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Low back injury risks during construction with prefabricated (panelised) walls: effects of task and design factors

Sunwook Kim*, Maury A. Nussbaum* and Bochen Jia

Industrial and Systems Engineering, Virginia Tech, 250 Durham Hall (0118), Blacksburg, VA 24061, USA

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New technology designed to increase productivity in residential construction may exacerbate the risk of work-related musculoskeletal disorders (WMSDs) among residential construction workers. Of interest here are panelised (prefabricated) wall systems (or panels) and facilitating an ongoing effort to provide proactive control of ergonomic exposures and risks among workers using panels. This study, which included 24 participants, estimated WMSD risks using five methods during common panel erection tasks and the influences of panel mass (sheathed vs. unsheathed) and size (wall length). WMSD risks were fairly high overall; e.g. 34% and 77% of trials exceeded the 'action limits' for spinal compressive and shear forces, respectively. Heavier (sheathed) panels significantly increased risks, although the magnitude of this effect differed with panel size and between tasks. Higher levels of risk were found in tasks originating from ground vs. knuckle height. Several practical recommendations based on the results are discussed.

Statement of Relevance: Panelised wall systems have the potential to increase productivity in residential construction, but may result in increased worker injury risks. Results from this study can be used to generate future panel design and construction processes that can proactively address WMSD risks.

Keywords: ergonomics; prevention through design; residential construction; risk assessment

1. Introduction

Although there have been recent declines, construction workers continue to experience a relatively high number of injuries and illnesses requiring days away from work, accounting for 11% of total non-fatal occupational cases requiring days away from work (BLS 2009). In addition, a 4.5-year follow-up study among carpenters and pavers showed that regular use of ergonomic measures remained low despite a large educational campaign at the sector level (van der Molen *et al*. 2009). Within the construction sector, residential carpenters in particular have relatively high rates of morbidity and overexertion has been identified as a major causal factor (Dement and Lipscomb 1999, Lipscomb *et al*. 2003a,b). More specifically, overexertion injuries appear to be associated with manual handling of construction materials. For example, overexertion was the second most costly injury cause and costs associated with overexertion largely resulted from lifting framed walls and setting steel beams (Lipscomb *et al*. 2003a).

Public and private efforts are being made to improve technology in housing with an emphasis on reducing work-related injuries and illnesses and increasing productivity and efficiency (National Association of Home Builders Research Center 2000, 2002). Panelised wall systems (i.e. use of panelised walls or panels) are an example of such technology, which are increasingly being adopted by residential US production builders (Wakefield *et al*. 2001). Panels are manufactured in a factory under controlled environments with material handling systems and/or assistive devices. As such, off-site production provides opportunities to reduce hazard levels, construction time and cost, the need for skilled and experienced workers on site, etc. (Toole 2001, Toole and Gambatese 2008).

Despite such potential benefits, panels typically are designed without considering the workers who will actually handle them. As a result, workers may be exposed to increased levels of ergonomic risks while handling panels due to their masses, sizes, changes in work process, etc. A panelisation design, or set of panels for a given structure, is developed from an architectural plan using a centralised design process involving a panel designer. These panel designers generally do not perceive the ergonomic effects of panel designs on construction workers and make design decisions largely based on transportation and panel stacking issues (Kim *et al*. 2008). Given that there is a centralised design aspect, and the potentially

*Corresponding author. Email: nussbaum@vt.edu

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broad 'downstream' impacts possible at this level, this group is employing the prevention-through-design (PtD) philosophy to develop a decision support system (DSS) that will allow panel designers to proactively address ergonomic concerns (Nussbaum *et al.* 2009). Note that PtD has been promoted and accepted as an effective way to 'design out' hazardous exposures from the workplace (e.g. Gambatese and Hinze 1999, Gambatese *et al.* 2005, Schulte *et al.* 2008).

