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The effect of drywall lifting method on workers' balance in a laboratory-based simulation

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Abstract. Voluntary body movement can import a perturbation to the postural stability/balance of a human body. Heavy manual material handling such as drywall lifting may increase this perturbation. The objective of this laboratory-based study was to quantify workers' postural stability while lifting drywall sheets through kinetic and kinematic analyses, and to identify the drywall lifting methods that caused the least perturbation on workers' balance. Sixty male construction workers participated in this study. A simulated drywall-lifting workstation was built and all subjects performed one of the four randomly assigned lifting methods. Kinetic and kinematic measurements were synchronized and collected using a piezoelectric force platform and a five-camera motion analysis system. Both center-of-pressure (COP) and center-of-mass (COM) data were analyzed to assess workers' postural stability. Univariate analyses and principal component analyses (PCA) were used to analyze 13 COP-based and 21 COM-based variables. Results from the univariate analyses and PCA significantly indicated that the three horizontal lifting methods created less perturbation than the vertical lifting method. Based on the results of this study and prior studies, it is concluded that horizontal lifting with both hands on top of the drywall appears to be the best work practice to reduce manual drywall handling hazards associated with fall potential and overexertion injuries.

Keywords: Drywall, lifting, kinematics, kinetics, center-of-pressure, center-of-mass, construction

1. Introduction

In spite of modern technological advancements and increased automation in the workplace, many construction tasks still require workers to lift building materials manually. Manual materials handling of heavy and bulky building materials, such as drywall sheets, requires excessive muscle forces, which in the short term, often result in muscle fatigue and discomfort [13]. Over time, continued exposure may result in health effects such as cumulative trauma muscuoloskeletal disorders [14]. Health outcomes associated with manual material handling have been studied extensively by researchers in an attempt to reduce exposures to such health outcomes as overexertion and back injuries [16,24,25,27].

In addition to musculoskeletal disorders, the construction industry is also plagued by fatal and non-fatal fall injuries. In a study of traumatic injuries of drywall installers, falls were found to be the second highest cause of injury [8]. Impacts with floors and wallboards were identified as the two leading sources

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of injury. Carpenters and drywall installers were the top two trades associated with fall injuries in the North Carolina and Saint Louis (USA) areas [11]. Furthermore, drywall-related injuries incur expensive medical costs. Fall-related injuries produced one of the top two most expensive claims in the construction industry [11].

To prevent fall-related injuries, research has been conducted to determine risk factors that contribute to falls, personal factors such as age and gender, and environmental factors such as lighting and floor slip resistance [3,8]. However, the effect of manual lifting on falls has had minimal study. The few studies that have been published, reported the effect of manual lifting on a single variable i.e. workers' balance control [19,28,35,36]. Due to the fact that a human body is a system of segments connected by joints, any voluntary movements will initiate an internal perturbation of balance [19]. This perturbation is even more pronounced when the voluntary movement involves an added load [19] and the blockage of peripheral vision associated with large building materials being handled by the worker [8]. Frontal lifting of a drywall sheet causes a forward shift of the body's center of mass (COM). Greater muscular force, involving more muscles and higher activation levels, are needed to counteract the shift of COM to reach equilibrium. Drywall installers face such perturbations of balance daily. Injury research associated with manual material lifting in the construction industry, however, has rarely been quantitatively and ergonomically evaluated [1,4,10,15,21,33]. To date, no well-controlled laboratory research has been conducted to determine the effect of lifting heavy and bulky drywall sheets on workers' biomechanical stresses associated with falls. Therefore, this study was undertaken to assess and quantify workers' postural stability while lifting drywall sheets; assessment was performed using both kinetic and kinematic analyses. Lifting methods which imposed the least perturbation on workers' balance were identified.

2. Method

2.1. Participants

The kinetic data of this study were collected from 60 male subjects (mean age = 34.4 ± 8.5 years; average weight: 89.1 ± 13 kg; average height: 1.78 ± 0.06 m) recruited from construction work sites and union meetings in northern West Virginia and Maryland (USA). Twenty-eight (mean age = 34.9 ± 8.9 years) of the 60 subjects were randomly selected for kinematic analyses. Each subject was assigned to one of four groups, with each group testing a unique lifting method. These subjects consisted mostly of union carpenters, union construction laborers, and a few individual construction contractors. At least 6 months of drywall installation experience (mean experience = 8.7 ± 6 years) was required for participation in this study. Subjects with a history of the following possibly confounding medical conditions were excluded from the study: uncontrolled hypertension, history of dizziness, tremor, vestibular disorders, neurological disorders, cardiopulmonary disorders, hernias, and chronic back pain. Safety shoes with rubber soles (Armor 75 X-tra Lite non-metallic toe cap shoes, Iron Age^{TM}) were worn by each subject in this study. Subjects were compensated for their participation and given the option of withdrawing from the study at any time. The National Institute for Occupational Safety and Health (NIOSH) Human Subjects Review Board (HSRB) committee approved the study protocol, and each subject signed an informed consent form.

