Advances in Occupational Ergonomics and Safety
A.C. Bittner Jr. et al. (Eds.)
IOS Press, 2001

KINEMATIC ANALYSIS OF DRYWALL LIFTING

Christopher S. Pan, Sharon S. Chiou, Long, D., Zwiener, J., and Cantis D.
National Institute for Occupational Safety and Health, Morgantown, WV 26505

Abstract. Drywall sheets are heavy and bulky. Depending on the thickness and size of the sheets, they can weigh between 55 and 200 pounds. Therefore, workers who constantly lift drywall sheets may be exposed to high risks for overexertion and fall injuries. The objective of this study was to quantitatively evaluate the kinematic stressors associated with lifting drywall sheets so that injury control strategies could be recommended. Twenty-eight construction workers (mean age = 35 ± 9 years) with at least 6 months of drywall-installation experience (mean experience = 9 ± 7 years) participated in this study. Each subject performed a lift of a 4-foot by 8-foot drywall sheet, weighing approximately 55 pounds using one of four lifting methods: (1) vertical lift of the drywall, (2) horizontal lift of drywall with both hands positioned on the top of the drywall, (3) horizontal lift of drywall with both hands positioned on the bottom of the drywall, and (4) horizontal lift of drywall with one hand positioned on the top and one positioned on the bottom. The study was completely randomized with lifting methods randomly assigned to each subject. Workers' kinematic variables were quantified using a video-based motion analysis system (PEAK MOTUS™). Kinematic variables included left and right elbow flexion, left and right arm/shoulder forward flexion, trunk flexion, left and right knee flexion, and left and right ankle dorsiflexion. Velocity and acceleration for each body part was also examined. These variables were used to examine workers' postures associated with each drywall lifting method. Analyses of variance (ANOVA) showed that the effects of different lifting methods were significant on all variables ($p < .05$) except for the left ankle dorsiflexion. The results of these analyses indicated that lifting methods 1 and 2 generated significantly less overexertion and fall hazards. An ongoing analysis is currently underway to examine kinetic variables (i.e., ground reaction forces). The findings from these quantitative studies will provide further understanding and focus for future research efforts on drywall-lifting, which can lead to the development of effective overexertion and fall injury prevention and intervention strategies.

1. Introduction

In Washington state, the composite incidence rate of musculoskeletal injury for the drywall industry (between 1992 and 1994) was 23.6 per 100 full-time workers, which was the highest of all industries [1]. According to the Bureau of Labor Statistics [2], the estimated traumatic-injury incidence rates for drywall installers were 7.7 and 5.4 per 100 workers for 1992 and 1993, respectively [3]. These rates were higher than those for all construction workers combined (5.2 for 1992 and 4.9 for 1993). In a focus-group study, drywall installation was considered to be one of the two most difficult carpentry specialties [4]. A recent study of injury characteristics of drywall installers indicated that drywall installers were at high risk for fall and overexertion injuries. Nearly half of the injured drywall installers suffered sprains, strains, and tears, mostly to the back. About one third of the trunk injuries occurred while lifting solid building materials, mainly drywall [5].

Little research has been conducted to quantitatively evaluate kinematic stresses associated with drywall lifting. Lifting massive and bulky drywall sheets is a task that increases the risk of overexertion and fall injuries during drywall installation. A typical drywall sheet weighs between 55 and 200 pounds and is 4 feet wide and 8 to 16 feet long. Since these sheets have no handholds and are less than 1 inch thick (ranging from 3/8 to 5/8 inches), it is not easy for workers to grasp them efficiently and adequately support the heavy weight. Therefore, lifting drywall sheets exposes workers to potential injuries [6]. Drywall lifting tasks require considerable muscle force and may force workers to adopt awkward working postures. The high musculoskeletal load imposed on workers may result not only in muscle fatigue, or over a longer time period, in musculoskeletal trauma disorders and chronic muscle pain [7], but it may also cause workers to suddenly lose their balance, which may potentially induce slip/fall injuries [8]. Therefore, the objective of this study was to quantitatively evaluate the kinematic stressors associated with lifting drywall sheets so that injury control strategies could be recommended.

