing and depositing respectively (Fig. 5). This finding may explain why the L5/S1 joint moment was smaller during combined jobs.

3.3.2. Trunk and knee angles

The peak trunk and knee angles were found to be different ($p < 0.05$) between combined and single-task jobs, for both removing and depositing (Figs. 6 and 7). For both the knee and trunk angles, the interaction between the task type (single vs. combined) and the removing/depositing height was found to be significant ($p < 0.05$). When the box was removed from a shelf that was 0.2 m above the floor, the peak trunk angle was larger and the knee angle smaller during the combined job (opposed to the single task). This suggests that the subjects used different techniques during the two job types. However, further analysis (beyond the scope of this paper) would be needed to relate these kinematic changes to the spinal moments during the tasks.

4. Discussion

It was found that the subjects experienced smaller spinal moments during the combined MMH jobs. Our results agree with the findings of Straker et al. (1997b), who found the L4/L5 compression forces to be smaller on average during the combined MMH job than in single-task removing and depositing. Specifically, Straker et al. (1997b) reported that the peak spinal compression forces during combined MMH are smaller than those in single-task removing by 15%, while our results show the peak L5/S1 moments in combined tasks to be smaller (by 13%, on average). The main differences between the two studies were that in the current study we used a 3-D biomechanical model, while Straker et al. (1997b) used a 2-D model. Furthermore, in the current study, spinal loading was evaluated by measuring the moments acting on the joint of the L5/S1 vertebrae, while Straker et al. (1997b) measured the compression and shear forces acting on the L4/L5 joint.

An important factor for the prediction of spinal loading and the risk of injury is the horizontal distance between the box and the L5/S1 joint (Waters et al., 1993), which is positively associated with the peak moments acting on the lower back (Schipplein et al., 1995). In the current study, the horizontal distance at the time of the peak spinal moment was shorter during the combined jobs than during the single-task jobs, which could explain the fact that the combined jobs exhibited smaller spinal moments. It is possible that the subjects shortened the horizontal distance during the combined jobs by beginning to turn their bodies during the removing phase. Decreasing the horizontal distance enabled the subjects to reduce the centripetal force and perhaps, as a result, to decrease muscle recruitment.

A risk factor for lower back pain is cumulative spinal loading (Coenen et al., 2013; Kumar, 1990), which in this study was found to be 29% smaller in combined jobs. In this study the workers determined their own pace and therefore the results represent the cumulative loads per task (e.g., for one removing task). Yet in many cases, workers are forced to work at a predetermined pace, and for these cases an adequate measure could be the cumulative moments per time unit. In order to use the results of the current study to analyze paced workplaces, it might be possible to normalize the results by dividing the cumulative loads by the task duration.

Cumulative loading is affected by the magnitude of the moments and by the task duration. In the current study, the peak moments were smaller and the task duration was shorter during the combined jobs, which also resulted in a smaller cumulative load. One possible explanation for the differences in the task duration and cumulative load might be the working technique.

The influence of working techniques on workers' health is still a matter of debate (Burgess-Limerick, 2003; Chaffin and Page, 1994; De Looze et al., 1998; Toussaint et al., 1997; Kjellberg et al., 1998; Bazrgari et al., 2007; Dolan et al., 1994). In the current study, when the subjects removed the box from a shelf that was 20 cm above the floor, they inclined their trunk less and bent their knees more (i.e., used the squat technique) in the single task. It is possible that when the subjects were conducting the single-task jobs, it was easier for them to concentrate on the technique, and therefore they chose the squat technique, which is the most commonly advised approach (Garg and Moore, 1992).

