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An integrated biomechanical modeling approach to the ergonomic evaluation of drywall installation

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ABSTRACT

Three different methodologies: work sampling, computer simulation and biomechanical modeling, were integrated to study the physical demands of drywall installation. PATH (Posture, Activity, Tools, and Handling), a work-sampling based method, was used to quantify the percent of time that the drywall installers were conducting different activities with different body segment (trunk, arm, and leg) postures. Utilizing Monte-Carlo simulation to convert the categorical PATH data into continuous variables as inputs for the biomechanical models, the required muscle contraction forces and joint reaction forces at the low back (L4/L5) and shoulder (glenohumeral and sternoclavicular joints) were estimated for a typical eight-hour workday. To demonstrate the robustness of this modeling approach, a sensitivity analysis was conducted to examine the impact of some quantitative assumptions that have been made to facilitate the modeling approach. The results indicated that the modeling approach seemed to be the most sensitive to both the distribution of work cycles for a typical eight-hour workday and the distribution and values of Euler angles that are used to determine the "shoulder rhythm." Other assumptions including the distribution of trunk postures did not appear to have a significant impact on the model outputs. It was concluded that the integrated approach might provide an applicable examination of physical loads during the non-routine construction work, especially for those operations/tasks that have certain patterns/sequences for the workers to follow.

1. Introduction

It is widely accepted that there are three types of external ergonomic exposure assessment strategies: subjective judgment, systematic observation, and direct measurement. These three methods are listed in general order of increasing precision (David, 2005; Li and Buckle, 1999; Van der Beek and Frings-Dresen, 1998). Subjective judgment comes from reviews of experts or self reports of workers. It usually provides only limited information on workplace exposure to physical and psychosocial risk factors for musculoskeletal disorders. When a certain occupational task involves movements of different body parts such as manual material handling during construction work, it is imperative to evaluate the required posture, muscle exertion forces, and joint moments through workplace observations, or direct measurements, or a combination of both. It has been reported that video observation and direct measurement could provide similar levels of accuracy and reliability (Leinonen and Ma, 1996). Although direct measurements are generally considered as the most accurate method to assess exerted forces, it is often problematic to conduct direct measurements in field studies, especially within the construction industry due to potential interference with the work.

The internal exposure of the musculoskeletal system can be best evaluated through biomechanical models, varying from two-dimensional static linked segment models to three-dimensional dynamic models (Van der Beek and Frings-Dresen, 1998). In order to more accurately assess the magnitude of physical loads during construction, biomechanical modeling requires proper estimation of input variables including anthropometric data, joint angles, external forces, and internal muscle parameters (Winkel and Mathiassen, 1994). The difficulty of application of direct measurements may suggest that a combination of other methods of measurement be chosen, with an ultimate goal of a representative

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sample of work and actual variation of exposure being captured (Tak et al., 2007).

Drywall installation is a typical type of strenuous construction work, which exposes workers to various ergonomic hazards, including handling of heavy and bulky materials, repetitive screwdriving motions, and awkward postures. The body parts most commonly injured are the axial skeleton and shoulder, where back sprains, simultaneous sprains to the back and neck, and shoulder strains occur frequently (Chiou et al., 2000; Hsiao and Stanevich, 1996; Lemasters et al., 1998; Lipscomb et al., 1997, 2000). Previous biomechanical analyses of drywall installation examined the physical stress and postural stability during lifting of the drywall panels (Pan and Chiou, 1999; Pan et al., 2002/2003). The authors realized many practical limitations to conducting accurate, non-invasive and reasonably priced ergonomic assessments at the worksite due to the dynamic nature of construction activities. Therefore, future study was needed to identify the most reliable exposure assessment methods, evaluate possible ergonomic solutions, and recommend the safest, biomechanically sound handling methods for construction workers and other related laborers (Pan and Chiou, 1999).

With the development and application of PATH (Posture, Activity, Tools, and Handling), an observational work sampling-based approach to direct observation (Buchholz et al., 1996), it has become practical to quantify the percent of time that construction workers are exposed to awkward postures, various tasks and activities, and manual handling (Buchholz et al., 2003; Forde and Buchholz, 2004; Fulmer et al., 2004; Paquet et al., 1999, 2001, 2005; Rosenberg et al., 2006). PATH has also been used in other industrial sectors that involve non-repetitive job activities including retail, agriculture, and healthcare industries (Earle-Richardson et al., 2005; Kurowski et al., 2012; Pan et al., 1999; Park et al., 2009).

The joint angle and load ranges that are represented by the PATH data are categorical rather than continuous. However, the Monte-Carlo simulation method, which is used to generate random numbers from a defined distribution, can be utilized to extract discrete values from the categorical PATH data for biomechanical analysis of the low back and shoulder (Tak et al., 2007). The Monte-Carlo method has also been successfully used both to capture the trunk muscle activity during torso bending (Mirka and Marras, 1993) and to simulate variability in muscle moment arms and physiological cross-sectional areas for prediction of shoulder muscle force (Chang et al., 2000; Hughes and An, 1997).

The objectives of this study were to first describe a hybrid model integrating work sampling, computer simulation, and biomechanical modeling to conduct the ergonomic analysis of drywall installation (Yuan, 2006, 2013a, 2013b; Yuan et al., 2007). The required muscle contraction forces and joint reaction forces at the low back and shoulder during a typical eight-hour drywall installation workday were estimated utilizing Monte-Carlo simulation to convert PATH categorical data into continuous variables as inputs for three-dimensional static biomechanical models. Then, a sensitivity analysis (See appendix) was conducted to examine the impact of some quantitative assumptions that have been made to facilitate the modeling approach, so that the robustness of this modeling approach could be demonstrated and the impact of drywall storage position and size on the physical demands for drywall installers could be evaluated later (Yuan and Buchholz, 2014).

2. Methods

2.1. Overview of methods

The study describes an integrated model through which the muscle contraction forces and joint reaction forces at the low back and shoulder during drywall installation were estimated (Fig. 1). The PATH methodology provided the basic characterization of drywall installation work by quantifying the percent of time that the drywall installers were conducting different activities with different body segment (trunk, arm, and leg) postures. The relative frequencies of key activities, recorded over two hours, were used to construct eight-hour-workday activity series using Monte-Carlo simulation (Step A in Fig. 1). The biomechanical model input variables, including anthropometric data, joint angles, external load force and position vectors, and internal muscle parameters including coordinates of muscle origins and insertions and physiological cross-sectional areas, were then generated for the analyses of the low back and shoulder (Steps B1 and B2 respectively in Fig. 1). Utilizing different optimization programs in MATLAB (The MathWorks, Natick, MA, USA), the three-dimensional static equilibrium equations were solved and the biomechanical model outputs of muscle contraction forces and joint reaction forces at the low back and shoulder were computed and summarized (Steps C1 and C2 respectively in Fig. 1). In order to demonstrate the robustness of this modeling approach, the sensitivity analysis (See appendix) was conducted at the end of the present study.

2.2. Observational work sampling – PATH

A total of 126 PATH data points were collected on a crew of eight drywall workers by two well-trained researchers from the Construction Occupational Health Program (COHP) at the University of Massachusetts Lowell. The observations were made from October 2003 to January 2004 at a condominium construction site in Boston, MA, USA. The researchers used handheld computers (Compaq Aero 1500 and Casio E-200) to record the PATH observations at sixty-second intervals, and the PATH template was programmed onto those PDAs using InspectWrite (Penfact Inc., Boston, MA, USA).