Required for this DSS are quantitative descriptions of ergonomic exposures and risks for panel erection tasks in relation to panel design factors (e.g. mass and size). Such data are needed to evaluate the ergonomic effects of alternative panel designs, panel stacking and erection methods, etc. However, to the authors' knowledge, no such formal assessments have been performed on panel erection tasks. The focus of the current work is thus to obtain risk assessments, the quantitative or qualitative value of risk associated with a given task condition. A primary emphasis was on the risk of a low back disorder. Such morbidity is relatively common in residential construction (Dement and Lipscomb 1999, Lipscomb *et al.* 2009, Fredericks *et al.* 2005) and workers who use panels reported this as the body part most likely to be injured (Nussbaum *et al.* 2009). It was hypothesised that panel design factors would affect risk levels during several common panel erection tasks and specifically that the magnitude of these design factor effects would vary between tasks. Quantifying these effects was anticipated to aid in future panel design efforts and more specifically to facilitate an assessment (e.g. using the DSS) of the trade-offs involved in alternative design approaches.

2. Methods

A convenience sample of 24 participants (19 males and five females) were recruited from the university and local community, whose mean (SD) age, stature and body mass were 24.2 (4.8) years, 174.2 (8) cm and 71.4 (12.8) kg, respectively. All participants reported being physically active and had no illnesses, injuries or musculoskeletal disorders within the past year that limited their daily activities. Participants completed three sessions. In the initial session, they watched a video recording of construction workers performing panel-handling tasks. They also confirmed, by handling panels in the laboratory, that they felt physically capable of completing the experimental tasks. Two experimental sessions were then completed, at least 2 d apart. Prior to participation, all participants completed informed consent procedures approved by the Virginia Tech Institutional Review Board.

2.1. Experimental design and procedures

A set of biomechanical, physiological and psychophysical measures were obtained in a balanced incomplete block design with block size = 2. Three independent variables (IVs) were experimentally manipulated: panel size [small (1.2 m × 2.4 m), medium (2.4 m × 2.4 m) and large (3 m × 2.4 m)]; panel mass [unsheathed (light) vs. sheathed (heavy)]; task type (eight levels, involving lifting, erecting, carrying and moving). The small panel masses were 30 kg and 53 kg, respectively, for the light and the heavy condition, with corresponding values of 44 kg and 87 kg for the medium panel and 54 kg and 108 kg for the large panel. These IVs and their levels were determined as representative of the most common activities based on extensive field and video observations (see Nussbaum *et al.* 2009). The tasks examined are illustrated in Figure 1 and were defined as follows:

- Two levels of lifting type L1: Lift panel horizontally. Panel initially placed on the ground (L1G) or at a participant's knuckle height (L1K) using jack stands. L1G is completed at standing knuckle height. L1K is completed when the panel is raised to a level when it can be carried away from the supporting stands (this was typically midway between knuckle and the elbow heights), which simulated lifting a panel off a panel stack.
- Lifting type L2G: Lift panel off the floor. L2G is completed with the panel oriented at approx. 45° to the group and with the participant in the upright standing position.
- Four levels of erecting E1: Erect panel from ground until it stands vertically while participant stands at panel top-plate (E1GTop) or side (E1GSide) or erect panel from knuckle height while participant stands at panel top-plate (E1KTop) or side (E1KSide).
- Carrying type C1: Carry panel approx. 3 m in a horizontal orientation. Panel is held in the final position of L1G.
- Carrying type C2: Carry panel approx. 3 m while holding it oriented approx. 45° to the ground. Panel is held in the final position of L2G.
- Moving M1: Push vertically oriented panel forward along bottom edge for approx. 1 m.

Each experimental session lasted approx. 3 h and involved a different panel size. Participants completed two sessions with a different panel size in each and each session involved all combinations of mass and task (Table 1). A slightly different set of tasks was used for the small panel vs. the medium and large panels

(Table 1); some combinations of tasks and panel size were not included as they were very rarely observed in the workplace. Trial order (i.e. combinations of IVs) was controlled such that the order of panel size was first counterbalanced, following the balanced incomplete block design. Then, for the given panel size, the order of panel mass was counterbalanced and the order of task type was randomised within each panel mass. Each trial lasted approx. 10–20 s and was replicated twice with approx. 2 min rest between trials.