2. Method

Subjects. Twenty-eight construction workers (mean age = 35 ± 9 years) with at least 6 months of drywall-installation experience (mean experience = 9 ± 7 years) participated in this study. Written informed consent was obtained from each subject after the objective and procedures of the study were explained. Subjects were compensated for their participation and given the option of withdrawing from the study at any time. All subjects underwent a medical screening by a physician (a licensed MD). Subjects with the following medical histories and/or conditions were excluded from the project: pregnancy; uncontrolled hypertension; history of dizziness; tremor; vestibular, neurological, or cardiopulmonary disorders; hernias; and chronic back pain.

Tasks. Each subject performed four lifts of a 4-foot by 8-foot drywall sheet, which weighed approximately 55 pounds, using one of the four lifting methods (Figures 1-4): (1) vertical lift of the drywall; (2) horizontal lift of drywall with both hands positioned on the top of the drywall; (3) horizontal lift of drywall with both hands positioned on the bottom of the drywall; and (4) horizontal lift of drywall with one hand positioned on the top and one positioned on the bottom.

A simulated drywall-lifting workstation was built in the human factors laboratory (as shown in Figures 1-4). The subject initially stood upright and motionless with his hands on the posterior portion of his hips. After 10 seconds, a voice command was given to direct the subject to reach and lift a piece of drywall sheet which had been placed on a specially designed rack in front of the subject. Each subject lifted the drywall sheet, in a posture according to one of four assigned methods and statically held the drywall for five seconds. Then, with a voice command, the subject was asked to place the drywall sheet back onto the rack and bring his torso back to an upright position. The subject stayed in this upright position for an additional 15 seconds.

Apparatus. The kinematic measurements were collected using a video-graphic motion measurement system (Peak™ Performance Technologies Inc., Englewood, CO). Twenty-two markers were placed on the subjects' anatomical landmarks (Table 1). The use of the reflective markers in conjunction with PEAK MOTUS™ allowed researchers to collect automatically digitized three-dimensional spatial movement parameters for each subject.

Dependent measures. Kinematic variables included left and right elbow flexion, left and right arm/shoulder forward flexion, trunk flexion, left and right knee flexion, and left and right ankle dorsiflexion. Velocity and acceleration of each body part (i.e., elbow, shoulder, trunk, knee, and ankle) were also measured. The joint angles were defined from the position of the 22 reflective markers (Table 2). Previous lifting-related studies indicated that increases in these variables (i.e., joint angle, velocity, and acceleration) are significantly associated with an increased risk for occupationally related back and upper-extremity injuries [9, 10, 11,12].

Experimental design and data analysis. The fourth lift of each method was selected to be analyzed. This study was a completely randomized design with lifting methods randomly assigned to each subject. Data collected on the kinematic parameters were analyzed by analyses of variance (ANOVA) with pair-wise contrasts.

