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Position and Size of Drywall on the Physical Demands for Drywall Installers

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ABSTRACT

The present study utilized an integrated biomechanical modeling approach that was previously developed by the researcher to investigate the effects of position and size of drywall on the physical demands for drywall installers. First, a sensitivity analysis was conducted to examine the impact of some quantitative assumptions that have been made to facilitate the modeling approach. Through setting up null hypothesis for each assumption and changing one parameter at a time, the new model output values were compared to the original ones. Using student t-tests to evaluate the statistical differences of the mean values, the sensitivity analysis was achieved by determining if any assumption or parameter has significant impact on the model. The results indicated that the modeling approach seemed to be the most sensitive to both the distribution of work cycles for a typical 8-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 significant impact on the model output values. It was concluded that the integrated approach might provide an applicable examination of exposure variability particularly reflected by the non-routine feature of the work.

The results from the second part of the study verified the hypotheses on the impact of drywall storage position and size. In particular, the required muscle contraction forces and joint reaction forces at the low back and shoulder reduced approximately 8% (with a range of 3.6% - 12.8%) if the drywall sheets were stored vertically and spiked if the size of drywall sheets increased. These changes were even more notable for the exclusive comparison of the activity 2 (lift), which could be used as guidance to help ASTM (American Society for Testing and Materials) make recommendations about drywall. Specifically, those 4x12 and 4x16 sheets increase the physical burden for drywall installers significantly and could expose them to a higher risk of musculoskeletal injuries and disorders.

KEY FINDINGS

1. The application of computer-aided simulation to convert observational work sampling data into continuous variables as inputs for biomechanical modeling permitted a valid estimation of the physical loads on the low back and shoulder during drywall installation.

2. If the drywall sheets were stored vertically instead of flat, it would reduce the required muscle contraction forces and joint reaction forces at the low back and shoulder approximately 8% on average during drywall installation. In particular, the L4/L5 disc compression forces and the absolute values of L4/L5 anterior-posterior shear forces decreased 6.1% and 8.5%, respectively, and at the shoulder during lifting the forces of rotator cuff muscles decreased 9.8%, and the coracohumeral ligament forces decreased 12.8%. The reaction forces at both the GH (glenohumeral) and SC (sternoclavicular) joints went down by 7.2% and 3.6%, respectively.

3. As a drywall stabilizing clip could be used to secure the sheets in a vertical storage position, more research is needed to examine how it is used in practice as well as how the work efficiency and productivity could be affected.

4. The bigger size (e.g., 4x12 and 4x16) of drywall sheets increased the physical burden for drywall installers significantly and could expose them to a higher risk of musculoskeletal injuries and disorders. In some simulations the average low back lateral shear forces increased to 1674.7 N and 2152.2 N, respectively. These forces are significantly above the 1000 N recommended for a single lift.

5. These results indicated that it would be physically too difficult or even impossible for one person alone to lift bigger and heavier drywall sheets. Therefore, sound engineering (e.g., lifting tables) and/or administrative (e.g., two-person team work) solutions to handling oversized drywall sheets are strongly recommended.

INTRODUCTION

Construction workers who perform drywall installation are at a high risk of various musculoskeletal injuries and disorders, especially to the low back and shoulder areas (Chiou et al., 2000; Hsiao and Stanevich, 1996; Lemasters et al., 1998; Lipscomb et al., 1997, 2000). The manufacturers of drywall recommend that it be stored flat, in part because they have been found liable for not warning customers of the risk of injury from drywall falling over if stored vertically. This has resulted in drywall installers using a significant amount of awkward postures and enormous forces during lifting of the sheets. In order to make drywall lifting easier, some contractors deliver the drywall to the site in a vertical position and then have it unloaded and stored vertically on a cart or directly on the floor against a wall. The installers then take the drywall off the cart or floor and hang it on the installation location. Nevertheless, the stability of drywall storage in a vertical position has caused great concerns.

Invented by RockSteady LLC, the *RockSteady® Clip* is a drywall stabilizing clip that virtually eliminates the risk of incidental or accidental tip-over of vertically stacked drywall (RockSteady LLC, 2009). It works by securing drywall sheets in a leaning position, keeping the stack from being pulled forward. The *RockSteady® Clip* costs about $2.50 per unit. It has been patented and has undergone certain types of performance evaluation by Mutual Engineering, Inc. (MEI). It is available for purchase at select distributors including Wind-lock Corporation and ToolPro, Inc., and has been sold to various drywall supply yards according to ConstructionKnowledge.net (2010).