The number of 'workers' was determined from field observations and depended on the levels of size, mass and task. For the small panel, one or two were involved: one for the E1GTop and M1 tasks in the light condition; two in the heavy condition. When handling the medium panel, one worker was involved for the E1GTop and E1KTop tasks in the light condition, two for the remaining tasks in the light condition and three in the heavy condition. For the large panel, two workers were used in the light condition and three in the heavy

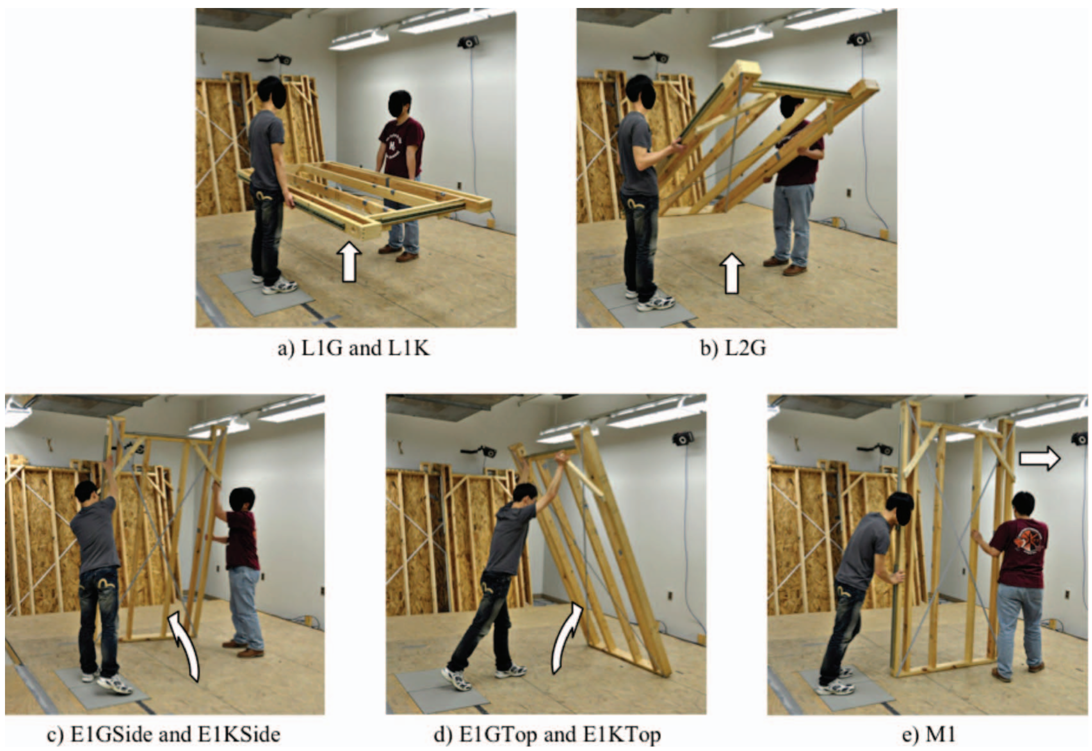

Figure 1. Illustrations of task types. The letters G and K respectively indicate origin at the ground or individual knuckle eight. The white arrows indicate the direction of panel movement. Note that carrying panel at the final position of L1G (a) or L2G (b) is C1 or C2.

Table 1. Overview of balanced incomplete block design (block size=2).

	Small			Medium			Large	
Task	Heavy	Light	Task	Heavy	Light	Task	Heavy	Light
L1G	P1 & P2		L1G	P1 & P2		L1G	P5 & P6	
L1K	P3 & P4		L1K	P3 & P4		L1K	P7 & P8	
L2G	P9 & P10		E1GTop	P5 & P6		E1GTop	P9 & P10	
E1GTop	P11 & P12		E1GSide	P7 & P8		E1GSide	P11 & P12	
E1KSide	P13 & P14		E1KTop	P13 & P14		E1KTop	P17 & P18	
M1	P15 & P16		E1KSide	P15 & P16		E1KSide	P19 & P20	
C1	P21 & P22		M1	P17 & P18		E1KSide	P21 & P22	
C2	P23 & P24		C1	P19 & P20		C1	P23 & P24	

P# = participant identifier.
For details of task, see 2.1. Experimental design and procedures' in this article.

condition. Experimenters (including the authors) served as additional workers.

2.2. Instrumentation

Trials began with participants standing with each foot on a separate force platform (AMTI OR6-7-1000; AMTI, Watertown, MA, USA). Practice trials were completed for the given task and participants indicated their preferred hand positions (inter-hand spacing) on the panel. At these positions, two load cells (AMTI MC3A-6) were attached to collect tri-axial hand forces. During each trial, force platform and load cell signals were sampled at 1080 Hz. These were subsequently low-pass filtered (12 Hz cut-off; second order Butterworth; bidirectional).