2.2. Experimental procedures

Each subject was required to perform one of four lifting tasks (Fig. 1) with a 4-foot (1.22-meter) by 8-foot (2.44-meter) by -inch (0.0127 meter) sheet of drywall, which weighed approximately 55 pounds

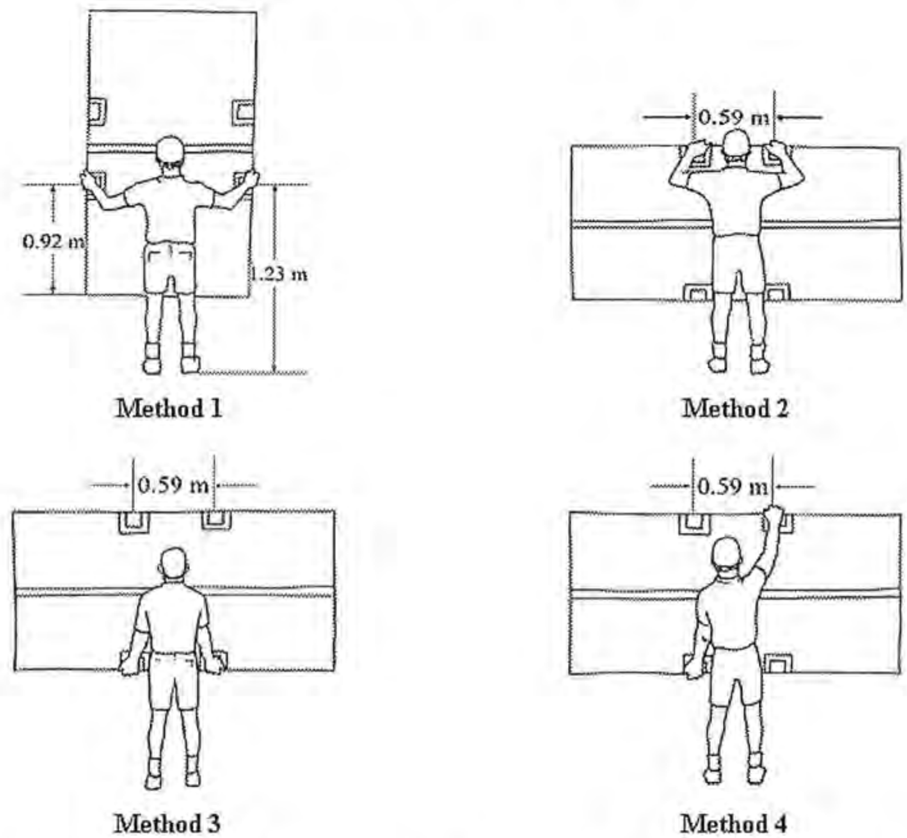

Fig. 1. Drywall lifting methods. Method 1: Vertical lifting; Method 2: Horizontal lift with both hands on top; Method 3: Horizontal lift with both hands on bottom; Method 4: Horizontal lift with both hands alternate.

(24.97 kilograms). The four different lifting tasks included vertical lift of the drywall (Method 1); horizontal lift of drywall with both hands positioned on the top of the drywall (Method 2); horizontal lift of drywall with both hands positioned on the bottom of the drywall (Method 3); and horizontal lift of drywall with one hand positioned on the top and one positioned on the bottom (Method 4). These four lifting tasks were identified from a field study as the most frequently used methods by workers [30]. Four repetitions for each lifting task were completed, and results were collected.

Prior to performing the tasks, each subject completed a 2-hour medical screening, orientation, and training session. Maximum lifting voluntary isometric muscle contraction force using a specific posture and hand location (sagittal lift at elbow height with a 46-cm hand separation) was measured after the training using the method described by Caldwell et al. [6]. Between two sequential lifts, subjects were instructed to relax and rest for 5 minutes to reduce effects of localized muscle fatigue [9,20,32,34]. To standardize subjects' feet positions, each subject stood on a force platform, with standardized footprints outlined for different sizes of shoes. Subjects' heel centers were 0.17 meters apart with an angle of 14 degrees between the long axes of the feet [26].

A simulated drywall-lifting workstation was built specifically for this study as shown in Fig. 2. The distance between each subject and the drywall sheet was standardized. The initial distance between the drywall and the center of the force platform was 23 cm for all four lifting methods. For Method 1, the distance from the bottom edge of the drywall sheet to the center of the hand grip on the vertical drywall