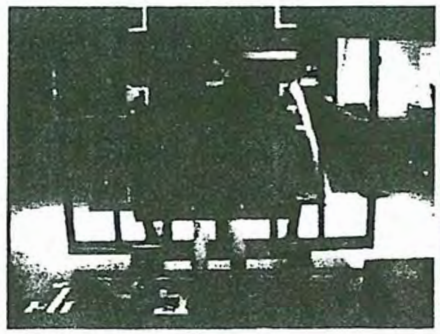

Figure 1: Vertical lift

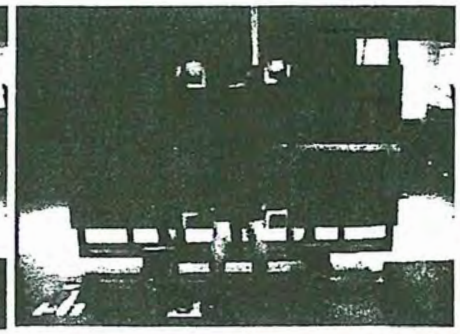

Figure 2: Horizontal lift with both hands on top

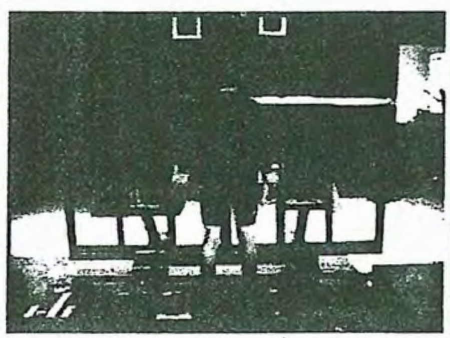

Figure 3: Horizontal lift with both hands on bottom

Figure 4: Horizontal lift with both hands alternate

3. Results

Analyses of variance (ANOVA) showed that the effects of different lifting methods were significant on all mean angular displacement variables ($p < .05$) except for the left ankle dorsiflexion. Table 3 presents the averages of mean angular displacement values for the four drywall lifting methods. The pair-wise contrast comparisons of the means indicated that methods 3 and 4 produced greater ranges of motion for different body segments than methods 1 and 2, except for the elbow.

ANOVA also showed that the effects of different lifting methods were significant on all median angular velocity ($p < .05$) except for the left elbow flexion. Table 4 presents the averages of median angular velocity values for the four lifting methods. The pair-wise contrasts indicated that methods 3 and 4 produced greater velocity of motion for different body segments than methods 1 and 2, except for the elbow.

Additionally, ANOVA showed that the effects of different lifting methods were significant on the knee, ankle, and right shoulder flexion acceleration ($p < .05$). Table 5 reveals the averages of median angular acceleration values for the four lifting methods. The pair-wise contrasts indicate that methods 3 and 4 produced greater acceleration of motion for several body segments (knee, ankle, and shoulder) than methods 1 and 2.

Table 1: Anatomical landmarks for reflective marker placement

Marker	Anatomical Position	Marker Number
Right fifth MTP	Base of the 5th metatarsal of the right foot	1
Right heel	Right calcaneus	2
Right ankle	Lateral malleolus of the right ankle	3
Right knee	Head of the fibula at the right knee	4
Right hip	Right upper femoral condyle	5
Right ASIS	Right anterior superior iliac spines	6
Left ASIS	Left anterior superior iliac spines	7
Back	Lumbar 3	8
Left hip	Left upper femoral condyle	9
Left knee	Head of the fibula at the left knee	10
Left ankle	Lateral malleolus of the left ankle	11
Left heel	Left calcaneus	12
Left fifth MTP	Base of the 5th metatarsal of the left foot	13
Right wrist	Radial styloid at the right wrist	14
Right elbow	Lateral epicondyle of the right elbow	15
Right shoulder	Right acromion	16
Left shoulder	Left acromion	17
Left elbow	Lateral epicondyle of the left elbow	18
Left wrist	Radial styloid at the left elbow	19
Neck	Occipital bone	20
Right temple	Right temple	21
Left temple	Left temple	22

4. Discussion

Results of this study suggest that vertical lift of a drywall sheet (method 1) and horizontal lift of a drywall sheet with both hands positioned on the top of the drywall (method 2) appeared to cause less overexertion hazards, and these methods currently are recommended as better lifting practices to reduce overall overexertion hazards. However, these two methods, in turn, create greater localized stresses on the elbow region. In the previous study [5], the results showed that only a limited number of the male population were estimated to have sufficient shoulder strength to perform lifting methods 3 and 4, respectively, with a 100-lb sheet. Also, lifting methods 1 and 2 created greater elbow stresses on the workers' elbows and only about 60-70% of the adult males in the population would have enough elbow strength to lift a 100 lb sheet [5]. Findings of this previous study associated overall overexertion hazards with drywall lifting using heavier sheets. The current study extended these findings to associate overexertion hazards with lighter drywall sheets, when tested under laboratory conditions using the simulated drywall-lifting workstation.