The sizes of drywall sheets are increasing due to industry demands. For decades, the standard size was 4x8, but now 4x12 is becoming standard and 4x16 is being used more frequently, especially on jobs where the workers are paid by the piece. This has unduly exacerbated the physical stress on the installers, and increased the needs for ergonomic solutions for drywall handling.

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 were aware of 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, more reliable and cost-effective ergonomic exposure assessment methods are warranted.

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; 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, 1997).

The researcher has previously explored a hybrid model integrating work sampling, computer simulation, and biomechanical modeling to conduct the ergonomic analysis of drywall installation (Yuan, 2006; Yuan et al., 2007). Since it is often infeasible to conduct direct measurements of ergonomic exposure assessment particularly within the construction industry, such a method has provided a reasonable alternative to estimate the physical demands during drywall installation. The present study was designed to examine the impact of drywall position and size on the physical demands for drywall installers and further demonstrate the validity and utility of this modeling approach. The specific aims of the study include:

Aim 1. Validate the integrated biomechanical modeling approach.

1) Examine the impact of the model assumptions on the results.
2) Re-execute the model to conduct the sensitivity analysis.

Aim 2. Evaluate the impact of drywall storage position and size on the physical demands.

1) Obtain model input values with changes in both storage position and size.
2) Re-execute the model to obtain model output values.
3) Compare the model output values to estimate the difference in back and shoulder stress due to the change of drywall storage position and size.

METHODS

The integrated modeling approach (Figure 1) started with the PATH methodology which 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 the eight-hour-workday activity series using Monte-Carlo simulation. The biomechanical model input variables, including anthropometric data, joint angles, external load force and position vectors, and internal muscle parameters, were then generated for the analyses of the low back and shoulder. Utilizing different optimization programs in MATLAB (The MathWorks, Natick, MA, USA), the three-dimensional static equilibrium equations were solved and the biomechanical model output variables of muscle contraction forces and joint reaction forces at the low back and shoulder were computed.

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. It was determined from the field observations that there were 12 possible work cycles, with 4 occurring during installation of a whole sheet and 8 denoting installation processes for a partial piece. The probability of each work cycle was calculated by multiplying the probability of every single activity during that cycle (Yuan, 2006). As studied 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. When the drywall sheets were stored vertically with the use of the *RockSteady® Clip*, activity 7 (other) represented the assembling/disassembling of the clip.

The drywall sheets studied in this project were Sheetrock® Brand Gypsum Panel from CGC Inc., with bulk density of 881 kg/m^3 (55 lb/ft^3). Summary statistics for subject weight, height, trunk widths and depths are acquired from Marras et al. (2001), because subject anthropometry was not obtained when the original PATH data were collected. 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 squares 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 calculated based on information from Drillis and Contini (1966) and Dempster (1955), respectively.