Seven main activities which represent a typical drywall installation task were examined in this study, including: 1. cut/measure; 2. lift; 3. carry; 4. hold/place; 5. screw; 6. in between; and 7. other. As determined by Pan and Chiou (1999), the drywall lifting method in which the worker used one hand to support the horizontal drywall sheet at its bottom and the other hand to grasp the sheet at its top produced the highest L4/L5 disc compression forces and therefore appeared to be the most stressful. It was assumed that the drywall installers in this study exclusively used such a lifting method as a demonstration of the worst case scenario. Activity 6 (in between) denoted exclusively loading/adjusting the screw guns and it always followed activity 5 (screw). Activity 7 (other) included climb/descend, communicate, mark/draw, and other miscellaneous job activities.

2.3. Generation of eight-hour-workday activity series

2.3.1. Basic drywall installation work cycles

Two different drywall installation work cycles were identified based on field observations, involving: 1) a whole sheet of drywall (Sheetrock® Brand Gypsum Panel from CGC Inc., typically 1.22-m (4-ft) wide, 2.44-m (8-ft) long and 15.9-mm (5/8-in) thick, with bulk density of 881 kg/m^3 (55 lb/ft^3)), and 2) a partial piece. The two installation processes were observed to entail a different series of activities.

For the whole sheet of drywall, the worker first lifts it from storage, where the drywall sheets are piled flat on the ground (Step A in Fig. 2). The worker then carries it to the hanging location with the postures shown in Step B (Fig. 2). The third step is to rotate the drywall sheet and to place it at the destination (Step C in Fig. 2). Last, the worker drives screws into the drywall sheet to fasten it to

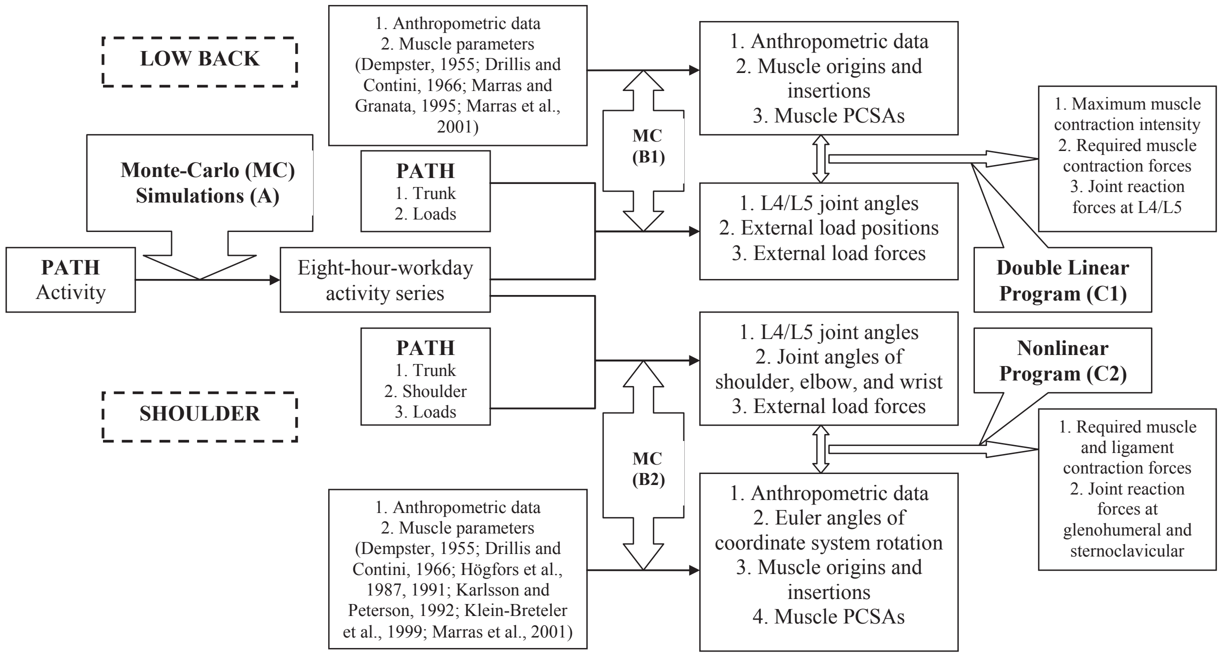

Fig. 1. Schematic diagram for the data analysis in this study. The analyses on the low back and shoulder parallel each other, although the shoulder analysis is more complicated. The analyses both started with Step A, the generation of eight-hour-workday activity series using Monte-Carlo simulation based on the PATH activity data. Steps B1 and B2 represent the Monte-Carlo simulation of biomechanical model input variables for the low back and shoulder respectively. In the end, steps C1 and C2 denote running different optimization programs to solve the force and moment equilibrium equations for muscle contraction forces and joint reaction forces at the low back and shoulder respectively.

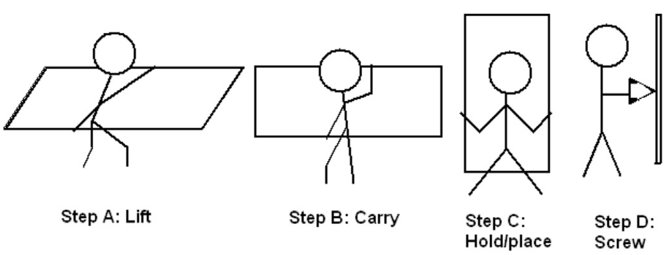

Fig. 2. Schematic diagram for installation of a whole drywall sheet. Lift: "Worker moves the whole drywall sheet upwards without walking; "carry: "Worker moves the drywall sheet with walking; "hold/place: "Worker stands still with the whole drywall sheet in the hands and makes adjustment of the sheet's position; "and screw: "Worker uses powered screwdriver to drive screws in to fasten the structure".

the structure (Step D in Fig. 2).

When the wall configuration does not allow a whole piece of drywall sheet to be installed, the worker measures the structure first and cuts the whole piece to get a partial one. During drywall cutting, the drywall sheet is stored vertically on a cart (Step A in Fig. 3). The worker then lifts and carries the partial piece of drywall sheet to the destination (Step B in Fig. 3), and holds it in place while driving screws (Step C in Fig. 3). The number of screws required to fasten varies depending on the size of the partial drywall sheet.

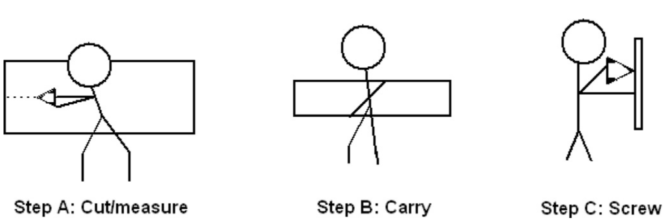

Fig. 3. Schematic diagram for installation of a partial drywall sheet. Cut/measure: "Worker uses both cutter and tape measure to cut the whole drywall sheet into pieces that fit the structure; "carry: "Worker moves the drywall sheet with walking; "and screw: "Worker uses powered screwdriver to drive screws in to fasten the structure".

2.3.2. Eight-hour-workday activity series

The PATH methodology presents a fixed-interval snapshot and the relative frequencies of different activities are obtained as proportions of observations. Because the activity series during the observed drywall installation were known and fixed in sequence, the PATH activity frequencies were used as proxies for the relative duration of each activity. The structure of the activity series could be drawn according to the relative ratios of the probabilities of the two activities that possibly happen at a specific moment (Fig. 4).