Table 2: Definition of the joint angles

Variables	Definition
Left Elbow Flexion	Calculate anatomical 180-degree angle between left wrist (P1), left elbow (V), and left shoulder (P2), from the P1-V segment to the V-P2 segment.
Right Elbow Flexion	Calculate anatomical 180-degree angle between right wrist (P1), right elbow (V), and right shoulder (P2), from the P1-V segment to the V-P2 segment.
Left Knee Flexion	Calculate anatomical 180-degree angle between left hip (P1), left knee (V), and left ankle (P2), from the P1-V segment to the V-P2 segment.
Right Knee Flexion	Calculate anatomical 180-degree angle between right hip (P1), right knee (V), and right ankle (P2), from the P1-V segment to the V-P2 segment.
Trunk Flexion (L5/S1)	Calculate vector angle between Y axis (P1), back (L5/S1) (V), and neck (P2), from the P1-V segment to the V-P2 segment.
Left Ankle Dorsiflexion	Calculate anatomical 90-degree angle between left toe (A1), left heel (A2), left knee (B1), left ankle (B2), from the A1-A2/B2 segment to the B1-A2/B2 segment.
Right Ankle Dorsiflexion	Calculate anatomical 90-degree angle between right toe (A1), right heel (A2), right shoulder (B1), right ankle (B2), from the A1-A2/B2 segment to the B1-A2/B2 segment.
Left Shoulder Forward Flexion	Calculate anatomical 180-degree angle between left hip (P1), left shoulder (V), and left elbow (P2), from the P1-V segment to the V-P2 segment.
Right Shoulder Forward Flexion	Calculate anatomical 180-degree angle between right hip (P1), right shoulder (V), and right elbow (P2), from the P1-V segment to the V-P2 segment.

Table 3: Averages of mean angular values for the four lifting methods

	left elbow flexion	right elbow flexion	left knee flexion	right knee flexion	trunk flexion	left ankle dorsiflexion	right ankle dorsiflexion	left shoulder forward flexion	right shoulder forward flexion
Method 1	84.87	79.59	4.67	6.03	12.57	6.35	5.08	140.46	137.19
Method 2	115.77	115.33	6.60	7.32	6.82	3.13	4.62	126.28	127.47
Method 3	41.07	43.03	36.51	37.20	32.21	18.21	10.83	154.81	156.15
Method 4	34.84	81.63	30.22	28.91	23.58	11.12	9.29	155.30	97.64

Table 4: Averages of median angular velocity values for the four lifting methods

	left elbow flexion	right elbow flexion	left knee flexion	right knee flexion	trunk flexion	left ankle dorsiflexion	right ankle dorsiflexion	left shoulder forward flexion	right shoulder forward flexion
Method 1	4.13	3.97	1.27	1.42	1.75	.89	.80	2.98	2.86
Method 2	3.29	3.30	1.65	1.33	2.07	.92	.79	2.86	3.44
Method 3	4.72	4.97	17.88	20.21	10.35	5.23	5.97	7.46	6.25
Method 4	4.55	5.65	9.98	8.05	5.59	3.36	2.21	5.07	4.59

Table 5: Averages of median angular acceleration values for the four lifting methods

	left elbow flexion	right elbow flexion	left knee flexion	right knee flexion	trunk flexion	left ankle dorsiflexion	right ankle dorsiflexion	left shoulder forward flexion	right shoulder forward flexion
Method 1	49.62	53.36	22.68	27.05	30.08	10.78	11.62	38.53	34.36
Method 2	46.02	55.46	34.14	26.43	33.83	15.68	12.56	39.82	47.90
Method 3	65.15	63.46	55.88	57.09	34.32	24.29	27.31	38.47	30.70
Method 4	64.72	71.96	67.44	59.65	41.79	24.25	20.64	44.45	45.11

To lift drywall using method 2 requires a considerable amount of gripping force in the hand and sufficient strength capability in the shoulders and arms. To perform gripping forces adequately, enough grip force must be supplied to prevent slips and loss of the object tangential to the surfaces. In contrast, extreme grip forces may cause musculoskeletal injuries [13]. The other three lifting methods reduced their gripping forces against the drywall sheet's weight by using coupling forces (i.e., feeding forces) between the hands and the drywall sheets (i.e., coefficient of friction multiplied by the drywall sheet's weight). However, these three lifting methods (1, 3, and 4) produced a higher overexertion potential because of a greater muscle strength requirement [14].