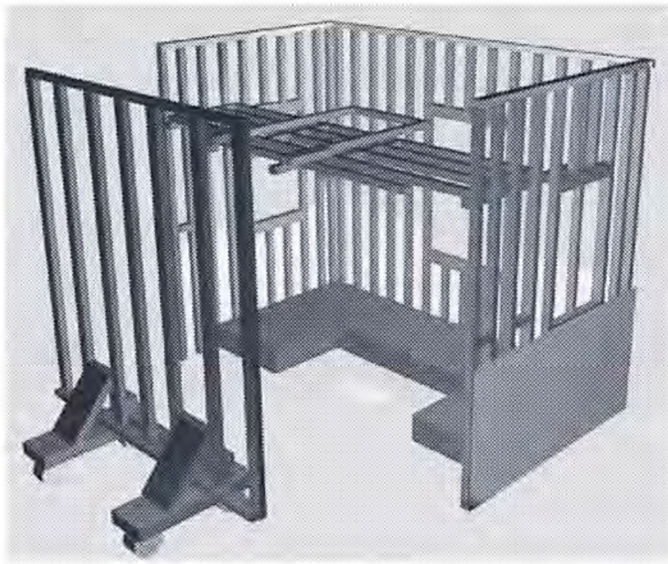

Fig. 2. Illustration of a simulated drywall-handling workstation.

sheet was 0.92 m (Fig. 1). As shown in Fig. 1, the distance from the center of the hand grip on the vertical drywall sheet to the force platform surface was 1.23 m since the drywall sheet was standing in the jig when gripped for Method 1. For lifting Methods 2 and 3, the distance between the hand grip position was 0.59 m (center of the hand grip to center of the other hand grip). Subjects were instructed to only use any their hands while lifting the drywall. The subject's neutral position was defined as having each subject standing upright and motionless with hands on the posterior portion of his hips.

In the beginning of the experiment, each subject assumed a neutral position for a 30-second baseline postural sway and stability measurement. Next, the subjects performed lifting trials, starting with a neutral position for 10 seconds. At the end of the 10 seconds, a voice command was given to instruct each subject to reach out and lift a drywall sheet which had been placed on a specially designed rack (Fig. 3) in front of the subject. Figure 4 illustrates the hand grip locations for different lifting methods. Each subject was asked to grip toward the center of the marked locations. Each subject gripped and lifted the drywall sheet in a posture according to one of four assigned methods (Fig. 1) and statically held the drywall for 7 seconds. Then, with a voice command, the subject was asked to place the drywall sheet back onto the rack and bring his torso back to an upright position. The subject stayed in this upright position for an additional 13 seconds. Each subject performed the lifting task four times.

2.3. Apparatus

Kinetic measurements were collected using a piezoelectric force platform (Kistler™, Type 9287, Kistler Instrument Corp., Amherst, NY) and a charged amplifier (Kistler™, Type 9865B, Kistler Instrument Corp., Amherst, NY). The force platform was placed flush with the floor of the laboratory. The force plate signals were sampled at 180 Hz and were delivered to an IBM-compatible personal computer with an A/D board (DT3010, Data Translation™). Forces and moments collected from the force plate were used to derive the center-of-pressure (COP) trajectory for each lifting trial.

Kinematic data were obtained using a five-camera Peak Motus™ system (Peak Motus™ Performance Technologies Inc., Englewood, CO) which provided 3-D marker trajectory at 60 Hz. A set of 22 reflective

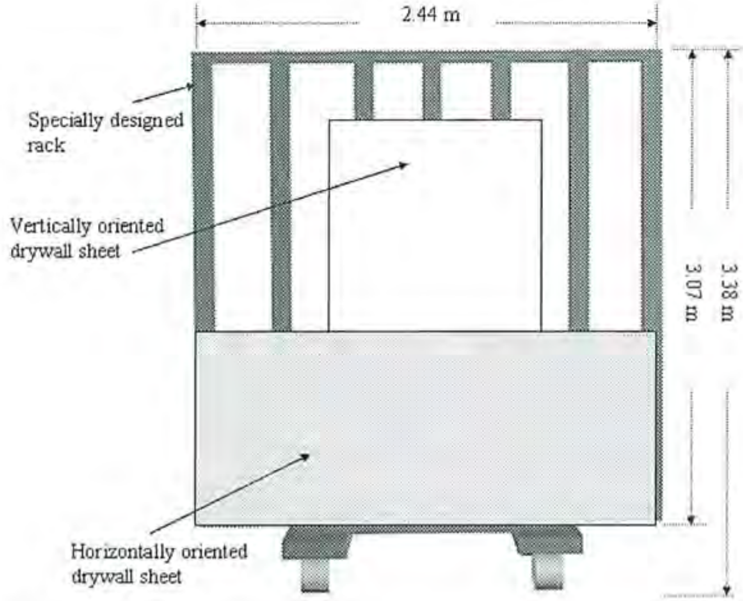

Fig. 3. Specially designed rack, vertically and horizontally oriented drywall sheet.

markers was placed on bony landmarks of the subject (Fig. 5). The kinematic data were low-pass filtered using a fourth-order Butterworth filter with a cutoff frequency of 6 Hz. The motion data were further analyzed to calculate whole body's COM trajectory for each trial of the 28 randomly selected subjects. Figure 6 illustrates an example trial cycle of acceleration data as a function of time using lifting Method 3.