It was determined from the field observations that there were twelve possible work cycles, with four occurring during installation of a whole sheet and eight denoting installation processes for a partial piece (Fig. 4). The probability of each work cycle could be calculated by multiplying the probability of every single activity during that cycle. For example, the probability of the work cycle, lift-carry-hold/place-screw-in-between (2-3-4-5-6), was 50%*100% *100%*45%*55% = 12%, where 45% represented the probability of conducting activity 5 and 6 (screw and in between) as opposed to activity 7 (other). Similarly, the probability of the work cycle, cut/measure-carry-other-screw-in-between (1-3-7-5-6), was 50%*37% *55%*100%*55% = 6%.

It was learned from field interviews of drywall installers that one worker usually installs about fifty pieces of whole drywall sheet and fifty pieces of partial sheets in a typical workday. In order to track a subject's motions in detail when generating the eight-hour-workday activity series, the time unit for use in the Monte-Carlo simulation was set to be 0.1 min (6 s), which equaled one tenth of the PATH data collection interval (60 s). This was done because the subject could use a series of varying postures when conducting the same activity within 1 min. On the other hand, the length of the basic time unit was equal to the time interval that was

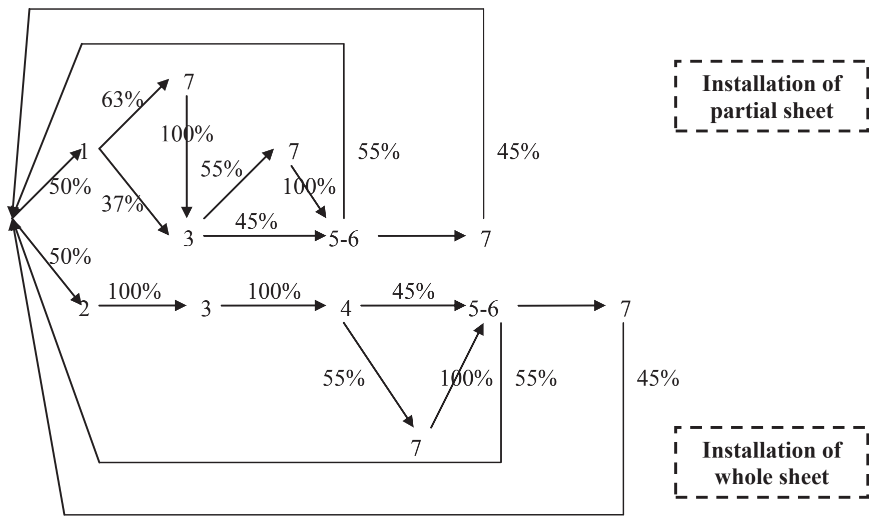

Fig. 4. Structure of eight-hour-workday activity series [Numbers 1–7 represent the relevant activities as described in Section 2.2 of the manuscript]. The top part of the figure describes the activity sequences during installation of a partial drywall sheet, whereas the bottom part refers to a whole sheet. The percentages on the arrows denote the probabilities of the two activities that possibly happen at a specific moment, assuming the average duration for every single activity based on the observed frequencies in the PATH data. The probability of each work cycle could be calculated by multiplying the probability of every single activity during that cycle.

selected in the one-compartment model to study muscle fatigue (Yuan, 2006). Because MATLAB requires equal-length work cycles during simulation, dummy activities were introduced and later deleted from the output. For an eight-hour workday, 8(hr/day) *60(min/hr)*60(sec/min)/6(sec/unit) = 4800 time units need to be assigned to activities. Therefore, one typical work cycle (for either a whole or partial sheet) was defined to include fifty-five time units and one hundred work cycles were simulated (55*100 = 5500 > 4800), with the consideration that the dummy activity would be deleted later. Eventually, one eight-hour workday included approximately 4800 activity series.

The relative duration of each single activity included in the study was then determined from the ratios of PATH activity frequencies and the total work cycles performed by the subject in the eight-hour workday. For example, when the average duration of activity 2 (lift) was defined as five time units, the average duration of activity 1 (cut/measure) was about 3 times that of activity 2 (lift) or fifteen time units since the frequencies of those two activities in the PATH data were 19.8% and 6.4%, respectively.

The overall probabilities of the twelve possible work cycles for a typical eight-hour workday of drywall installation were assumed to follow the general discrete distribution. Such a distribution type was chosen because the probabilities for all the different work cycles could be calculated and they were nonnegative. Also, the sum of the probabilities equaled 1.00 (Hossack et al., 1999).

2.4. Biomechanical analysis of the low back

2.4.1. Biomechanical modeling

Using the Double Linear Program (DLP) optimization technique proposed by Bean et al. (1988), the required contraction forces of ten trunk muscles, the left and right pairs of lumbar erector spinae (LEL and LER), latissimus dorsi (LDL and LDR), external oblique (EOL and EOR), internal oblique (IOL and IOR), and rectus abdominus (RAL and RAR), and joint reaction forces of disc compression, lateral shear, and anterior-posterior shear were obtained. Data from the biomechanical model developed by Marras and Granata (1995) were used to determine the trunk muscle force vectors and moment arms in this DLP.

The coordinate system is aligned with the upper body of the subject. Its origin is located in the joint center of the lumbar spine at L4/L5. When the subject is standing erect, the X-axis is defined laterally pointing from left to right, the Y-axis is directed forward, and the Z-axis is directed upward and perpendicular to X and Y. When the trunk is moving, the coordinate system is rotated correspondingly following the Cardan angles in the order of Z (twist), Y (lateral bend), and X (flexion). Therefore, the external load force and position vectors are transformed into the L4/L5 coordinate system.

2.4.2. Generation of independent variables

1) L4/L5 joint angles

The numeric values of L4/L5 joint angles were simulated from the categorical PATH data (Table 1). There are five categories in terms of trunk posture in PATH, which delineate the trunk motions in three dimensions. Specifically, i is defined as trunk flexion, which is rotation about the X-axis; j is defined as lateral bending, rotation about the Y-axis; whereas k is defined as twist, rotation about the Z-axis.

The rotation matrix to transform load force and position vector coordinates into the L4/L5 system is:

$$T = \begin{bmatrix} \cos j*\cos k & -\cos i*\sin k + \sin i*\sin j*\cos k & \sin i*\sin k + \cos i*\sin j*\cos k \\ \cos j*\sin k & \cos i*\cos k + \sin i*\sin j*\sin k & -\sin i*\cos k + \cos i*\sin j*\sin k \\ -\sin j & \sin i*\cos j & \cos i*\cos j \end{bmatrix} \quad (1)$$

It is noteworthy that while trunk flexion occurs in only one direction, trunk lateral bend and twist have two possible directions.

Table 1
Frequencies of PATH trunk posture data associated with different activities.