During heavy lifting tasks such as lifting drywall sheets, it is evident that the highest compressive forces on the vertebral column are in the lowest five lumbar vertebrae and sacrum [15, 16]. Degenerative vertebrae discs in the vertebral column are the usual cause of back injuries [15]. In this study, a marker was placed on the L5/S1 for evaluation. The results indicated that a significantly greater amount of kinematic stresses were placed on this back region for method 3 than for the other three methods. According to the conclusions of previous studies [9, 10, 11, 12], these kinematic stresses are strongly correlated with low back disorder as this study suggested. The results from this study echoed the findings that the back is the most frequently injured body part among drywall installers [14].

Previously, researchers used electromyographic responses to evaluate muscle activation for projecting kinematic hazards [17, 18, 19]. This study evaluated the kinematic hazards by using a direct measure of the pertinent variables through the PEAK MOTUS software package to analyze the motion. Findings from this study allowed the researchers to determine better work practices for reducing overexertion injuries in drywall lifting. Kinetic data (ground forces) will need to be assessed to categorically evaluate other biomechanical stresses associated with drywall lifting for reducing both overexertion and fall injuries. Ground reaction force data and kinematic data will be further combined in an inverse dynamic solution to calculate muscle and joint forces and moments. The findings from these quantitative studies will provide further understanding and focus for future research efforts on drywall-lifting, which can lead to the development of effective overexertion and fall injury prevention and intervention strategies.

5. Acknowledgments

The authors are pleased to acknowledge the contributions of Dr. Tom Hodous and Dr. Cathy Inman to conduct physical exams for subjects. The authors are grateful to Becky Giorcelli, and Richard Whisler for their valuable assistance in human subject recruitment and data collection. The authors also thank Linda Morton for her editorial support.

6. References

[1] Washington State Department of Labor and Industries, 1996. Work-Related Musculoskeletal Disorders: Washington State Summary.
[2] Bureau of Labor Statistics, 1998. Occupational Injuries and Illness: Counts, Rates, and Characteristics, 1995: Washington, DC: US Government Printing Office, US Department of Labor, Bulletin 2493.
[3] S. Chiou, C. S. Pan, and D. E. Fosbroke, 1997. Identification of risk factors associated with traumatic injuries among drywall installers. In: B. Das and W. Karwoski (Eds.), *Advances in Occupational Ergonomics and Safety*, IOS Press, Amsterdam, pp. 377-380.
[4] J. Warren, A. Bhattacharya, G. Lemasters, H. Applegate, and R. Stinson, 1994. 'Focus Groups: An aid for ergonomics assessment of carpentry tasks,' American Industrial Hygiene Conference and Exposition, Anaheim.
[5] C. S. Pan, and S. Chiou, 1999. 'Analysis of Biomechanical Stresses during Drywall Lifting' *International Journal of Industrial Ergonomics*, 23, pp. 505-511.
[6] S. Schneider and P. Susie, 1994. ' Ergonomics and Construction: A Review of Potential Hazards in New Building Construction, *American Industrial Hygiene Association Journal* 55(7), pp. 635-649.
[7] A. Mital, A. S. Nicholson, and M. M. Ayoub, 1993. A Guide to Manual Materials Handling. Taylor & Francis, London, England.
[8] C. S. Pan, S. Chiou, D. Long, J. Zwiener and P. Skidmore 'Postural Stability During Simulated Drywall Lifting and Hanging Tasks,' paper was presented at *IEA 2000/HFES 2000 Congress*, July 30 - August 4, 2000, San Diego, California and was published in the *Proceedings of the IEA 2000/HFES 2000 Congress.*
[9] W. S. Marras, S. A. Lavender, S. E. Leurgans, F. A. Fathallah, S. A. Ferguson, W. G. Allread, S. L. Rajulu, 1995. 'Biomechanical Risk Factors for Occupationally Related Low Back Disorders,' *Ergonomics*, 38(2), pp. 377-410.
[10] W. S. Marras, & G. A. Mirka, 1992. 'Trunk Muscle Activity and Intra-abdominal Activity during Changes in Trunk Position, Velocity and Acceleration,' *Proceedings of the Annual International Industrial Ergonomics and safety Conference*, pp. 933-937.
[11] W. S. Marras, 1992. 'Toward an Understanding of Dynamic Variables in Ergonomics,' *Occupational Medicine*, 7(4), pp.655-677.
[12] S. A. Ferguson, & W. S. Marras, 1991. 'Differences in Back Motion Characteristics as a Function of Task Direction,' *Proceedings of the Human Factors Society 35th Annual Meeting*, pp. 800-803.
[13] H. Kinoshita, L. Backstrom, J. R. Flanagan, R. S. Johnsson, 1997. 'Tangental Torque Effects on the Control of Grip Forces When Holding Objects with a Precision Grip,' *Journal of Neurophysiology*, 78(3), pp. 1619-1630.
[14] S. Chiou., C. S. Pan, and P. Keane, 2000. 'Risk Factors Associated with Traumatic Injuries among Drywall Installers' Journal of Occupational and Environmental Medicine, 42(11), November, pp 1101-1108.
[15] D. B. Chaffin, G. D. Herrin, W. M. Keyserling, and A. Garg, 1977. 'A Method for Evaluating the Biomechanical Stresses Resulting from Manual Material Handling Jobs' *American Industrial Hygiene Association Journal*, 38, 661-675.
[16] E. Grandjean, 1989. Fitting the task to the man. 4th edition, Taylor and Francis, London.
[17] N.B. Alexander, N. Shepard, M. J. Gu, A. B. Schultz, 1992. 'Postural Control in Young and Elderly Adults When Stance Is Perturbed: Kinematics,' *Journal of Gerintology*, 47(3), pp. 79-87.