However, contrary to the conventional wisdom that advises the use of the squat technique, in the current study, during the combined task, the subjects used more of a stoop technique and experienced lower spinal moments. This result aligns with a previous review study that investigated the effect of using the stoop vs. squat technique on spinal loads (Van Dieën et al., 1999). In that study the authors concluded that, in cases where a load is not lifted from between the legs (e.g., it is removed from a shelf), spinal loading is lower when using the stoop

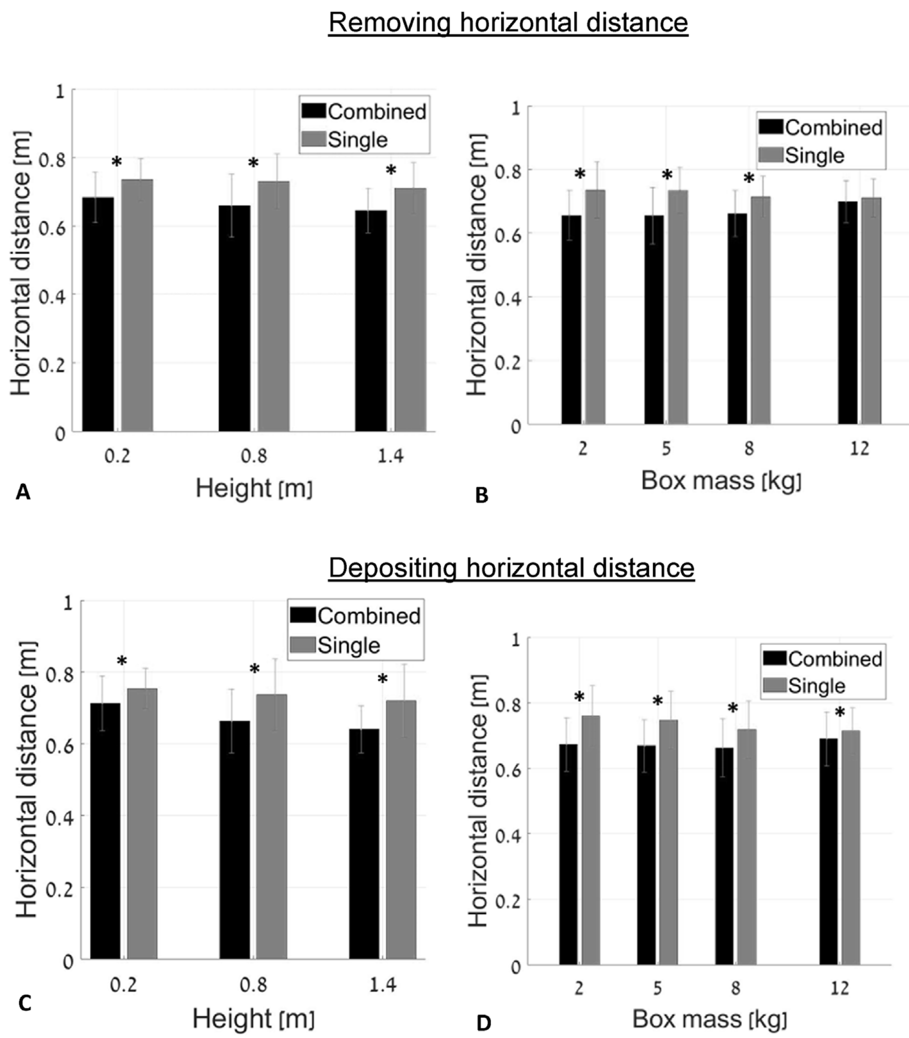

Fig. 5. Horizontal distance between the handled mass and the L5/S1 joint at the time-frame of the peak spinal moment, during the single-task and combined jobs. A) Removing task, different removing heights; B) Removing task, different box masses; C) Depositing task, different depositing heights; D) Depositing task, different box masses. * indicates a significant difference between the single and combined jobs ($p < 0.05$). Error bars = 1 standard deviation.

technique.

The working technique (i.e., the stoop technique) might also explain why subjects completed the tasks faster during the combined part of the experiment. A previous study showed that in tomato picking, workers performed tasks twice as fast when using the stoop technique as opposed to the squat technique (Riemer and Bechar, 2016). Furthermore, additional studies have shown that the stoop technique requires less energy and is rated as being less tiring than the squat technique (Garg and Herrin, 1979; Kumar, 1984). Therefore, it is possible that when the subjects performed the combined tasks (i.e., used the stoop technique), they were less tired and thus performed the tasks faster.