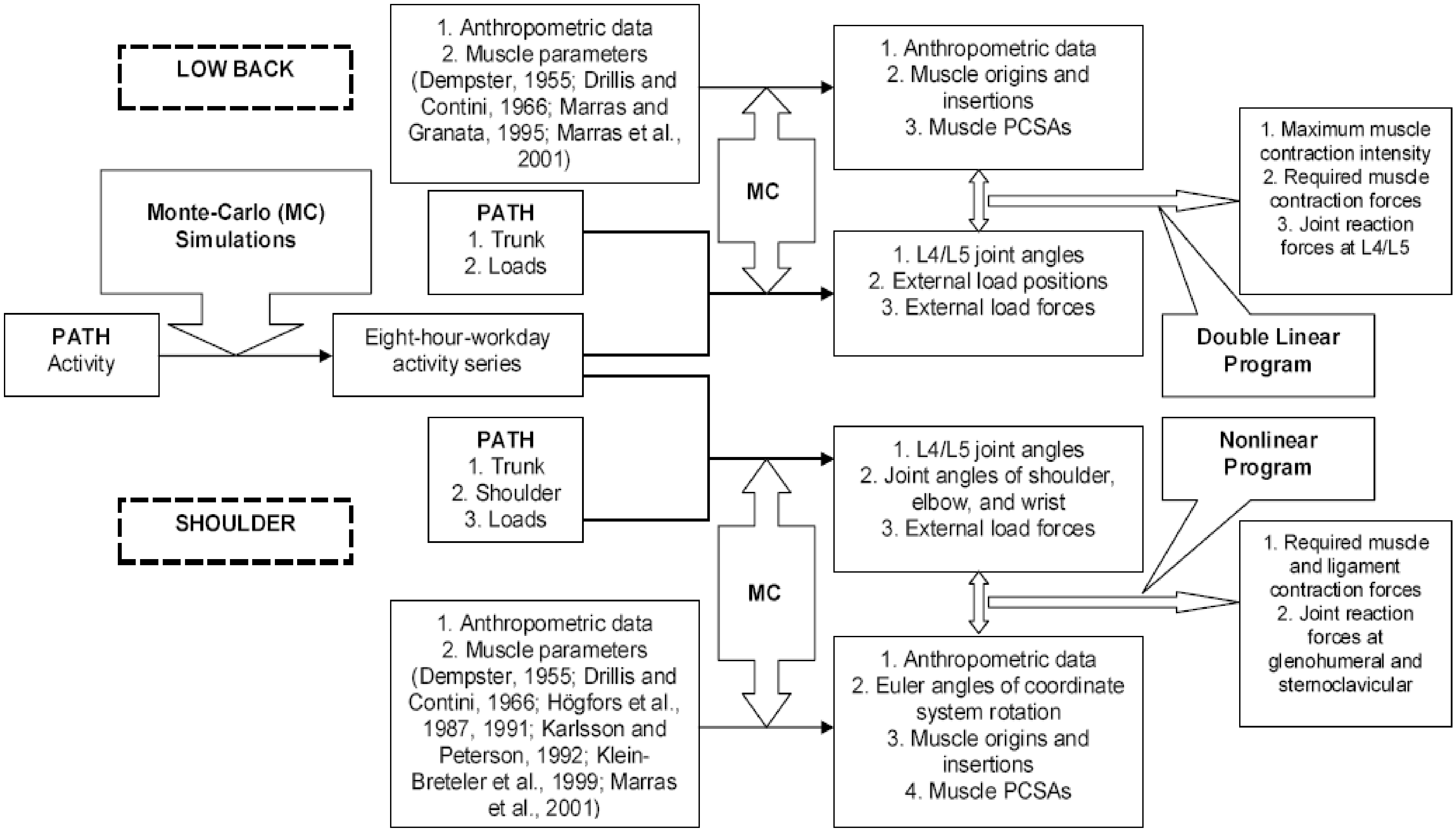

Figure 1. Schematic diagram for the data analysis in this study

The specific aims of the present study were accomplished through the following tasks.

Task 1: Validate the modeling approach by conducting a sensitivity analysis.

First, a list of the important quantitative assumptions that have been made to facilitate modeling was created. These assumptions include, but are not limited to, the following:

1) The overall probabilities of the possible work cycles for a typical drywall installation task follow the general discrete distribution.
2) For a right-handed person, the trunk tends to lean toward the left side and twist counterclockwise for 80% of time during manual work (Tak et al., 2007).
3) Trunk flexion angles follow a lognormal distribution, whereas trunk lateral bend and twist angles both have normal distributions.
4) Values of the external load position on the Z-axis (directed upwards when the subject is standing erect) are dependent on the trunk flexion angles and show a normal distribution.
5) Shoulder flexion angles display a normal distribution, and other motions of the shoulder, elbow, and wrist all have triangular distributions.
6) Values of Euler angles that are used to determine the "shoulder rhythm" (Högfors et al., 1991) have a normal distribution.

From this list, the researcher selected 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 for further examination. Through setting up the following null hypotheses for each assumption and changing one parameter at a time, the new model output values were compared to the original ones.

Hypothesis 1: The distribution of work cycles for a typical 8-hour workday has significant impact on the low back model.

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 significant impact on the low back model.

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

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

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

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 8-hour workday, the sensitivity analysis was achieved by determining if the model is sensitive to any assumption or parameter.

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).

Task 2: Apply the modeling approach to estimate the difference in back and shoulder stress due to the change of drywall storage position and size.

The following two hypotheses were examined for Task 2:

Hypothesis 6: The required muscle contraction forces and joint reaction forces at the low back and shoulder will decrease if the drywall sheets are stored vertically instead of flat.

Hypothesis 7: The required muscle contraction forces and joint reaction forces at the low back and shoulder will increase if the size of drywall sheets increases.