[18] M. H. Woolacott, C. von Hosten, B. Rosblad, 1988. 'Relation between, Muscle Response Onset and Body Segmental Movements during Postural Perturbations in Humans,' *Experimental Brain Research*, 72, pp. 593-604.

[19] E. A. Keshner, M. H. Woollacott, B. Debu, 1986. 'Neck, Trunk, and Limb Muscle Responses during Postural Perturbations in Humans,' *Experimental Brain Research*, 71, pp. 455-466.

Advances in Occupational Ergonomics and Safety

Edited by

Alvah C. Bittner Jr.
Battelle Seattle Research Center, Seattle, WA, USA

Paul C. Champney
Paul Champney Consulting, Prosser, WA, USA

and

Stephen J. Morrissey
Oregon OSHA, Portland, OR, USA

IOS
Press
Ohmsha

Amsterdam • Berlin • Oxford • Tokyo • Washington, DC

ISBN 1 58603 174 0 (IOS Press)
ISBN 4 274 90444 X C3050 (Ohmsha)
Library of Congress Catalog Card Number: 2001089561

Publisher
IOS Press
Nieuwe Hemweg 6B
1013 BG Amsterdam
The Netherlands
fax: +31 20 688 33 55
e-mail: order@iospress.nl

Distributor in the UK and Ireland
IOS Press/Lavis Marketing
73 Lime Walk
Headington
Oxford OX3 7AD
England
fax: +44 1865 75 0079

Distributor in the USA and Canada
IOS Press, Inc.
5795-G Burke Centre Parkway
Burke, VA 22015
USA
fax: +1 703 323 3668
e-mail: iosbooks@iospress.com

Distributor in Germany, Austria and Switzerland
IOS Press/LSL.de
Gerichtsweg 28
D-04103 Leipzig
Germany
fax: +49 341 995 4255

Distributor in Japan
Ohmsha, Ltd.
3-1 Kanda Nishiki-cho
Chiyoda-ku, Tokyo 101
Japan
fax: +81 3 3233 2426

PRINTED IN THE NETHERLANDS