2.4. Description of dependent measures

There are many ways to measure postural stability; in other words, postural stability can be estimated by characterizing COP and COM trajectories from many different perspectives [17,23,35,36]. This study adapted 13 COP-based variables that have been used by previous researchers to examine postural stability [3,23]. The complexity of postural stability of a human body cannot simply be represented by just one variable. Therefore, this study incorporated 13 COP-based variables including postural sway length, anterior-posterior (AP) sway, medial-lateral (ML) sway, root-mean-square of sway (RMS), mean speed of sway, average sway of COP in the AP and ML directions, average radial displacement, standard deviation of radial displacement, sway area, and three non-dimensional indices of the Index of Proximity to Stability Boundary (IPSB), Stability Area Ratio (SAR), and Weighted Residence Time Index (WRTI). The formulas for calculating the three indices are given in Bagchee et al. [10].

Sway length is the distance along the path traveled by the body's COP during the test period. Sway area is the area of the region contained within the outer envelope of the x-y plot of the movement pattern of the body's COP. The IPSB measures how close the body's COP travels to a person's stability boundary, which is defined by the outer perimeter of the feet (shoe) placement during the test period. The SAR considers the spread of the stabilogram during task performance in comparison to the stability boundary, which is defined as the ratio of sway area to the stability boundary. The WRTI is the weighted measure of the time that the subject's COP lies in various zones of the stability boundary. The methodology for obtaining the three indices was developed and validated by Bagchee et al. [3], and Chiou et al. [7].

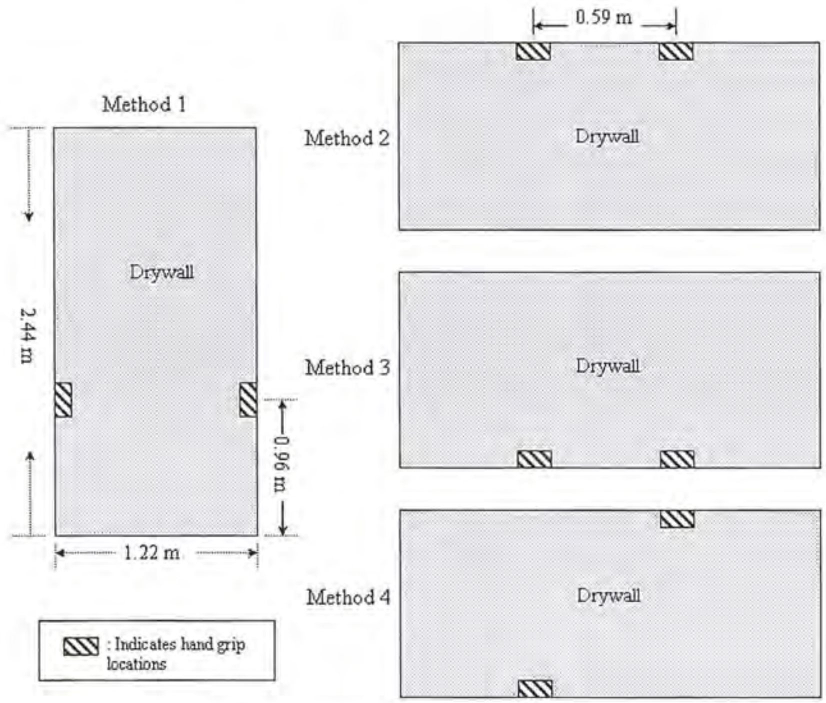

Fig. 4. Illustration of hand grip locations.

The previously mentioned 13 variables were also calculated using COM trajectory data. Furthermore, eight additional variables were calculated to examine the subjects' COM movement. They were mean sway and range of sway in the vertical direction and maximum accelerations in anterior, posterior, medial, lateral, upward, and downward directions.

2.5. Data analysis

2.5.1. Determination of the COM before, during and after drywall lifting

The location (x, y, and z coordinates) of the whole body's COM before and after drywall lifting was determined by a 12-link biomechanical model of the human body. Segment mass and center of mass were derived from equations and data in the literature [12]. Based on the movement of 22 reflective markers placed on the subject's body landmarks, the 3-D trajectory of the COM of each body segment was computed. The 3-D trajectory of the whole body's COM was then computed from the weighted sum of the COM of each body segment.

The location of the COM of the human-drywall system during lifting was localized somewhere between the whole body COM prior to lifting and the location of the COM of the drywall sheet. In this study, the location of the COM of the human-drywall system was calculated based on the following equation:

$$COM_{lifting} = (COM_{body} \times Mass_{body} + COM_{drywall} \times Mass_{drywall}) / (Mass_{body} + Mass_{drywall}) \quad (1)$$

where $COM_{lifting}$: the 3-D position of the whole body's COM during drywall lifting
COM_{body}: the 3-D position of the whole body's COM without lifting drywall
$COM_{drywall}$: the 3-D position of COM of drywall sheet

Fig. 5. Reflective markers placed over anatomical landmarks.