Muscle activity was monitored using surface electromyography (sEMG). Pairs of pre-gelled, bipolar, Ag/AgCl electrodes (AccuSensor; Lynn Medical Instrument Co., Bloomfield Hills, MI, USA) with a 2.5 cm inter-electrode spacing were placed bilaterally over eight accessible muscles crossing the lower lumbar region: internal oblique; external oblique; rectus abdominis; iliocostalis lumborum pars lumborum; latissimus dorsi; multifidus; longissimus thoracis pars lumborum; longissimus thoracis pars thoracis. Before electrode placement, the skin was shaved, lightly abraded and cleaned with 70% isopropyl alcohol; inter-electrode impedance was verified as <10 KΩ. Electrode placement followed existing protocols (Potvin *et al.* 1996, van Dieën 1997). sEMG signals were obtained using two × eight-channel telemetered systems (Telemyo 900; Noraxon, Scottsdale, AZ, USA) and sampled at 1080 Hz. Prior to the experimental trials in each session, initial procedures were completed to calibrate an electromyographic (EMG)-based model (Nussbaum and Chaffin 1998, Jia *et al.* submitted). These included measures of resting and maximal sEMG and a passive trunk flexion (i.e. full trunk flexion with relaxed trunk muscles).

Body segment positions and orientations were monitored using passive markers attached bilaterally or in the mid-sagittal plane over several anatomical landmarks: calcaneus; second and fifth metatarsal heads; lateral and medial malleoli; lateral and medial tibial epicondyles; acromial processes; lateral and medial humeral epicondyles; radialis and ulnar styloid processes; the spinous processes of the seventh cervical (C7) and eighth thoracic (T8) vertebrae; incisura jugularis; xiphoid process; anterior and posterior iliac superior spines. In addition, clusters of two to four markers were placed midway between C7 and T8, over the lumbosacral joint, and on the lower legs, upper arms, lower arms and heels. Marker data were collected at 120 Hz using a six-camera system (Vicon 524; Vicon System, Los Angeles, CA, USA) and subsequently low-pass filtered (9 Hz cut-off; second order Butterworth; bidirectional).

Selected anatomical markers were removed prior to the panel handling trials, after being referenced to corresponding clusters. Removed markers were reconstructed using clusters on the corresponding body segments (Challis 1994). The joint coordinate system for each segment was defined, in large part, based on International Society of Biomechanics recommendations (Wu and Cavanagh 1995, International Society of Biomechanics 2002, Wu *et al.* 2005) and joint angles were calculated using the Z-X-Y sequence of Euler angles. Derived joint angles were low-pass filtered (5 Hz cut-off; second order Butterworth; bidirectional). For the carrying tasks (C1 and C2), lower extremity angles were not calculated due to loss of marker data. All off-line data processing was completed using Matlab 7 (Mathworks™ Inc., Natick, MA, USA).

2.3. Risk assessments

Five methods were used to assess the relative risk posed during common panel erection tasks. These specific methods were selected for relevance to the current tasks and to ensure a reasonably diverse approach to risk assessment. Tools that provided assessments of low back disorder risk were also sought. Each method is summarised below.

2.3.1. Spinal loads

A free-dynamic 3-D, EMG-based model (Jia *et al.* submitted) was used to estimate muscle and passive tissue forces. This model was based on an earlier approach (Nussbaum and Chaffin 1998), but included more detailed representations of lumbar muscle anatomy, using the AnyBody™ modelling system (v3.0, repository 7; AnyBody Technology, Aalborg Ø, Denmark) and muscle contraction dynamics. Participant-specific parameters (of which there are five) were determined through calibration procedures. Values of participant-specific parameters were comparable to earlier studies (e.g. Granata and Marras 1993, Nussbaum and Chaffin 1998) and detailed values are reported in Jia *et al.* (submitted). Normalised sEMG were used to estimate muscle forces, which were then combined with postural and resultant (external) kinetics to predict lumbosacral (L5/S1) reaction kinetics (i.e. compression and shear forces). The revised model exhibited reasonable levels of the predictive ability during the panel erection tasks examined here (Jia *et al.* submitted). Within each panel handling trial, 95th percentile (max) compressive and shear forces were determined; these were normalised to individual body weight (Hof 1996) and the normalised values were used for statistical analyses.