The model input values were changed when the drywall was stacked vertically instead of flat on the ground, or when the size of the drywall sheet increased. Based on the validation analysis from Task 1, it was assumed that the drywall installers used the same posture to handle bigger drywall sheets; yet, those sheets caused increases in the weight that was being handled as well as in the number of screws that were required to fasten the sheets. Furthermore, the drywall installers' hand location on the drywall sheets might have changed when the size increased. The impact on the low back and shoulder when the hands were placed approximately 1 foot right of the vertical middle line of the drywall sheets during activity 2 (lift) was examined.

When the drywall sheets were stacked vertically, the drywall installers were able to use more neutral trunk postures during activity 2 (lift). Activity 7 (other) referred to the assembling/disassembling of the *RockSteady® Clip* exclusively. Based on a video that was previously recorded on this particular activity, the drywall installers usually used the same screwdriver (DeWalt Heavy-Duty VSR Drywall Screwdriver – DW252, weighing 12 N) that was used for activity 5 (screw) to both fasten the clip to the drywall sheets and take it off. Thus, similarly to activity 5 (screw), both a horizontal reaction force along the Y-axis (directed forward) of the coordinate system for the low back model (Yuan, 2006) and a reaction torque about the Y-axis were added due to the manipulation of the screwdriver. Their values were assumed as 10 N and 7 N*m, respectively, according to the screwdriver's specifications. These data, along with the assumptions that have been validated from Task 1, were used as bases for generating the new model input values.

Percent Decrease/Increase of the model output values, primarily the required muscle contraction forces and joint reaction forces at the low back and shoulder under different case scenarios including changes of drywall storage position and size, were calculated to demonstrate the impact of drywall position and size on the physical demands for drywall installers. The general equation for calculating Percent Decrease/Increase is

$$Percent\ Decrease/Increase = \frac{V_{pre} - V_{post}}{V_{pre}} * 100\% \qquad (1)$$

Where,
V_{pre} = Value of model output values before change
V_{post} = Value of model output values after change

Because of the limitations of the shoulder model, the impact of drywall storage position and size on the shoulder was examined based on the comparisons of model output values for activity 2 (lift) for an average subject working on 10 hypothetical work cycles of a typical 8-hour workday.

RESULTS

Task 1: Sensitivity analysis

Hypothesis 1: The distribution of work cycles for a typical 8-hour workday has significant impact on the low back model.

In the original model, the overall probabilities of the possible (12) work cycles for a typical 8-hour workday of drywall installation were assumed to follow the general discrete distribution. The present study examined the following two new assumptions and compared them with the original one:

1) The 12 work cycles had equal probability; in other words, they follow the uniform distribution. And
2) The 4 work cycles for whole-sheet installation and the 8 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 8-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) and the forces of two major paired trunk muscles (Erector Spinae and Latissimus Dorsi) 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 8-hour workday appeared to be similar to that of the original model. And as a result,
2) 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 8-hour workday determines the frequency of the seven activities that were examined in this study; and consequently, has significant impact on the low back model output values.

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 significant impact on the low back model.

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 changed such a 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 paired 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 paired 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 paired 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 significant impact on the low back model.

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 significant impact on the low back model.

The original ranges of PATH (Posture, Activity, Tools, and Handling) trunk posture categories are shown in Table 1 below.

Table 1 Original Ranges of PATH Trunk Posture Categories

Category		i (degree)	j (degree)	k (degree)
Neutral		0 ~ 20	-20 ~ 20	-20 ~ 20
Mild Flexion		20 ~ 45	-20 ~ 20	-20 ~ 20
Severe Flexion		45 ~ 80	-20 ~ 20	-20 ~ 20
Bend & Twist	Left*	0 ~ 20	20 ~ 35	-45 ~ -20
	Right	0 ~ 20	-35 ~ -20	20 ~ 45
Bend & Twist & Flexion	Left	20 ~ 80	20 ~ 35	-45 ~ -20
	Right	20 ~ 80	-35 ~ -20	20 ~ 45

Note: i – Flexion; j – Lateral bend; k – Twist; * – Assuming the trunk bended left and twisted anticlockwise (view from above) with a probability of 80%.