Gender has been shown to affect workers' biomechanics during MMH tasks (e.g., Plamondon et al., 2017; Li and Zhang, 2009; Marras et al., 2003). In this study we found that for spinal moments, the difference between single and combined tasks was not affected by subject gender. Further, even for the kinematics, the difference between single and combined tasks had the same sign for each gender (although not the same magnitude). These results suggest that both genders experience the same effects when shifting from a single task to a combined task.

4.1. Relevance to industry

The results of the current study suggest that task-analysis tools that were developed based on single-task data might overestimate the spinal moments or the risk of injury when they are used to analyze combined jobs. The current findings could also be used to help improve models for predicting workers' pace (e.g., Harari et al., 2018), motion (e.g., Qu and Nussbaum, 2009; Pasciuto et al., 2014) and kinetics (e.g., Lavender et al., 2003; Hoozemans et al., 2008) during single-task and combined MMH jobs. Improvement of these prediction models could benefit digital human modeling software (Chaffin, 2008) and workplace design methodologies (e.g., Harari et al., 2019; Harari et al., 2017; Ben-Gal and Bukchin, 2002; Del Rio Vilas et al., 2013), which in turn could result in improved working conditions.

4.2. Limitations

The subjects in this research were young and healthy students. While this may be representative of MMH workers in some fields (e.g., agriculture, warehouses), other industries may include older and less fit populations. In addition, the subjects were measured during only 1 h of work. While this is a good representation of the beginning of the work shift, it is possible that the work technique and the subjects' joint moments would be different if measured after several hours of continuous work time. Finally, in this study we aimed to investigate work settings in which the workers are able to determine their own work pace. While this is the case in many workplaces, in some situations the workers are

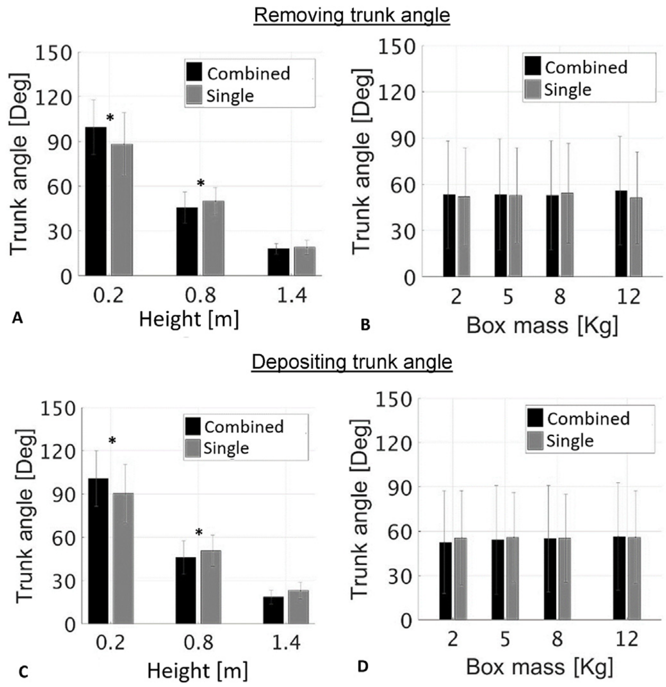

Fig. 6. Peak trunk flexion angle during the single-task and combined jobs. A) Removing task, different removing heights; B) Removing task, different box masses; C) Depositing task, different depositing heights; D) Depositing task, different box masses. * indicates a significant difference between the single-task and combined jobs ($p < 0.05$). Error bars = 1 standard deviation.