2.3.2. Lumbar injury risk model

The multiple logistic regression model of Marras *et al.* (1993) was used to estimate the probability of membership in a group at high risk (P_{Risk}) of a low back disorder. This model includes five factors describing trunk motion and workspace factors: lift rate; average twisting velocity; maximum L5/S1 moment; maximum sagittal flexion; maximum lateral velocity. To obtain trunk kinematics, the lumbar segment was defined from T8, the xiphoid process and the lumbosacral joint centre according to Dumas *et al.* (2007) and was expressed with regard to the pelvic segment. The angular velocity of the lumbar segment was then calculated following the International Society of Biomechanics recommendations. Although developed for manufacturing tasks, the model was assumed to be relevant here as the current tasks also involved lifts, pushes, etc. In each trial, the maximum L5/S1 moment was determined from inverse dynamics using AnyBody^{TM}. Lift rate was conservatively set to 12 lifts/h; of note, the risk model is relatively insensitive to lift rate (smallest coefficient).

2.3.3. Lifting assessment

The revised NIOSH lifting equation (Waters *et al.* 1993, 1994) is a well-known analytical tool designed specifically to assess injury risks during two-handed manual lifting tasks. Marker positions and load cell data, only from trials involving lifting (L1G, L1K and L2G) were used to determine the recommended weight limit and the lifting index (LI). Throughout these analyses, the frequency multiplier was set to 1; from field observations, lifting frequency was typically below 2/min and the duration of lifting tasks was short. The coupling type was set to fair.

2.3.4. Postural assessment

The Rapid Entire Body Assessment tool (REBA: Hignett and McAtamney 2000) was used to assess whole body postures. This tool considers most major body parts (trunk, neck, legs, upper arms, lower arms and wrists) using a scoring system that associates postures with numerical values, similar to the related Rapid Upper Limb Assessment (McAtamney and Corlett 1993). Using joint angles and load cell data from each trial, a REBA score was obtained at every 10% of the trial duration. Neck and wrist angles were not monitored during the experiment; hence, scores for the neck and the wrist were conservatively set to be = 1. In addition, for carrying tasks, the leg score was set to be = 2 by assuming that knee flexion angles were 30–60°. The maximum REBA score within each trial served as a dependent variable.

2.3.5. Perceptual ratings

After completing the two replications of each task, participants provided ratings of perceived exertion (RPE) for the whole body (RPE_{WB}) and lower back (RPE_{LB}). Ratings were obtained using Borg's CR-10 scale (Borg 1990). This instrument is a 10-point category scale and was provided together with a human body schematic with graphical descriptors anchored at selected body regions.

2.4. Statistical analyses

Since an incomplete factorial design was used (i.e. not all tasks were done for all panel sizes), a two-phase analysis approach was used. In the first, the analysis focused on the subset of six tasks that were performed with each panel size (Table 1). For these, repeated measures ANOVA (RANOVA) were used to evaluate the effects of the three IVs (mass, size and task) on each of the risk assessment measures. The second was a complementary assessment of the alternative tasks that are specific to the panel sizes and was performed separately for corresponding panel sizes. Specifically, for the small panel size, separate RANOVA were performed with the following IVs: mass and task (L1G, L1K, L2G, C1 and C2). For the medium and large panel sizes, RANOVA were performed with three IVs: mass, size and task (E1GTop, E1GSide, E1KTop and E1KSide). The levels of task were included to provide information not available from the first analysis (which involved only the tasks common to all three panel sizes). Normalised spine loads and LIs were log-transformed prior to statistical analyses to achieve normally distributed residuals, although summary statistics are presented below in the original units. Significant effects were followed by *post-hoc* pairwise comparisons (Tukey's HSD or Student's *t* tests), and significant interaction effects were further examined using simple effect analysis. In these, the focus was on alternatives within a given task type (e.g. L1G vs. L1K, or panel mass/size within a specific task) as such differences represent potentially modifiable aspects of the panelised construction process. All statistical analyses were performed using JMP 8.0 (SAS Institute Inc., Cary, NC, USA) and statistical significance was determined when $p < 0.05$. All summary data are presented as means (SD) in original units.