Based on these ranges, the distribution parameters for trunk postures were obtained as follows (Table 2):

Table 2 Distribution Parameters for Original PATH Trunk Posture

Variable		Distribution Type	Distribution Parameter	
			Mean/GM (degree)	SD/GSD (degree)
Trunk Posture	i	Lognormal	2.9	0.8
	j	Normal	2.8	10.9
	k	Normal	-3.2	12.9

In the present study, the new ranges of PATH trunk posture categories were assumed to be (Table 3):

Table 3 New Ranges of PATH Trunk Posture Categories

Category		i (degree)	j (degree)	k (degree)
Neutral		-10 ~ 20	-20 ~ 20	-20 ~ 20
Mild Flexion		20 ~ 50	-20 ~ 20	-20 ~ 20
Severe Flexion		50 ~ 80	-20 ~ 20	-20 ~ 20
Bend & Twist	Left*	0 ~ 20	20 ~ 40	-50 ~ -20
	Right	0 ~ 20	-40 ~ -20	20 ~ 50
Bend & Twist & Flexion	Left	20 ~ 80	20 ~ 40	-50 ~ -20
	Right	20 ~ 80	-40 ~ -20	20 ~ 50

The new distribution parameters for trunk postures are shown in Table 4.

Table 4 New Distribution Parameters for PATH Trunk Posture in the Present Study

Variable		Distribution Type	Distribution Parameter	
			Mean/GM (degree)	SD/GSD (degree)
Trunk Posture	i	Lognormal	2.5	1.1
	j	Normal	3.0	11.9
	k	Normal	-3.5	13.9

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 paired trunk muscles tended to be lower, but 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 significant impact on the shoulder model.

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), the researcher was 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 output values 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 6 should not be rejected. As there is still a strong need to continue studying the "shoulder rhythm," the examination of Hypothesis 6 might indicate that Euler angles are indeed crucial in term of the understanding of the shoulder model.

Task 2: Examination of drywall storage position and size

Hypothesis 6: The required muscle contraction forces and joint reaction forces at the low back and shoulder will decrease if the drywall sheets are stored vertically instead of flat.

For the low back model, the absolute values of trunk flexion, lateral bending, and twisting angles for an average subject working on a typical 8-hour workday decreased 3.8%, 15.4%, and 8.6%, respectively, when the drywall sheets were stored vertically instead of flat. The MMCI and the forces of two major paired trunk muscles also decreased an average of 8.2%. The absolute values of L4/L5 lateral shear forces did not change; however, the L4/L5 disc compression forces and the absolute values of L4/L5 anterior-posterior shear forces decreased 6.1% and 8.5%, respectively. These reductions were even more apparent when only activity 2 (lift) was compared.

For the shoulder model, the absolute values of trunk flexion, lateral bending, and twisting angles, as well as the shoulder flexion angles for an average subject working on 10 hypothetical work cycles of a typical 8-hour workday decreased 4.0%, 7.0%, 19.2%, and 9.2%, respectively, when the drywall sheets were stored vertically instead of flat. For activity 2 (lift), the forces of rotator cuff muscles (consisting of supraspinatus, infraspinatus, subscapularis, and teres minor) decreased 9.8%, and the coracohumeral ligament forces decreased 12.8%. The reaction forces at both the GH (glenohumeral) and SC (sternoclavicular) joints went down by 7.2% and 3.6%, respectively.

These results indicated that the physical loads at the low back and shoulder during drywall installation, especially during drywall lifting, were reduced if the drywall sheets were stored vertically. Therefore, Hypothesis 7 should not be rejected.

Hypothesis 7: The required muscle contraction forces and joint reaction forces at the low back and shoulder will increase if the size of drywall sheets increases.

If the size of drywall sheets increased from 4x8 to 4x12, the MMCI and the forces of two major paired trunk muscles would increase an average of 12.3% (Table 5). This would also result in an average increase of 11.6% (Table 6) for the absolute values of the L4/L5 joint reaction forces (disc compression, lateral shear, and anterior-posterior shear, respectively). If the hands were placed approximately 1 foot right of the vertical middle line of the drywall sheets, the average increases of the MMCI and required muscle contraction forces, and joint reaction forces were even higher at 19.4% (Table 5) and 26.1% (Table 6), respectively. However, these increases were not symmetrical as the right lumbar erector spinae muscle forces and L4/L5 anterior-posterior shear forces showed much smaller increases compared to others. All of the increases were even more evident when only activity 2 (lift) was compared.