Activity	Amount	Neutral	Mild flexion	Severe flexion	Bend & twist	Bend & twist & flexion	Activity percent	Neutral	Mild flexion	Severe flexion	Bend & twist	Bend & twist & flexion
1 (cut/ measure)	25	12	4	3	1	5	19.8%	9.5%	3.2%	2.4%	0.8%	4.0%
2 (lift)	8	0	2	1	0	5	6.4%	0.0%	1.6%	0.8%	0.0%	4.0%
3 (carry)	16	15	0	1	0	0	12.7%	11.9%	0.0%	0.8%	0.0%	0.0%
4 (hold/ place)	6	2	1	2	1	0	4.8%	1.6%	0.8%	1.6%	0.8%	0.0%
5 (screw)	20	7	5	3	3	2	15.9%	5.6%	4.0%	2.4%	2.4%	1.6%
6 (in between)	24	22	2	0	0	0	19.1%	17.5%	1.6%	0.0%	0.0%	0.0%
7 (other)	27	13	2	8	0	4	21.4%	10.3%	1.6%	6.4%	0.0%	3.2%
Total	126	71	16	18	5	16	100.0%	56.4%	12.7%	14.3%	4.0%	12.7%

Unfortunately, there are no data describing how likely trunk lateral bends or trunk twists occur in one direction versus the other. Tak et al. (2007) estimated that for a right-handed person, the trunk tends to lean toward the left side and twist counterclockwise with approximately 80% probability during manual work.

A lognormal distribution was assumed for trunk flexion, because the values of trunk flexion angles were always positive according to the ranges for the PATH categories. Its geometric mean (2.9°) and geometric standard deviation (0.8°) were calculated based on the rule of using the median value of every range for trunk flexion categories to represent such a range. For example, for neutral and bend/twist trunk posture, the median of the range from 0 to 20° is 10° and there are 76 observations; for mild flexion, the median of the range from 20 to 45° is 32.5° and there are 16 observations; for severe flexion, the median of the range from 45 to 80° is 67.5° and there are 18 observations; and for bend/twist & flexion, the median of the range from 20 to 80° is 50° and there are 16 observations. Therefore, the geometric mean equals $\ln(10)*76+\ln(32.5)*16+\ln(47.5)*18+\ln(50)*16/126=2.9$.

Given that only summary statistics including means and standard deviations could be calculated, normal distributions were used for trunk lateral bend and twist, and their means (2.8° and −3.2°, respectively) and standard deviations (10.9° and 12.9°, respectively) were calculated in a similar way as what was done for trunk flexion, except for the assumption of 80% probability of trunk bending toward the left side and twisting counterclockwise.

2) External load position and force vectors

Different values of the external load positions on the X- and Y-axes were assigned when the subject was conducting different activities and using different trunk postures. Since the whole sheets of drywall were symmetric and lied horizontally on the ground, the external load position on the X-axis during activity 2 (lift) was zero and the location on the Y-axis was simply calculated as half of the sheet width.

Values of the external load position on the Z-axis were simulated in accordance with the PATH trunk flexion data. A specific range was defined associated with a given trunk posture category. The median value was then selected to represent such a range. The mean (0.11 m) and standard deviation (0.37 m) were calculated for the purpose of simulation and a normal distribution was chosen.

In order to simulate the external load force vectors, especially their values on the Z-axis, PATH data on the load in the hands were extracted (Table 2). A lognormal distribution was considered. A similar method as was used for simulating the trunk flexion angles was applied to determine the geometric mean (3.0 N) and geometric standard deviation (1.2 N). Since values for the weight of tools during activity 1 (cut/measure), 5 (screw) and 6 (in between), and the weight of materials during activity 2 (lift) and 4 (hold/place) were known, random number generation was needed only for activity 3 (carry) and 7 (other).

During activity 1 (cut/measure), there is also a “drag” force along the X-axis, which acts against the cutting process. It was assumed to be 10 N, five times the assumed weight of the cutter (Drywall Hammer Cutter), in the absence of information on the true value. During activity 5 (screw), both a horizontal reaction force along the Y-axis and a reaction torque about the Y-axis were added due to the manipulation of the drywall screwdriver (DeWalt Heavy-Duty VSR Drywall Screwdriver − DW252, weighing 12 N). Their values were determined as 10 N and 7 N*m, respectively, based on the screwdriver's specifications.

2.5. Biomechanical analysis of the shoulder

2.5.1. Biomechanical modeling

An idealized mechanical model of the shoulder, presented by Högfors et al. (1987) and tested by Karlsson and Peterson (1992),

Table 2
Frequencies and ranges of PATH loads (N) in the hands data.

Activity	Amount	Very light (0−23)	Light (23−67)	Medium (67−223)	Heavy (223−408)	Activity percent	Very light (0−23)	Light (23−67)	Medium (67−223)	Heavy (223−408)
1 (cut/ measure)	25	25	0	0	0	19.8%	19.8%	0.0%	0.0%	0.0%
2 (lift)	8	0	0	0	8	6.4%	0.0%	0.0%	0.0%	6.4%
3 (carry)	16	1	5	4	6	12.7%	0.8%	4.0%	3.2%	4.8%
4 (hold/place)	6	0	0	0	6	4.8%	0.0%	0.0%	0.0%	4.8%
5 (screw)	20	0	20	0	0	15.9%	0.0%	15.9%	0.0%	0.0%
6 (in between)	24	0	24	0	0	19.1%	0.0%	19.1%	0.0%	0.0%
7 (other)	27	27	0	0	0	21.4%	21.4%	0.0%	0.0%	0.0%
Total	126	53	49	4	20	100.0%	42.1%	38.9%	3.2%	15.9%

was utilized in this study to determine the shoulder muscle associated parameters. The nonlinear optimization program widely accepted in previous research (Dul et al., 1984; Högfors et al., 1995; Karlsson and Peterson, 1992) was applied to solve a total of twenty-two internal force variables, including nineteen major muscles attached to the humerus; the coracohumeral ligament, which is assumed to be able to produce an overall moment; and two reaction force vectors at the glenohumeral (GH) and sternoclavicular (SC) joints.

2.5.2. Generation of independent variables

1) Joint angles for the shoulder, elbow and wrist

The external load positions change with body segment movement. Coordinates of muscle and ligament origins and insertions around the shoulder joints also vary for different shoulder postures. Joint angles for the trunk, shoulder, elbow and wrist need to be quantified during different activities. Simulations of the trunk motion angles were described above. Similarly for the shoulder, elbow and wrist, angles representing their rotations about the three axes (X, Y and Z) which were defined the same as for the trunk were defined as *i*, *j*, and *k* respectively. The external load positions for different activities with different postures could be calculated, using the position vector under neutral postures multiplying the following rotation matrix:

$$T_1 = \begin{bmatrix} \cos j^*\cos k & \cos j^*\sin k & -\sin j \\ -\cos i^*\sin k + \sin i^*\sin j^*\cos k & \cos i^*\cos k + \sin i^*\sin j^*\sin k & \sin i^*\cos j \\ \sin i^*\sin k + \cos i^*\sin j^*\cos k & -\sin i^*\cos k + \cos i^*\sin j^*\sin k & \cos i^*\cos j \end{bmatrix} \quad (2)$$

PATH has three categories to describe shoulder postures in terms of flexion: two arms down, one arm up, and two arms up. The threshold value is a sixty-degree angle between the arm and the trunk in any plane. For ease of simulation, such a threshold value was defined exclusively in the sagittal plane in this study. Table 3 summarizes the frequencies of shoulder postures associated with the different activities. In order to generate a numeric value, specific ranges of *i*, *j*, and *k* for shoulder, elbow, and wrist were first assigned. Different distributions were then assumed and the distribution parameters were determined.