3. Results

Overall, the panel erection tasks examined here resulted in fairly high levels of musculoskeletal injury risk. Mean (SD) shear and compressive forces were 885 (478) and 3073 (1268) N, respectively. Shear forces exceeded the 'action limit' of 500 N suggested by McGill *et al.* (1998) in 77% of trials, while the corresponding limit for compression of 3400 N (National Institute for Occupational Safety and Health 1981) was exceeded in 35% of trials. Mean (SD) P_{Risk} was 51 (38)% and 28% and 47% of trials had P_{Risk} $>90\%$ and 50%, respectively. LI values had a mean (SD) of 2.0 (0.7) and 8% and 94% of lifting trials had LI >3 and 1, respectively. With regard to REBA scores, the mean (SD) was 7.9 (2.3) and 50% and 18% of trials were at high (>8) or very high (>11) risk levels, respectively. In contrast, perceived exertion was relatively low, with participants reporting weak to moderate levels of exertion.

3.1. *Effects of mass, size and task*

RANOVA results for all risk assessment measures are summarised in Table 2 (recall that these were based on the subset of six tasks common to all panel sizes). Regarding spine loads, antero–posterior shear (F_X), compression (F_Y) and lateral shear (F_Z) forces were significantly higher in the heavy vs. light condition [F_X: 901 (446) N $>$ 807 (497) N; F_Y: 3215 (1256) N $>$ 2870 (1252) N; F_Z: 175 (227) N $>$ 148 (198) N]. There were significant size × task interaction effects on F_X and F_Y (Figure 2). Lateral shear force was significantly affected by panel size [medium $>$ large $\approx$ small] and task [C1 $>$ E1GTop $\approx$ L1G $\approx$ E1KSide $\approx$ M1 $>$ L1K].

The P_{Risk} was significantly affected by mass, size and task. Further, mass × task and size × task interaction effects were both significant and had comparable effects on P_{Risk}, with higher probabilities found for L1G and E1GTop compared with other tasks (e.g. Figure 3). Only the E1KSide task was significantly affected by mass (heavy $>$ light) and size (medium = large $>$ small).

LIs were significantly affected by several main and interaction effects of mass, size and task (Table 2). The small and the medium panels yielded larger LI values for the heavy vs. light condition [small: 1.8 (0.4) $>$ 1.3 (0.4); medium: 2.4 (0.9) $>$ 1.8 (0.5)]. Yet, the large panel had statistically the same LI values between the heavy [2.3 (0.9)] and the light [2.2 (0.6)] conditions. Further, LI values were significantly larger for the L1G [heavy = 2.5 (0.9); light = 2.1 (0.5)] vs. L1K [heavy = 1.9 (0.5); light = 1.3 (0.3)].

Table 2. Repeated measures ANOVA results [*F* value (*p*)] for effects of mass (M), size (S) and task (T) on risk measures.

	Mass	Size	Task	M × S	M × T	S × T	M × S × T
AP shear force (F_X)	**9.00 (0.0028)**	1.01 (0.36)	**47.38 (<0.0001)**	0.28 (0.75)	2.08 (0.067)	**2.62* (0.0041)**	0.97 (0.47)
Compression force (F_Y)	**25.99 (<0.0001)**	**3.64 (0.0027)**	**108.00 (<0.0001)**	0.44 (0.64)	1.61 (0.16)	**2.90† (0.0016)**	0.83 (0.60)
Lat. shear force (F_Z)	**6.33 (0.012)**	**4.96 (0.0083)**	**20.97 (<0.0001)**	2.02 (0.13)	0.88 (0.49)	0.70 (0.73)	1.16 (0.32)
P_{Risk}	**34.2 (<0.0001)**	**4.62 (0.017)**	**818.2 (<0.0001)**	0.99 (0.37)	**5.39 (<0.0001)**	**5.16 (<0.0001)**	0.8 (0.63)
LI	**80.38 (<0.0001)**	**39.43 (<0.0001)**	**233.26 (<0.0001)**	**13.12‡ (<0.0001)**	**9.39‡ (0.0026)**	1.23 (0.29)	1.23 (0.29)
REBA	**7.17 (0.0077)**	1.01 (0.36)	**245.33 (<0.0001)**	1.4 (0.25)	**4.54 (0.0005)**	**3.50 (0.0002)**	**3.27 (0.0004)**
RPE_{LB}	**39.31 (<0.0001)**	1.23 (0.29)	**32.00 (<0.0001)**	1.02 (0.36)	1.13 (0.34)	**2.43 (0.0093)**	0.18 (1.00)
RPE_{WB}	**51.65 (<0.0001)**	0.96 (0.38)	**26.98 (<0.0001)**	0.61 (0.54)	0.44 (0.82)	**2.82 (0.0025)**	0.21 (1.00)