Table 5 Percent Increases of MMCI and Two Major Paired Trunk Muscle Forces for Installation of 4x12 and 4x16 Drywall Sheets

Percent Increase	MMCI	LEL	LER	LDL	LDR	Average
4x12 VS 4x8	11.6%	12.1%	12.2%	13.3%	12.3%	12.3%
4x12 Right VS 4x8	20.3%	21.5%	8.8%	27.4%	18.8%	19.4%
4x16 VS 4x8	25.4%	26.9%	27.2%	31.1%	30.2%	28.2%
4x16 Right VS 4x8	37.4%	39.9%	21.8%	50.4%	40.6%	38.0%

Note: MMCI – Maximum Muscle Contraction Intensity; LEL – Left Lumbar Erector Spinae; LER – Right Lumbar Erector Spinae; LDL – Left Latissimus Dorsi; LDR – Right Latissimus Dorsi.

Table 6 Percent Increases of the L4/L5 Joint Reaction Forces for Installation of 4x12 and 4x16 Drywall Sheets

Percent Increase	COMP	ABS(LS)	ABS(APS)	Average
4x12 VS 4x8	10.8%	10.6%	13.5%	11.6%
4x12 Right VS 4x8	19.1%	52.2%	7.0%	26.1%
4x16 VS 4x8	23.7%	15.1%	33.0%	23.9%
4x16 Right VS 4x8	34.8%	74.7%	24.9%	44.8%

Note: COMP – Disc compression force; ABS(LS) – Absolute value of lateral shear force; ABS(APS) – Absolute value of anterior-posterior shear force.

The shoulder model results yielded increases in muscle (rotator cuff muscle, 5.0%, and coracohumeral ligament, 59.9%) forces and joint (GH, 38.1%, and SC, 37.5%) reaction forces as well, when 4x12 drywall sheets were installed.

If the size of drywall sheets increased from 4x8 to 4x16, the percent increases on average for the MMCI and required muscle contraction forces, and joint reaction forces were 28.2% (Table 5) and 23.9% (Table 6), respectively. When the subject lifted the sheets from 1 foot right of the vertical middle line, it resulted in even more percent increases. Surprisingly, the absolute values of the L4/L5 lateral shear forces went up by 74.7%, and when only activity 2 (lift) was compared, such forces were higher than three times of the ones when 4x8 sheets were lifted.

Similar patterns occurred to the shoulder model, where much higher muscle contraction forces and joint reaction forces were required to lift the 4x16 sheets (Table 7). In particular, the rotator cuff muscle forces almost tripled, which indicated much different increases when compared to the installation of 4x12 sheets.

Table 7 Percent Increases of Rotator Cuff (RC) Muscle and Coracohumeral (COL) Ligament Forces and Glenohumeral (FGH) and Sternoclavicular (FSC) Joint Reaction Forces for Lifting of 4x16 and 4x12 Drywall Sheets

Percent Increase	RC	COL	FGH	FSC
4x12 VS 4x8	5.0%	59.9%	38.1%	37.5%
4x16 VS 4x8	192.8%	100.6%	94.9%	85.7%

DISCUSSION

The present study utilized an integrated biomechanical modeling approach that was previously developed by the researcher to investigate the effects of position and size of drywall on the physical demands for drywall installers. It first validated the modeling approach through a sensitivity analysis. The results indicated that both the distribution of work cycles for a typical 8-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 significant impact on the model output values.

The results from the second part of the present study verified the hypotheses on the impact of drywall storage position and size. In particular, the required muscle contraction forces and joint reaction forces at the low back and shoulder reduced approximately 8% (with a range of 3.6% - 12.8%) if the drywall sheets were stored vertically and spiked if the size of drywall sheets increased. These changes were even more notable for the exclusive comparison of the activity 2 (lift), which could be used as guidance to help ASTM (American Society for Testing and Materials) make recommendations about drywall. Specifically, those 4x12 and 4x16 sheets increase the physical burden for drywall installers significantly and could expose them to a higher risk of musculoskeletal injuries and disorders.

Sensitivity Analysis

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 8 workers over two hours. As it is desired to determine the most efficient number of worker participating in the study relative to the number of repeated measurements for each of these workers (Van der Beek and Frings-Dresen, 1998), there might be other work cycles in reality besides the 12 that were analyzed. Yet, for a simplified simulation of a typical 8-hour workday, only these 12 work cycles were examined. Similarly, the activity sequences for the observed drywall installation work were able to be established to allow the generation of eight-hour-workday activity series. The acceptance of Hypothesis 1 in the present study suggested that these activity sequences eventually determine both the overall probabilities of the 12 work cycles and the low back model output values.