The distribution for shoulder flexion (angle *i*) was assumed to be lognormal, based on the ranges of the PATH categories. Using the median value of each range for *i-shoulder* to represent such a range, the geometric mean (3.8°) and geometric standard deviation (0.6°) could be calculated. According to Porac and Coren (1981) and Tak et al. (2007), when one arm was up, there was a 72% chance that the right arm was up.

The distributions for other motions of the shoulder, elbow and wrist were all assumed as triangular ones, because there was only limited information about the motion ranges and the modal value within each range could be approximated. Specifically, the modal value for *j-shoulder* was assumed to be 45°, which meant the shoulder was most likely abducted in the 45-degree plane corresponding to the coronal plane. During activity 5 (screw) and 6 (in between), *j-shoulder* was zero meaning no abduction.

The modal value for *i-elbow* was assumed to be 90° and each single value was bigger than *i-shoulder*. The difference between *i-elbow* and *i-shoulder* was used to locate the positions of the forearm and hand in the sagittal plane. For *j-elbow*, the mode was zero, which meant that the forearm and the upper arm were most likely in the same line. During activity 5 (screw), *j-elbow* was zero.

The modal values for the remaining triangular distributions were all considered to be zero. During activity 2 (lift) and 3 (carry), *k-wrist*, which represents the forearm rotation, was assumed to be −90°. During activity 5 (screw), *j-wrist* was assumed zero constantly in order to operate the screwdriver powerfully.

The coordinates of muscle and ligament origins and insertions around the shoulder joints were calculated slightly differently, where *j-shoulder* is the rotation about the Z-axis representing the angle of abduction. Thus, *i*, *j*, and *k* compose a set of Euler angles. The rotation matrix is defined as:

$$T_2 = \begin{bmatrix} \cos k^*\cos j - \sin k^*\cos i^*\sin j & \cos k^*\sin j + \sin k^*\cos i^*\cos j & \sin k^*\sin i \\ -\sin k^*\cos j - \cos k^*\cos i^*\sin j & -\sin k^*\sin j + \cos k^*\cos i^*\cos j & \cos k^*\sin i \\ \sin i^*\sin j & -\sin i^*\cos j & \cos i \end{bmatrix} \quad (3)$$

2) Coordinate system rotation – shoulder rhythm

The interplay between the motions of the different parts of the shoulder is known as the “shoulder rhythm.” Högfors et al. (1991) examined the shoulder rhythm by determining the ranges of Euler angles (α, β, γ) of the thorax system oriented along the bone-

Table 3
Frequencies of PATH shoulder posture data associated with different activities.

Activity	Amount	2 down	1 up	2 up	Percent	2 down	1 up	2 up
1 (cut/measure)	25	13	4	8	19.8%	10.3%	3.2%	6.4%
2 (lift)	8	4	1	3	6.4%	3.2%	0.8%	2.4%
3 (carry)	16	10	3	3	12.7%	7.9%	2.4%	2.4%
4 (hold/place)	6	3	0	3	4.8%	2.4%	0.0%	2.4%
5 (screw)	20	9	6	5	15.9%	7.1%	4.8%	4.0%
6 (in between)	24	23	0	1	19.1%	18.3%	0.0%	0.8%
7 (other)	27	18	2	7	21.4%	14.3%	1.6%	5.6%
Total	126	80	16	30	100.0%	63.5%	12.7%	23.8%

fixed coordinate systems. Since there is a lack of information on the relationship between the values of those Euler angles and a specific shoulder motion, the Euler angles were simulated using the Monte-Carlo method. Using the median value to represent each range, the means and standard deviations of different Euler angles for different bones were calculated. Random values could then be simulated, assuming the Euler angles follow normal distributions with those means and standard deviations and fall in the ranges determined by Högfors et al. (1991).

3) External load force vectors

Since subjects were all right-handed, the external load force vectors defined in the biomechanical analysis of the low back could be applied to the shoulder analysis for activities that were conducted by the right hand exclusively. During activities 2 (lift), 3 (carry), 4 (hold/place) and 7 (other) when both two hands were required to be in use, the external loads were equally distributed in two hands since the drywall sheets were symmetric though they were not handled symmetrically.

2.6. Data analysis

Summary statistics for subject weight, height, trunk width and depth were acquired from Marras et al. (2001) because subject anthropometry was not obtained when the PATH data were collected. Subjects were all healthy right-handed males. Using normal distributions for those anthropometric parameters, ten subjects were randomly generated using Monte-Carlo simulation. The present study assumes subject height and weight follow a normal distribution because height and weight are generally known to be normally distributed (Roebuck et al., 1975). This assumption has been validated by Jung et al. (2009) using the 1988 US Army data (Gordon et al., 1988).

The relationships between subject trunk muscle parameters and anthropometric characteristics, such as subject height and weight, body mass index, and trunk width and depth at the planes of muscle origins and insertions, were determined by Marras et al. (2001). The regression equations with higher R^2 values were chosen in this study to represent those relationships. The weight percentages of different body segments of the whole body and the distance coefficients between the body segment center of mass and the proximal joint were then calculated based on information from Drillis and Contini (1966) and Dempster (1995), respectively.

For both the low back and shoulder analyses, anthropometric data on body height and weight, trunk width and depth at both muscle origins and muscle insertions for the ten subjects were summarized. Histograms of simulated eight-hour-workday activities were compared to the observed frequencies of PATH activity data.

Summary statistics of the Maximum Muscle Contraction Intensity (MMCI), the calculated trunk muscle contraction forces and joint reaction forces for the average of ten randomly generated subjects were obtained. Disc compression forces were compared against the load tolerance values proposed by NIOSH (1981) and Waters et al. (1993), where frequencies of disc compression forces above the load tolerance values for the simulated eight-hour workday were calculated. Statistical information about shoulder muscle and ligament contraction and reaction forces at the GH and SC joints was also summarized, including the mean, median, standard deviation or geometric standard deviation (GSD), minimum, and maximum.

3. Results

3.1. Low back analysis

3.1.1. Description of ten simulated subjects

The ten hypothetical drywall installers for the low-back analysis averaged 176.2 ± 9.8 cm in height and 83.1 ± 10.6 kg in weight. The simulations of eight-hour-workday activities generated similar values to the frequencies of observed PATH activities, except for activity 5 (screw), which was overestimated (Fig. 5).

3.1.2. Maximum Muscle Contraction Intensity (MMCI)

The average of MMCI means for the ten simulated subjects was 41.0 ± 7.7 N/cm^2. The average of MMCI standard deviations was 30.6 ± 8.5 N/cm^2, which was understandable since subjects conducted various activities requiring different muscle strengths during the eight-hour workday. The average of MMCI maximum values was 178.2 ± 42.8 N/cm^2 and the maximum reached 251.9 N/cm^2.

3.1.3. Required muscle contraction forces

The averages of LEL, LER, LDL, and LDR contraction force means for the ten simulated subjects during the simulated eight-hour workday were 989.7 ± 243.5, 1009.7 ± 237.0, 591.0 ± 146.9, and 603.8 ± 162.6 N, respectively. The averages of the maximum contraction forces for those four muscle groups were 4785.9 ± 1097.1, 4686.4 ± 1021.1, 3363.4 ± 578.0, and 3727.8 ± 809.7 N, respectively. The highest muscle contraction forces of LEL and LER among the ten subjects were 6688.7 and 6413.3 N respectively, which were greater than the published maximum value estimated by Farfan (1973).