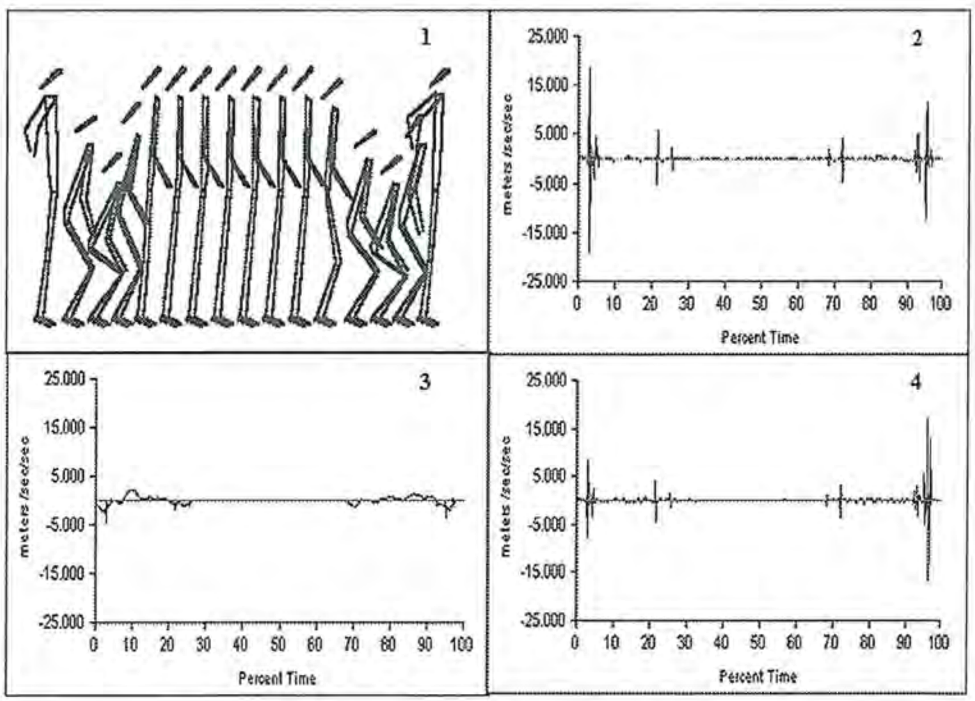

Fig. 6. An example cycle of a lifting trial using method 3: (1) a sequence of stick figures (upper left panel), (2) accelerations in M/L directions (upper left panel), (3) accelerations in A/P directions (lower left panel), (4) accelerations in vertical directions (lower right panel) as a function of time in a trial.

$\text{Mass}_{\text{body}}$: the subject's body mass
$\text{Mass}_{\text{drywall}}$: the mass of the drywall sheet

The $\text{Mass}_{\text{body}}$ and $\text{Mass}_{\text{drywall}}$ were known values obtained from the subjects and the drywall manufacturer. The COM_{body} was derived after digitizing the video tapes of the experiment. The $\text{COM}_{\text{drywall}}$ was estimated based on the 3D trajectories of the subjects' left wrists during lifting. As shown in Fig. 1,

Table 1
Means and standard errors (in parenthesis) of COP and COM measures for four lifting methods

	COP-based measures			COM-based measures		
	Mean AP sway (cm)	Range of ML sway (cm)	IPSB	Mean AP sway (cm)	Range of ML sway (cm)	RMS
Method 1	15.26 (0.96)	3.90 (0.38)	0.05 (0.01)	17.50 (1.43)	3.47 (0.23)	6.4 (0.77)
Method 2	9.84 (1.61)	1.73 (0.67)	0.24 (0.03)	9.70 (0.78)	1.07 (0.49)	3.42 (0.17)
Method 3	11.13 (2.0)	1.80 (0.22)	0.19 (0.06)	12.49 (2.02)	1.81 (0.27)	3.98 (0.91)
Method4	9.50 (0.80)	1.34 (0.16)	0.07 (0.03)	12.49 (2.00)	1.34 (0.22)	2.61 (0.63)

the subjects' hand grip locations were standardized when lifting the drywall sheet. Assuming that the density of the drywall sheet is evenly distributed, the $COM_{drywall}$ is located at the center of the drywall. By knowing the relative positions between the fixed left hand grip location and the center of the drywall, the $COM_{drywall}$ was derived through a simple transformation as follows:

$COM_{drywall}$ for Method 1 = (x+0.6096 m, y, z+0.3048 m)

$COM_{drywall}$ for Method 2 = (x+0.3048 m, y, z−0.6096 m)

$COM_{drywall}$ for Method 3 = (x+0.3048 m, y, z+0.6096 m)

$COM_{drywall}$ for Method 4 = (x+0.3048 m, y, z+0.6096 m)

where (x, y, z): left wrist location during drywall lifting in meters.

More detailed information regarding this transformation will be discussed in the last paragraph of the discussion section.

2.5.2. Statistical analysis

This study was a completely randomized repeated-measure design with lifting methods randomly assigned to each subject. The subjects replicated the assigned method four times for each task. Measurements for each replication were used to generate a mean value for each subject. Correlation analyses were performed to determine the relationship between subjects' muscle strength kinetic and kinematic variables. In addition, univariate analyses of variance (ANOVA) were performed to determine the effect of different lifting methods on each of the kinetic and kinematic variables. For any significant effect, multiple comparisons (Duncan's multiple range tests) were performed to compare the four lifting methods.