AP = antero–posterior; P_{Risk} = probability of membership in a group at high risk; LI = lifting index; REBA = Rapid Entire Body Assessment; RPE_{LB} = ratings of perceived exertion for the lower back; RPE_{WB} = ratings of perceived exertion for the whole body.
*Effects of size are significant for all tasks except L1G and M1.
†Effects of size are significant for all tasks except L1G and L1K.
‡Effects of mass are significant for all tasks.
Note: Values shown in bold are significant.

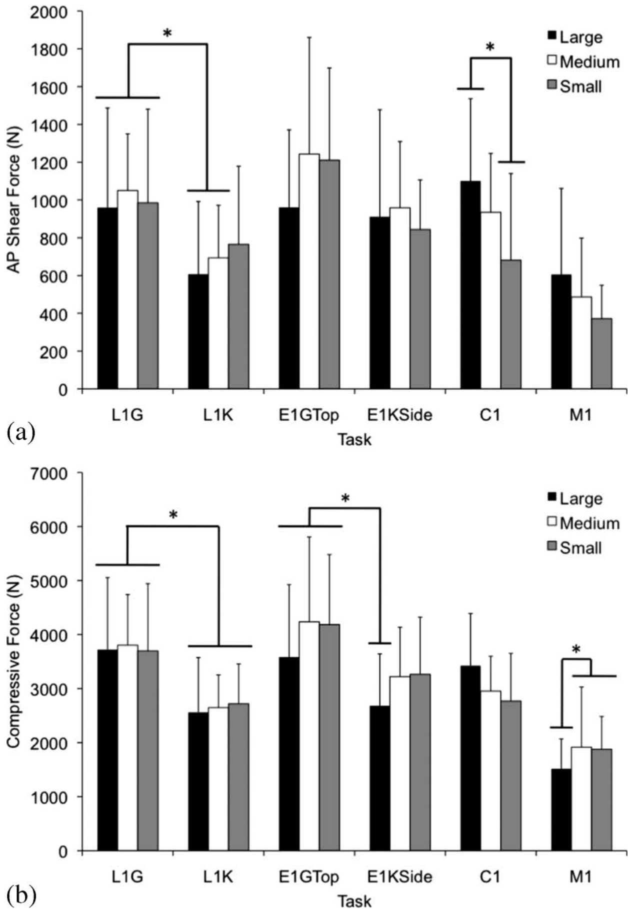

Figure 2. Panel size × task interaction effects on anterior/posterior (AP) shear (a) and compressive forces (b). *Indicates significant differences between panel sizes within the same task type. Error bars indicate standard deviations.

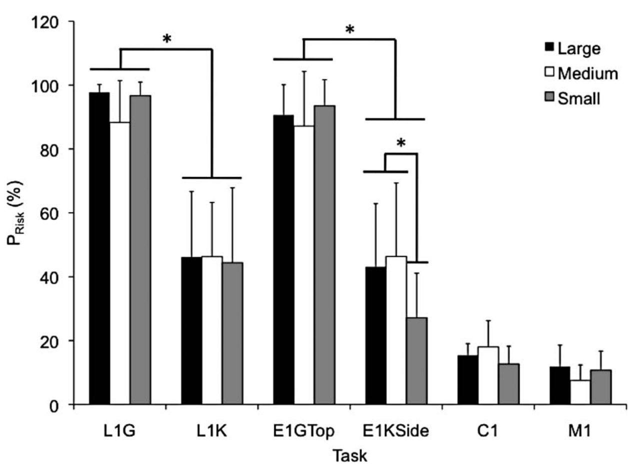

Figure 3. Panel size × task interaction effects on the probability of high-risk group membership (P_{Risk}). *Indicates significant differences between panel sizes within the same task type.