3.1.4. Joint reaction forces

The averages of the means of the disc compression forces, lateral shear forces and anterior-posterior shear forces (absolute values) were 1724.9 ± 205.1, 291.1 ± 75.6, and 487.5 ± 296.8 N, respectively. The averages of the geometric standard deviations of those three joint reaction forces were 0.57, 1.08, and 1.28 N, respectively, with a small standard deviation. In addition, the averages of the maximum values of the joint reaction forces were 6899.9 ± 542.0, 2385.7 ± 707.3, and 3038.0 ± 1710.0 N, respectively, and the highest value for disc compression force was found to be 7784.8 N. There was 8.5% of time during the eight-hour workday, on average, that the calculated disc compression forces exceeded the NIOSH action limit of 3400 N. For the maximum permissible limit of 6400 N, the percentage was 0.8%.

3.2. Shoulder analysis

3.2.1. Description of ten simulated subjects

The mean weight and height for the ten randomly generated subjects for the shoulder analysis were 81.6 ± 6.5 kg and 175.5 ± 5.8 cm. The simulated eight-hour-workday activities for the ten subjects on average produced underestimates for activities 1 (cut/measure), 3 (carry) and 7 (other), and overestimates for activities 5 (screw) and 6 (in between), compared to the PATH observations (Fig. 5).

3.2.2. Required muscle contraction forces

The coracohumeral ligament produced the highest values of force on average, in terms of both the mean (233.6 N) and the maximum (3257.5 N). Muscles with high average force values included biceps brachii (short head) (77.2 N), supraspinatus (61.5 N), teres major (52.4 N), and triceps (51.5 N). The average maximum values of muscle forces generated by the three different parts of deltoideus were also notable. The average standard

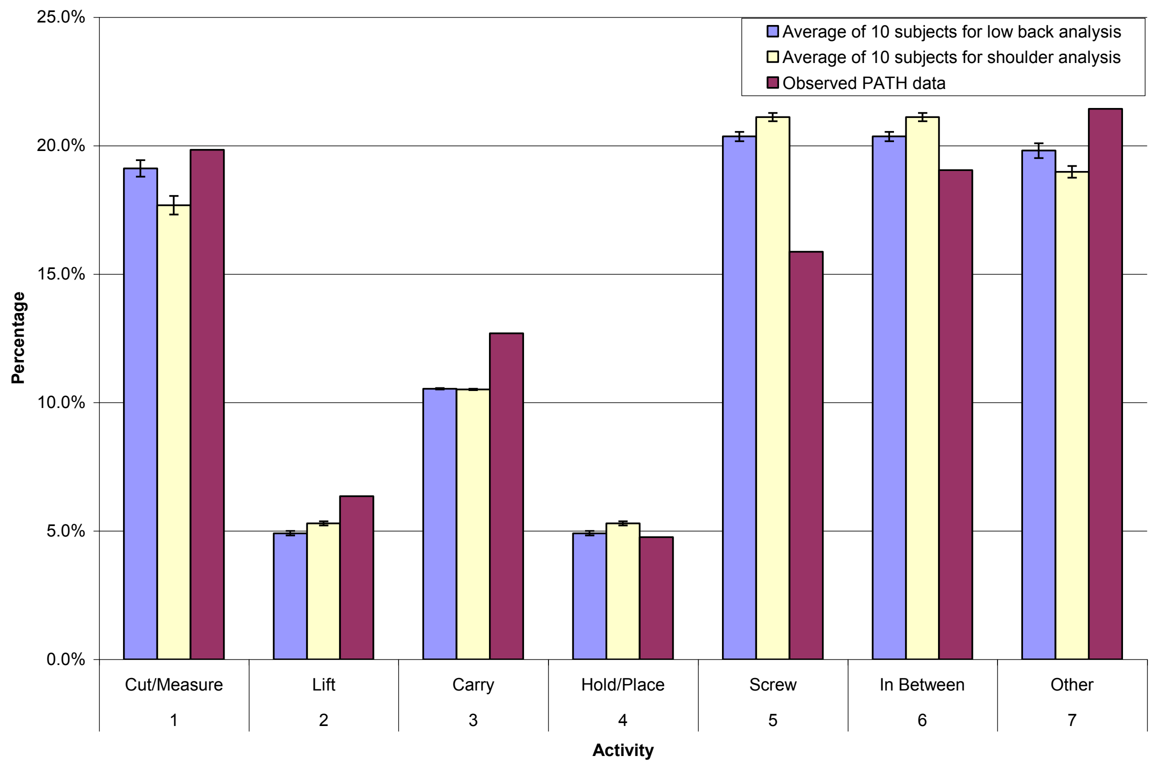

Fig. 5. Frequencies of eight-hour-workday activities for the ten simulated subjects and observed PATH data for low back and shoulder analyses.

deviations for all muscle groups were fairly high, indicating big differences in the physical loads among different activities.

3.2.3. *Joint reaction forces*

The averages of mean joint reaction forces for the ten simulated subjects were 480.9 (GSD 1.02) N and 574.4 (0.98) N for GH and SC, respectively. The averages of maximum values of joint reaction forces reached 4158.3 N and 4237.5 N, with the highest one approaching 5000 N.

4. Discussion

The present study focused on using simulation to integrate data from PATH and biomechanical modeling for an approximation of physical loads on the low back and shoulder during drywall installation. The average muscle contraction forces and joint reaction forces at the lumbar spine (L4/L5) and shoulder (GH and SC) during a simulated eight-hour workday were calculated to delineate the physical demands for drywall installers. The average of L4/L5 disc compression forces during lifting of a whole drywall sheet was slightly higher than the result shown earlier in studies which had only examined the lifting component (Pan and Chiou, 1999). These results may help to explain why the low back and shoulder are frequently reported injured by drywall installers.

The results of the sensitivity analysis indicated that both the distribution of work cycles for a typical eight-hour workday and the distribution and values of Euler angles that are used to determine the "shoulder rhythm" seemed to have the biggest impact on the modeling approach. Other assumptions including the distribution of trunk postures did not appear to have a significant impact on the model outputs.

The calculated maximum values of MMCI were much higher than the range from 35 to 137 N/cm^2 that has been usually reported (Buchanan, 1995). Buchanan (1995) concluded that the maximum muscle stress (similar as MMCI) was not a constant, based on the differences in specific tension in elbow flexors and extensors. It is surmised that the maximum stress for trunk muscles, especially the erector spinae, can vary too.

Akurathi et al. (2002) found that the intensity of lumbar erector spinae for the knee level lift of a 10-kg load was about 100 N/cm^2. Considering that the whole drywall sheet selected in the study weighed more than 40 kg and was stored on the ground, it is not unreasonable to imagine higher MMCIs. Also, the combination of trunk postures during drywall lifting from the simulation in this study might have been too awkward resulting in the seemingly infeasible MMCI values, although they were byproducts of the Monte Carlo simulation.

During the random generation of the subjects' anthropometric data, the authors have specified ranges of subject weight (65–110 kg) and height (160–200 cm) to ensure relatively more realistic anthropometries of construction workers. The chosen R^2 values from Marras et al. (2001) are approximately 0.50 or higher, which might unduly underestimate the muscle moment arms. As a result, the predicted MMCIs, muscle contraction forces, as well as the disc compression forces could be overestimated. Subsequently, the comparison of those forces against the published maximum values by other researchers (Farfan, 1973) as well as by NIOSH could be biased even though the results did indicate the strenuousness of drywall installation, especially the handling of the sheets.