Because 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, 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 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 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 important 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).

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 exposure variability particularly reflected by the non-routine feature of the work.

Application of the Modeling Approach

To ensure more accurate comparisons of model output values due to the changes of drywall storage position and size, the present study used previously collected and/or available data including observational, anthropometric, and muscular ones as bases for computer simulation. Only minimum necessary changes were made to the model input values for the evaluations of vertical storage position and bigger sizes of sheets, respectively; and it was assumed that the drywall installers would have to maintain the same productivity for a typical 8-hour workday under different circumstances.

Nevertheless, the PATH data especially those postural ones could have changed significantly when the drywall sheets were stored vertically or even when the size of the sheets increased. Similarly, the changes of PATH activity data with the use of the *RockSteady® Clip* could also warrant more PATH data collection. On the other hand, the present study assumed that the clip allowed the storage of drywall in a safe and secure manner and did not produce negative impact on the work efficiency and productivity; yet, it would be still useful to visit a site to see how the clip is used in practice.

Both the low back and shoulder model output values including the MMCI, the required muscle contraction forces, and joint reaction forces became much higher, especially for lifting of 4x12 or 4x16 sheets. Some of the results are beyond the normal ranges that have been published by previous studies. For example, the average erector spinae forces for lifting a 4x16 sheet were estimated to be approximately 7400 N, which is bigger than the normal range (2200 N - 5500 N) of the strength capability in a healthy population (Farfan, 1973). If the installer was to lift the 4X12 and 4X16 sheets from 1 foot right of the vertical middle line, the average L4/L5 lateral shear forces would increase to 1674.7 N and 2152.2 N, respectively, which are significantly above the 1000 N recommended for a single lift (McGill 1997). These results indicated that it would be physically too difficult or even impossible for one person alone to lift bigger and heavier drywall sheets. Therefore, sound engineering (e.g., lifting tables) and/or administrative (e.g., two-person team work) solutions to handling oversized drywall sheets are strongly needed.

Future Plans

The researcher plans to share the study results with ASTM. ASTM has a Technical Committee C11 on Gypsum and Related Building Materials and Systems, which "covers specifications and guides for gypsum products and gypsum board, metal lath, studs, fasteners and related metal products, as well as practices for the application of stucco and EIFS products." (ASTM, 2011a) The committee meets twice a year to discuss various issues about gypsum products including drywall. On the other hand, ASTM also has a Committee E34 on Occupational Health and Safety who issues industrial hygiene and safety standards that "specify the materials and detail the test methods that are relevant in recognizing, assessing, and controlling the physical, chemical, and environmental hazards involved in the workplace that could disrupt worker's health and well-being." (ASTM, 2011b) Of note, ASTM has developed ASTM E2350 - 07 *Standard Guide for Integration of Ergonomics/Human Factors into New Occupational Systems*. The researcher hopes that the study results will be of use for information on the health and safety of drywall handling due to the change of drywall size and storage position.

In order to further examine the efficacy and effectiveness of the *RockSteady® Clip*, the researcher has started working on a proposal *Ergonomic Evaluation of Drywall Stabilizing Clip* for application of the ASSE (American Society of Safety Engineers) Foundation Research Grant Program. Beyond this, the researcher plans to propose a larger study based on the results of these two projects to continue investigating reasonable intervention strategies to reduce the physical burden of drywall installation.

CONCLUSION

The application of computer-aided simulation to convert observational work sampling data into continuous variables as inputs for biomechanical modeling permitted a valid estimation of the physical loads on the low back and shoulder during drywall installation. The results of the sensitivity analysis of the modeling approach indicated that the distribution of work cycles for a typical 8-hour workday and the distribution and values of Euler angles that are used to determine the "shoulder rhythm" seemed to have the most significant impact on the modeling approach. The distribution of trunk postures, on the other hand, did not appear to have significant impact on the low back model output values. The sensitivity analysis allowed the researcher to look at errors associated with converting the PATH categorical data to actual joint angles, with a purpose of validating the modeling approach.

When the modeling approach was used to study the impact of the drywall storage position and size on the physical demands for drywall installers, it was determined that the required muscle contraction forces and joint reaction forces at the low back and shoulder decreased if the drywall sheets were stored vertically instead of flat. On the other hand, the bigger size (e.g., 4x12 and 4x16) of drywall sheets increased the physical burden for drywall installers significantly and could expose them to a higher risk of musculoskeletal injuries and disorders.

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