The contribution of various COP and COM variables to the overall postural stability is significant, however, it is computationally intensive to determine the contribution analytically due to the large number of COP- and COM-related variables and their interactive effects. To reduce the dimensionality of the large data set, principal component analysis (PCA) was applied, which classified COP and COM data into homogeneous groups and determined the most significant variables upon postural stability. PCA was performed for the 13 COP-based and 21 COM-based variables, which were first standardized separately.

3. Results

3.1. Correlation analyses

Correlation analyses between maximum muscle strength and the COP- and COM-variables did not show any significant results (all p values > 0.05), indicating no relationships exist. In addition, no

Table 2
Maximum accelerations (m/sec^2) and standard errors (in parenthesis) of COM movement in six directions

	Method 1	Method 2	Method 3	Method4
Anterior (cm)	338.2	103.8	150.11	116.21
	(30.65)	(18.2)	(49.4)	(31.4)
Posterior (cm)	345.55	81.2	152.1	101.1
	(25.1)	(11.9)	(49.5)	(36.4)
Medial (cm)	419.4	268.2	199.8	164.3
	(30.8)	(8.22)	(9.8)	(43)
Lateral (cm)	423.2	267.1	200.4	159.6
	(28.6)	(7.43)	(9.8)	(47.6)
Upward (cm)	287.3	725.8	726.1	778.7
	(134.6)	(73.8)	(59.99)	(118.6)
Downward (cm)	290.4	732.1	714.4	521.1
	(135.1)	(75.1)	(60.1)	(141.7)

significant variations (p value $= 0.817$) were identified for the four assigned groups in regard to their maximum muscle strength measures. Therefore, muscle strength was not included in subsequent analyses as a covariate. The mean maximum muscle strength for all 60 subjects was 411 newtons (± 140 newtons).

3.2. Univariate analyses of variance

Results from univariate ANOVA on the COP-based variables revealed that the effect of the lifting method was significant on three variables of mean ML sway ($p < 0.01$), IPSB ($p < 0.02$), and range of AP sway ($p < 0.04$). Table 1 presents the means and standard errors of COP and COM measures for four lifting Methods. Lifting Method 1 had significantly greater mean ML sway (3.9 cm) than the other three methods (all $\leqslant 1.8$ cm). The IPSB for Method 1 (IPSB $= 0.05$) was significantly smaller than those of Methods 2 (IPSB $= 0.24$) and 3 (IPSB $= 0.19$). In addition, Method 1 had a greater range of AP sway (15.26 cm) than Methods 2 (9.84 cm) and 3 (9.5 cm).

Similar univariate analyses on the COM-based variables showed that the effect of the lifting method was found to be highly significant on the RMS, range of COM motion in ML and vertical direction, mean AP and ML sway and maximum accelerations in six directions of anterior, posterior, medial, lateral, upward, and downward vertical directions (all p values <0.01). Significantly greater RMS, range of motion in AP and vertical direction, and mean ML sway were found for Method 1 compared to the other three methods (Table 1). A similar trend was observed for variables of maximum acceleration in anterior, posterior, medial, and lateral directions (Table 2). However, Method 1 had significantly smaller maximum accelerations in upward and downward directions.

3.3. Principal component analysis for COP-based variables

Results from PCA indicated that the first three principal components contributed 84% of the total variation in the original thirteen COP-based variables. Using lifting method as the independent variable, three separate ANOVAs were performed for each of the three principal component scores. The results showed that there were significant differences of the second principal component scores among four different lifting methods ($p < 0.01$). Further multiple comparisons revealed that the mean value of the second principal component scores for lifting Method 1 was significantly greater than those of lifting Methods 2, 3, or 4.

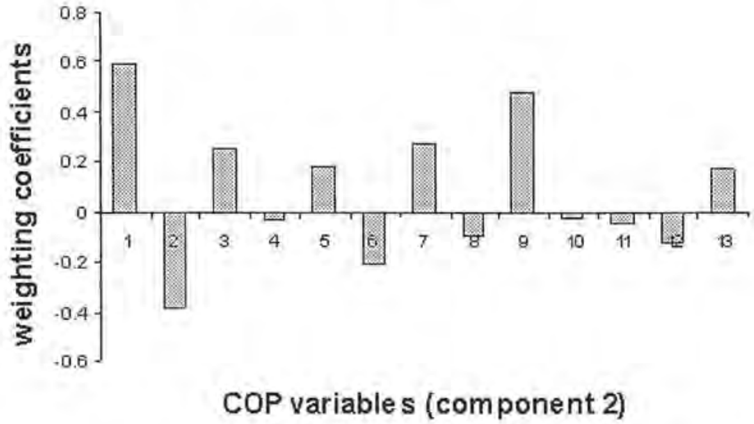

Fig. 7. Weighting coefficients obtained by PCA of COP-based variables: (1) range of AP sway, (2) IPSB, (3) range of ML sway, (4) RMS of sway, (5) SAR, (6) WRTI, (7) mean radial displacement, (8) mean AP sway, (9) mean ML sway, (10) sway length, (11) mean speed of sway, (12) standard deviation of radial displacement, and (13) sway area.