As expected and examined by previous researchers, there was a variety of muscles around the shoulder joints involved in shoulder movement during installation of drywall. The coracohumeral ligament had the highest calculated force in general, which may have meant it was an important contributor to generate force and moment, if the assumed upper limit of 10,000 N is reasonable (Mohamed et al., 1996). Muscle groups with fairly high forces included biceps (short head), supraspinatus, teres major, triceps, and different parts of the deltoideus, which agreed with the results from other investigations (Karlsson and Peterson, 1992; Siemienski et al., 1995).

The reaction force at the sternoclavicular joint was higher generally than the glenohumeral joint reaction force, which contradicts the result of Siemienski et al. (1995). Possible explanations include that multiple activities besides screwdriving were analyzed in this study, with others being the application of muscles around the glenohumeral joint to the sternoclavicular joint.

The present study considered the variability of trunk muscle parameters, including the coordinates of muscle origins and insertions and physiological cross-sectional areas (PCSAs), based on their relationship with the anthropometric data (Marras et al., 2001). Compared to the biomechanical analysis of the low back, the shoulder analysis did not find large inter-subject variability. We surmise that part of this was because we used average values of muscle parameters as opposed to anthropometrically-sized values. Should shoulder muscle parameters have varied significantly, the variability of physical loads on the shoulder could be better understood.

This study extracted information from PATH data and applied it to the simulation of a hypothetical subject. It was noteworthy that PATH observations were made on a crew of eight workers over two hours. There might be other work cycles in reality besides the twelve that were analyzed. Yet, for a simplified simulation of a typical eight-hour workday, only these twelve work cycles were examined. In addition, the activity sequences for the observed drywall installation work were able to be established to allow the generation of an eight-hour-workday activity series. The acceptance of Hypothesis 1 (See appendix) in the present study suggested that these activity sequences eventually determine both the overall probabilities of the twelve work cycles and the low back model outputs.

Despite the fact that most construction work involves non-routine activities, it is not uncommon to see that there are certain patterns/sequences that construction workers usually follow in order to finish the work. For example, ironworkers would have to put the rebar in place before tying it. The method in this study can be used for the ergonomic evaluation of those types of construction work. However, for some other types of construction work, the activity sequence may not be necessarily fixed: e.g., laborers will have to do many miscellaneous activities based on project schedule and needs. Also, it may be difficult to identify all possible activity series. Thus, a comprehensive understanding and capturing of work are always required and it may also involve more reasonable assumptions in order for a realistic simulation of cumulative activities.

In order to generate random numbers from the observational data categories, many assumptions had to be made in terms of distribution type and pertinent parameters. Particularly, different distributional assumptions about body part postures were made, due to a lack of information on how body postures change over time even when repeating the same job activities (Tak et al., 2007). As Tak et al. (2007) has tested the validity of the simulation model as a whole, the sensitivity analysis of the impact of the trunk postures on the low back model output in this study might have provided some useful information about the validation of the integrated modeling approach. The rejection of Hypotheses 2, 3, and 4 indicated that the different probabilities, types, and ranges of parameter distributions did not affect the results significantly.

On the other hand, it seems that there is a lack of sufficient information regarding the shoulder model input values, particularly on the distributions of joint (shoulder, elbow and wrist) angles and the Euler angles that determine the "shoulder rhythm." Because of these limitations, the results of the shoulder model sensitivity analysis were less robust than those of the low back analysis; and thus, may need further evaluation and verification.

As construction work always involves a variety of activities that incur different biomechanical demands, it is imperative to determine the probabilistic representation of biomechanical stress in order to understand both acute and cumulative trauma risk (Mirka et al., 2000). Mirka et al. (2000) developed the Continuous Assessment of Back Stress (CABS) method by estimating the time-weighted distribution of biomechanical stress throughout the workday, therefore providing an important insight into some of the activities that would have been neglected using traditional task analysis methods. The present study explored similar idea by examining the continuous physical loads on the drywall installers' low back and shoulder. In contrast to Mirka et al. (2000), it considered activity sequences for the purpose of studying muscle fatigue characteristics (Yuan, 2006).

It should be noted that there is no gold standard for validation of the average muscle forces and joint reaction forces for a typical eight-hour workday. However, the results from a previous research study (Yuan, 2006) suggested that: 1) the Monte Carlo simulation did generate the same activity distribution as the PATH observations; and 2) the output for the low back model gives similar results to the 3DSSPP (The University of Michigan, 1999).

The present study used a static biomechanical model which could lead to underestimates of joint loading due to the lack of consideration of dynamics. Advanced motion capture devices and sensors have been made available to allow for the direct measurement of kinematics. This would be the most accurate method to quantify the physical loads. However, it would still be problematic and inconvenient to attach the instruments to the research subjects over an extended period of time. Since the construction workers are constantly moving, it makes it even harder to capture the representative work exposure. On the other hand, previous biomechanical analyses of drywall lifting by Pan and Chiou (1999) and Tak et al. (2007) used the 3DSSPP. Absolute values will be underestimated, but relative comparisons should be valid. Additionally, the field observations conducted by the researchers in the present study indicated that the accelerations used by the installers during drywall lifting were low, such that a static model was not too inaccurate in predicting the forces.

Overall, the present study attempted to integrate observational work-sampling, computer simulation, and biomechanical modeling for ergonomic exposure assessment in a typical construction drywall installation work, where it is infeasible to perform direct measurement in the field. The results of the sensitivity analysis implied that such integration might provide an applicable examination of physical loads during the non-routine construction work, especially for those operations/tasks that have certain patterns/sequences for the workers to follow.

Considering that the integrated modeling approach used in the present study is somewhat complicated, there may be a need for extensive computer programming in order to develop software so that such an approach can be applied in the field. Luckily, the use of low-cost on-body sensors, e.g., inertial measurement units, has allowed direct measurement with a minimum interference with work. With the necessary model input variables being measured conveniently and accurately, it is reasonable to foresee the applicability of the modeling approach in the near future.

5. Conclusions

The application of computer-aided simulation to convert observational work sampling data into continuous variables as inputs for biomechanical modeling permitted estimation of the physical loads on the low back and shoulder during drywall installation. The results of the average muscle contraction and joint reaction forces at the lumbar spine (L4/L5) and shoulder (GH and SC) exemplified the strenuous physical requirements for such an operation. Specifically, the average of L4/L5 disc compression forces during lifting a whole drywall sheet is close to 7000 N and is above the limit of the NIOSH maximum permissible limit. The results of the sensitivity analysis demonstrated the robustness of this modeling approach and might provide an applicable examination of physical loads during the non-routine construction work, especially for those operations/tasks that have certain patterns/sequences for the workers to follow.

With the difficulty to conduct direct measurement for field studies of ergonomic exposure assessment, the approach presented in this study has provided important insights into more comprehensive evaluation of different exposure parameters.

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Appendix. Sensitivity analysis

First, a list of the important quantitative assumptions that were made to facilitate modeling was created. From this list, a small number of those assumptions (e.g., the probability of distribution type for trunk flexion angles) which are likely to have the biggest impact on the results were selected for further examination. Through setting up the following null hypotheses for each assumption and changing one parameter at a time, the new model outputs were compared to the original ones.

Hypothesis 1: The distribution of work cycles for a typical eight-hour workday has a significant impact on the low back model outputs.