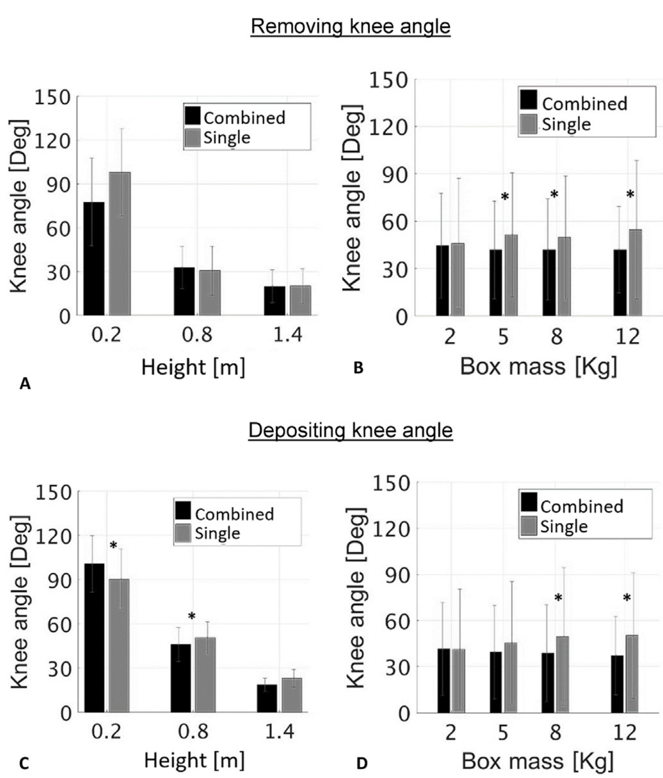

Fig. 7. Peak knee bending angle during the single-task and combined jobs. A) Removing task, different removing heights; B) Removing task, different box masses; C) Depositing task, different depositing heights; D) Depositing task, different box masses. * indicates a significant difference between the single-task and combined jobs ($p < 0.05$). Error bars = 1 standard deviation.

paced, which could affect the task duration and cumulative loads.

4.3. Future work

Since combined jobs are common in industry, future research should focus on the analysis of combined jobs and on the development of new tools for risk assessment during combined jobs. The current study focused on two-handed removing and depositing tasks; future work should also analyze differences between the single-task and combined modes for other MMH tasks. Further, there is a need to extend the current study by including subjects with a wider range of ages, body mass index levels, and experience in MMH. In addition, this study investigated the moments acting on each subject's spine, while future experiments could also use electromyography to measure the electrical activity of muscles, and could compare compression and shear forces between single-task and combined jobs.

5. Conclusions

This study contributes to a better understanding of the biomechanical differences when a removing or depositing task is conducted as a single task, versus as part of a combined MMH job. We found that the subjects' spinal moments, kinematics, and work pace were significantly different between the single-task and combined paradigms. When the removing and depositing tasks were conducted as part of a combined job, the subjects experienced smaller peak and cumulative moments on the L5/S1 joint, and completed the tasks faster. The results suggest that investigations of the separate tasks that comprise a combined MMH job have a limited ability to predict spinal loadings and kinematics during the combined job.

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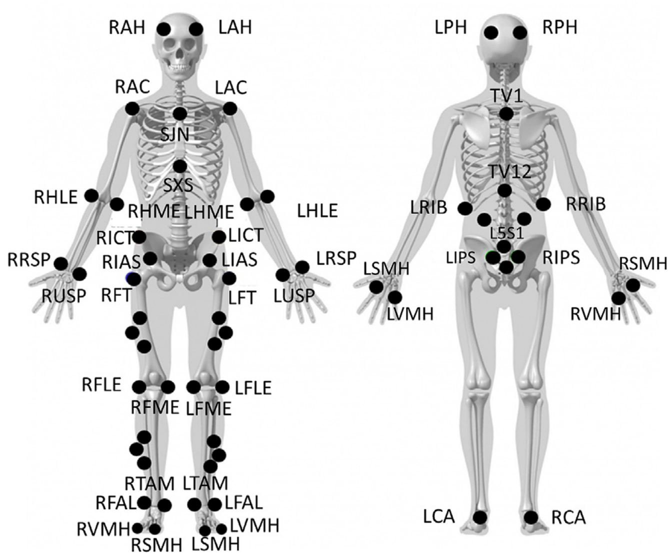
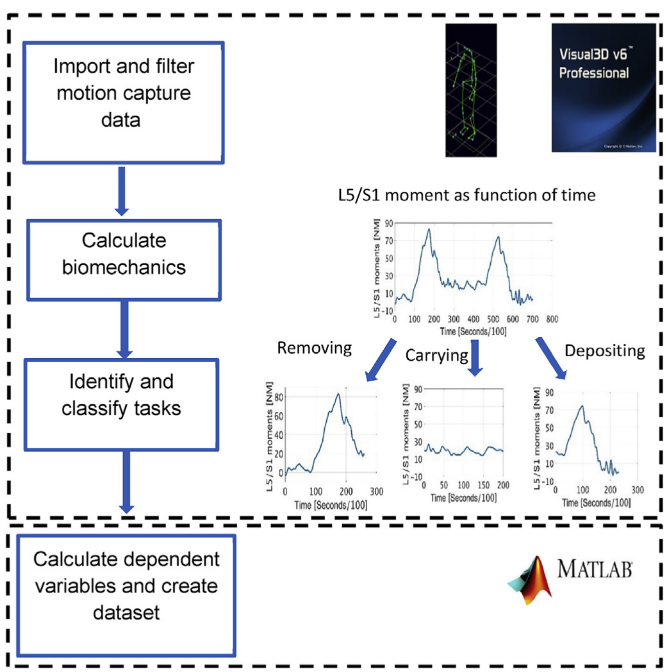
Appendix 1. An example of the combinations of removing and depositing heights [m] in one trial of the combined part of the experiment