The second principal component (which explained 16% of the total variance) gave large factor weighting coefficients for IPSB (−0.38), mean ML sway (0.48), and the range of sway in the AP direction (0.59). The second principal component appeared to be related to the AP and ML sway and the distance of COP to the outer perimeter of base of support. Figure 7 illustrates the weighting coefficients and the second principal component generated from COP-based variables.

3.4. *Principal component analysis for COM-based variables*

Principal components were also computed to represent the COM data, resulting in five principal components accounting for 83% of the total variation in the original 21 COM-based variables. Five separate ANOVAs were performed for each of the five principal component scores, using lifting method as the independent variable. The results showed that only the first principal component scores were significantly different among four lifting methods ($P < 0.01$). The mean values of the first principal component scores (which explained 41% of the total variance) for Method 1 were significantly greater than those of Methods 2, 3, and 4. The coefficients (or weightings, loadings) of the first principal component suggested an involvement of most of the 21 original variables with the exceptions of the range of ML sway (0.01) and the WRTI (0.02). These two variables had extremely low weighting coefficients, indicating that they did not explain the same characteristics of the COM movement as the rest of the variables. The first principal component appeared to relate to the magnitude and acceleration of the COM trajectory.

4. Discussion

This study examined postural stability associated with four lifting methods that are commonly used by drywall installers and carpenters. Thirteen COP-based sway variables and 21 COM-based sway variables were measured in this study. A complete description of postural stability during drywall lifting requires the consideration of both COP-based and COM-based parameters. Postural stability is achieved by controlling body movements to maintain the body's COM within the base of support. COP is the position of the resultant applied force vector that is determined by 3-D forces produced by body segment accelerations and their contributions to moments around orthogonal axes at the horizontal plane [17]. COP reflects the response of the neuromuscular system to correct the COM of the body to maintain balance [38]. Knowledge of both COP and COM measures is essential not only for better understanding of static human movement but also for the investigation of dynamic balance control.

The maintenance of the body in balance during voluntary movement is an essential requirement for daily activities. The regulation of body balance is achieved through multiple levels of central nervous system activation/control and requires precise control over posture and movement. The maintenance of body balance is even more critical when performing industrial tasks such as lifting a drywall sheet. The added load to the human body when lifting a drywall sheet causes the COM to shift forward and thus presents the subject with an expected perturbation of dynamic balance. Previous studies suggested that the coordination of body balance seems to be task specific and relates to the biomechanics of the body [2, 3,36]. This was shown in the current study, as different lifting methods resulted in significant differences in COP and COM movements.

In general, lifting Method 1 induced greater range of AP sway and mean ML sway for both COP and COM than Methods 2, 3, and 4. Lifting Method 1 is a work practice often used in constructing commercial buildings with ceilings greater than 8 feet tall [15,29]. This method can also be classified as a vertical lifting method, while Methods 2, 3, and 4 represent a horizontal lifting method that is often seen in residential home construction. Results from this study showed that different lifting methods significantly affected the accelerations of the COM trajectories. Vertical lifting of drywall resulted in greater maximum accelerations in the AP and ML directions but smaller maximum acceleration in the vertical direction (upward and downward directions) compared with horizontal lifting (Fig. 8). To perform horizontal lifting, subjects had to stretch and bend their trunk to reach the bottom or top of the drywall and then lift it up. In addition, the horizontal lifting methods required subjects to lift the drywall sheet for larger vertical distances from the fixture. These activities resulted in higher COM accelerations in both downward and upward directions (range, 521 to 779 m/sec^2). In contrast, lifting and holding the two sides of the drywall (Method 1) required relatively small movement of the body in the vertical direction, therefore, the acceleration in the vertical direction was minimized (range, 287 to 291 m/sec^2).

Regarding the greater AP and ML accelerations that were found for the vertical lifting method, the larger rotational torques occurred in the sagittal and frontal planes due to a higher COM location of the drywall, which is positioned vertically. Previous research has documented that lateral stability was found to be related to the risk of falling and that the control of lateral stability may be an important area for fall intervention [23]. Vertical lifting of drywall appeared to cause a greater range of AP sway and mean ML sway of COP and COM movement as well as higher COM accelerations in the AP and ML directions.

To reduce the number of interrelated variables, PCA was performed. PCA has been widely applied to psychometrics, econometrics, and marketing research [5,18,37]. Many biomechanical studies have used PCA to generate variables and/or indicators for EMG variables and their effects on gait measures to determine the most significant variables among large and computationally intensive data sets [22,31, 39,40]; however, little in the published literature exists on the use of PCA to assess workers' balance control during large-sized manual materials handling activities such as the lifting of drywall sheets in construction work. Applying PCA methods to identify factors affecting control over COP and COM presents an objective approach of combining correlated dependent variables which are believed to be a measure of a workers' ability to control balance. Results from PCA indicated that vertical lifting resulted in greater instability than horizontal lifting as indicated by both the second principal component of COP data and the first principal component of COM data.