Hypothesis 2: The probability of the trunk tending to lean toward the left side and twist counterclockwise for a right-handed person during manual work has a significant impact on the low back model outputs.

Hypothesis 3: The distribution of trunk flexion angles has a significant impact on the low back model outputs.

Hypothesis 4: The ranges of PATH trunk posture categories have a significant impact on the low back model outputs.

Hypothesis 5: The distribution and values of Euler angles that are used to determine the "shoulder rhythm" have a significant impact on the shoulder model outputs.

Using student t-tests ($p < 0.05$) to evaluate the statistical differences of the means of major model input and output values including joint angles, muscle forces and joint reaction forces for the low back and shoulder for an average subject working on a typical eight-hour workday, the sensitivity analysis was achieved by determining if the model output is sensitive to any assumption or parameter.

Hypothesis 1. *The distribution of work cycles for a typical eight-hour workday has a significant impact on the low back model outputs.*

In the original model, the overall probabilities of the possible (twelve) work cycles for a typical eight-hour workday of drywall installation were assumed to follow the general discrete distribution. The following two new assumptions were examined and compared with the original one:

a) The twelve work cycles had equal probability; in other words, they follow the uniform distribution.
b) The four work cycles for whole-sheet installation and the eight work cycles for partial-sheet installation had equal probability. This means that there is 1/8 probability for each cycle of whole-sheet installation and 1/16 probability for each cycle of partial-sheet installation, respectively.

The comparison between the first assumption and the original one indicated that:

1) The ratio of activity 1 (cut/measure) over activity 2 (lift) was higher, which means that there were more work cycles of partial-sheet installation and the eight-hour workday tends to be less strenuous. However, the total work productivity (measured by the square foot of installation) might be reduced.
2) The angles of trunk flexion, lateral bending, and twisting were the same.
3) The MMCI (Maximum Muscle Contraction Intensity) ($t = 5.606$, $p < 0.0001$) and the forces of two major pairs of trunk muscles (Erector Spinae and Latissimus Dorsi) (for LEL, $t = 5.441$, $p < 0.0001$; for LER, $t = 5.346$, $p < 0.0001$; for LDL, $t = 4.772$, $p < 0.0001$; and for LDR, $t = 5.179$, $p < 0.0001$) were statistically significantly smaller.
4) The absolute values of the L4/L5 joint reaction forces (disc compression, lateral shear, and anterior-posterior shear) were statistically significantly smaller ($t = 5.715$, $p < 0.0001$; $t = 2.414$, $p = 0.008$; and $t = 5.705$, $p < 0.0001$, respectively).

The comparison between the second assumption and the original one indicated that:

1) The frequency of the seven activities for a typical eight-hour workday appeared to be similar to that of the original model.
2) As a result, there were no statistically significant differences among the joint angles, MMCI, muscle forces, and joint reaction forces.

Based on these findings, it appears that Hypothesis 1 could not be rejected. In other words, the distribution of work cycles for a typical eight-hour workday determines the frequency of the seven activities that were examined in this study; and consequently, has a significant impact on the low back model outputs.

Hypothesis 2. *The probability of the trunk tending to lean toward the left side and twist counterclockwise for a right-handed person during manual work has a significant impact on the low back model outputs.*

In the original model, it was assumed that "For a right-handed person, the trunk tends to lean toward the left side and twist counterclockwise for 80% of time during manual work." The present study compared that probability to 50%, 75%, and 85%, respectively.

For the comparison between 50% and 80%, the results indicated that:

1) The angles of trunk flexion were the same, but the absolute values of trunk lateral bending and twisting angles were smaller.

2) There were no statistically significant differences among the MMCI and the forces of two major pairs of trunk muscles.
3) Similarly, there were no statistically significant differences among the absolute values of the L4/L5 joint reaction forces.

For the comparison between 75% and 80%, the results indicated that:

1) The angles of trunk flexion were the same, but the absolute values of trunk lateral bending and twisting angles were smaller.
2) There were no statistically significant differences among the MMCI and the forces of two major pairs of trunk muscles, as well as the absolute values of the L4/L5 joint reaction forces.

For the comparison between 85% and 80%, the results indicated that:

1) The angles of trunk flexion and twisting were the same, but the absolute values of trunk lateral bending angles were larger.
2) There were no statistically significant differences among the MMCI and the forces of two major pairs of trunk muscles, as well as the absolute values of the L4/L5 joint reaction forces.

Based on these examinations, it seems that Hypothesis 2 could be rejected.

Hypothesis 3. *The distribution of trunk flexion angles has a significant impact on the low back model outputs*.

Trunk flexion angles were assumed to follow lognormal distribution in the original model. The researcher changed it to normal distribution and the comparison between those two indicated that there were no statistically significant differences among the model input and output values. This could suggest that Hypothesis 3 be rejected.

Hypothesis 4. *The ranges of PATH trunk posture categories have a significant impact on the low back model outputs*.

The original ranges for the PATH trunk posture categories had a minimum of 0 for neutral (in terms of flexion) and 45° for severe flexion, and a maximum of 35° for lateral bending and 45° for twist. These were compared with ranges that had a minimum of −10° for neutral (in terms of flexion) and 50° for severe flexion, and a maximum of 40° for lateral bending and 50° for twist. The comparison between those two ranges did not yield statistically significant differences on the model input and output values, except for the absolute values of the L4/L5 lateral shear force ($t = 4.264$, $p < 0.0001$). The forces of two major pairs of trunk muscles tended to be lower, although the differences were not statistically significant.

It seems that Hypothesis 4 could be rejected in general; however, further analysis might be needed to find out why the L4/L5 lateral shear forces were statistically different.

Hypothesis 5. *The distribution and values of Euler angles that are used to determine the "shoulder rhythm" have a significant impact on the shoulder model outputs*.

In the original shoulder model, the means and standard deviations of the Euler angles were obtained independently from the ranges of such angles for three subjects in the motion studies conducted by Högfors et al. (1991). Through the review of a modified shoulder rhythm model by Makhsous (1999), we were able to find the following equations describing the estimates for the Euler angles for the clavicle and scapula relative to the humerus.

$$\alpha_c = -35.15 + 11.15\cos[0.75(\beta_h + 90)](0.08\alpha_h) \quad (1)$$

$$\beta_c = 18\{1 - \cos[0.8(\beta_h + 90)]\} + 9 \quad (2)$$

$$\gamma_c = 30\{1 - cos[0.75(\beta_h + 90)]\} + 3 \quad (3)$$

$$\alpha_s = 200 + 20\, cos[0.75(\beta_h + 90)] \quad (4)$$

$$\beta_s = -87 + 42\, cos[-0.75\beta_h - 70](0.1\gamma_h/90 + 1) \quad (5)$$

$$\gamma_s = 82 + 8\, cos\{(\alpha_h + 10)\sin[0.75(\beta_h + 90)]\} \quad (6)$$

The new Euler angles seem to be different from the old ones, especially the values of $\beta_{Scapula}$. The comparison of the model outputs indicated that the majority of muscle forces tended to be significantly bigger; whereas the coracohumeral ligament force was significantly smaller ($t = 8.738$, $p < 0.0001$). On the other hand, the glenohumeral and sternoclavicular joint reaction forces were larger but the increases were not statistically significant, compared to those yielded from the original model.

Based on these comparisons, it seems that Hypothesis 5 should not be rejected.

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