Condition#	Removing height	Depositing height	Condition#	Removing height	Depositing height
1	0.2	0.5	10	1.1	0.8
2	0.5	0.2	11	0.8	1.7
3	0.2	1.1	12	1.7	0.8
4	1.1	0.2	13	1.1	1.4
5	0.2	1.7	14	1.4	1.1
6	1.7	0.2	15	1.4	1.7
7	0.5	0.8	16	1.7	1.4
8	0.8	0.5	17	1.4	0.5
9	0.5	1.4	18	0.8	1.1

Appendix 2. Motion capture model: marker positions. The skeleton figure is taken from the C3D website (www.c-motion.com/v3dwiki).



Appendix 3. The automated data-processing program that processes raw marker data to yield joint moments, classified by task. The main parts of the program are as follows: 1) Import the motion capture data and filter it. 2) Calculate the kinematics and kinetics of the body. 3) Identify the initial and final time frame for each task (e.g., removing), and classify each task. 4) Calculate the values of the dependent variables for each task and create a database for each task, for subsequent statistical analysis.



Appendix 4. Results of the LMM tests for the removing and depositing tasks. For each dependent variable, this table presents the number of degrees of freedom (df), F-test value (F), and significance level (p). The column *type* shows the significance of the difference between the two task types (single-task and combined). The remaining columns show the significance of the interaction between the task type and one of the following task parameters: box mass (BM), initial removing height (PCH), final depositing height (DPH), and subject gender (GEN).

Dependent variable		Removing				Depositing			
		type	type* BM	(type)* PCH	(type)* GEN	type	(type)* BM	(type)* DPH	type*GEN
L5/S1 peak moment [N m]	**df**	1	3	2	1	1	3	2	1
	F	125.2	1.96	4.5	0.98	29.8	1.98	44.3	1.29
	p	< 0.01	0.12	0.02	0.32	< 0.01	0.11	< 0.01	0.26
L5/S1 cumulative moment [N m s]	**df**	1	3	2	1	1	3	2	1
	F	373.5	13.1	1.26	0.06	220.8	0.36	0.37	0.32
	p	< 0.01	< 0.01	0.28	0.8	< 0.01	0.78	0.69	0.57
Task duration [s]	**df**	1	3	2	1	1	3	2	1
	F	345.1	1.1	5.7	6	323	0.039	7.1	0.01
	p	< 0.01	0.33	< 0.01	0.014	< 0.01	0.98	< 0.01	0.98
Peak trunk inclination angle [°]	**df**	1	3	2	1	1	3	2	1
	F	9.5	4.9	55.3	17.4	0.37	4.3	57.4	10.9
	p	< 0.01	< 0.01	< 0.01	< 0.01	0.56	< 0.01	< 0.01	< 0.01
Peak knee bending angle [°]	**df**	1	3	2	1	1	3	2	1
	F	29.8	1.98	44.27	8.1	20.3	4.43	53.4	2.55
	p	< 0.01	0.12	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.11
Horizontal distance [m]	**df**	1	3	2	1	1	3	2	1
	F	308	15.7	3.04	14.5	316	12.4	13.1	2.3
	p	< 0.01	< 0.01	0.047	< 0.01	< 0.01	< 0.01	< 0.01	0.12

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