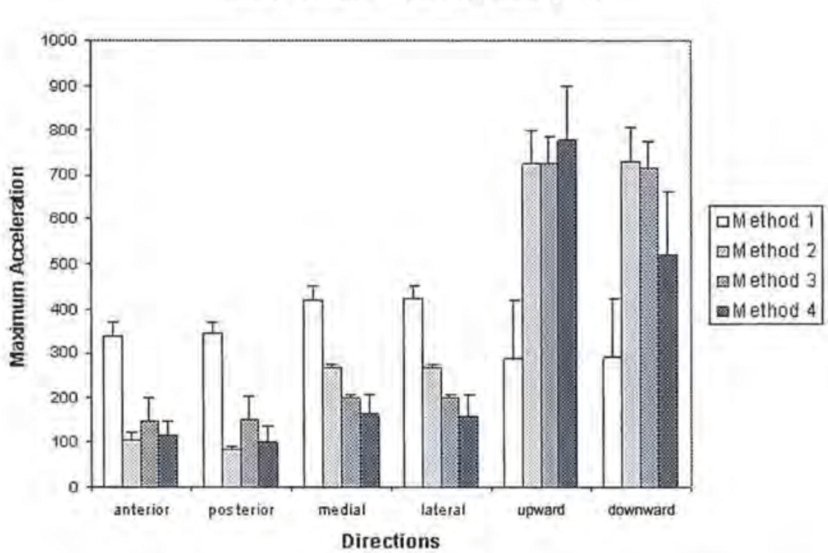

Fig. 8. Maximum accelerations of COM movement in six directions.

In summary, findings from this study indicated that vertical lifting (Method 1) placed greater demands on the subjects' dynamic balance control than horizontal lifting methods, as indicated by the higher COM accelerations and greater sway in AP and ML directions. Thus, workers using the vertical lifting method appeared to have a greater fall potential. Previous studies [29,30] evaluating these same four lifting methods examined the estimated strength capabilities, disc compression forces, and other biomechanical risk factors of drywall lifting, and these studies indicated that both vertical lifting (Method 1) and horizontal lifting with both hands on top (Method 2) resulted in less overexertion hazards than the other two methods. However, all of these four manual lifting methods appeared to produce significant amounts of biomechanial stress [29,30]. Additionally, Chiou [8] reported that the most frequently injured body part for drywall installers is the trunk (i.e., more than 60%). In these previously mentioned studies [29,30], methods 3 and 4 produced considerably higher biomechanical stresses at the workers' trunks. Consequently, the horizontal drywall lifting method with both hands on top (Method 2) appears to be the best manual work practice for reducing both overexertion and fall potential hazards. However, workers using lifting Method 2 may need a considerable amount of grip strength, since workers who lift smooth-surfaced materials such as drywall sheets–which have low coefficients of friction and poor coupling conditions–need to compensate with much stronger grips from both hands. Future studies are needed, focusing on traumatic occupational injuries associated with the use of high hand-grip force (e.g., struck by/against), and on effective intervention technologies such as assistive devices for drywall-lifting applications. The findings of this study should be interpreted and applied with caution since the cause-and-effect relationship between postural instability and actual falls among industrial workers has not been well established.

In this study, no markers were placed on the drywall during data collection. Since the drywall was considered to be a rigid and uniform material, the COM can be determined mathematically. The grip location of the drywall is standardized by marking on the drywall so that the global COM can be calculated theoretically. This assumption is reasonable because the errors from the nonuniformity of the material and the drywall dimensions, compared to the overall measurement errors, are negligible. However, errors, which are limited in the study, may be induced by the repeatability of the actual grip locations on the drywall in different trials (± 1 cm).

5. Conclusions

In summary, the conclusions reached from this investigation were:

1. Results from the univariate analyses and PCA indicated that the three horizontal lifting methods (Methods 2, 3, and 4) created less perturbation of postural balance than the vertical lifting method (Method 1).
2. Based on the results of this study and previous studies [8,29,30] related to the biomechanics of drywall lifting, horizontal lifting with both hands on top of the drywall (Method 2) results in less fall potential hazards, and this lifting method produced relatively less overexertion risks (comparing with the other three lifting methods). However, manual materials handling with drywall sheets using any of the methods examined in this study may expose workers to overexertion hazards, and this exposure has been noted in previous studies [8,29,30].
3. The findings of this study should be interpreted with the cautionary note that prolonged handling of drywall sheets using any of the common methods of materials handling in this industry may result in overexertion exposure, and that work-practice methods (job rotation, rest periods, team-work applications, and the use of assistive devices) should be considered at the worksite to limit continued exposure to this hazard.

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