Several significant main and interaction effects of mass, size and task were found on maximum REBA scores (Figure 4). Similar to P_{Risk} results, REBA scores were significantly higher for E1GTop and L1G vs. the other tasks. In the case of perceived exertion, RPE_{WB} and RPE_{LB} were significantly affected by mass and task, as well as the size × task interaction. RPE scores were higher in the heavy vs. light conditions [RPE_{WB}: 2.6 (1.6) > 1.9 (1.2); RPE_{LB}: 2.4 (1.6) > 1.7 (1.3)]. The size × task interaction had comparable effects on RPE_{WB} and RPE_{LB}, (e.g. Figure 5).

3.2. *Complementary assessment of alternative tasks by size*

As noted above, the second-step analyses were done separately for small vs. medium and large panels with

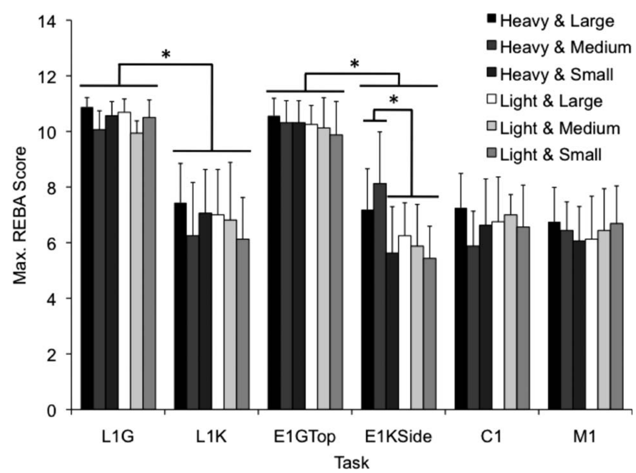

Figure 4. Panel mass × size × task interaction effects on maximum Rapid Entire Body Assessment (REBA) scores. *Indicates significant differences between panel sizes within the same task type.

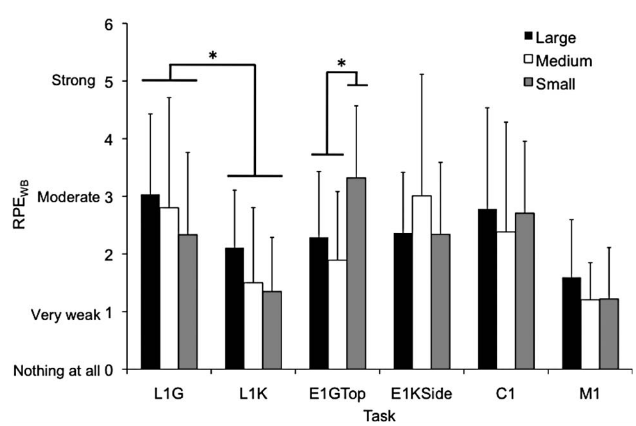

Figure 5. Panel size × task interaction effects on whole body ratings of perceived exertion (RPE_{WB}) scores. *Indicates significant differences between panel sizes within the same task type.

Table 3. Repeated measures ANOVA results [F value (p)] for effects of mass (M) and task (T) on risk measures for the small panel size.

	Mass	Task	M × T
AP shear force (F_X)	2.51 (0.12)	**8.25 (<0.0001)**	1.79 (0.13)
Compression force (F_Y)	**9.39 (0.0026)**	**20.09 (<0.0001)**	1.97 (0.10)
Lat. shear force (F_Z)	**9.25 (0.0028)**	**19.99 (<0.0001)**	0.54 (0.71)
P_{Risk}	**6.50 (0.0019)**	**338.50 (<0.0001)**	1.34 (0.26)
LI	**372.38 (<0.0001)**	**259.16 (<0.0001)**	2.69 (0.074)
REBA	1.60 (0.21)	**110.71 (<0.0001)**	1.54 (0.19)
RPE_{LB}	**28.83 (<0.0001)**	**6.05 (0.0004)**	0.42 (0.79)
RPE_{WB}	**29.74 (<0.0001)**	**6.50 (0.0003)**	0.68 (0.61)

AP = antero–posterior; P_{Risk} = probability of membership in a group at high risk; LI = lifting index; REBA = Rapid Entire Body Assessment; RPE_{LB} = ratings of perceived exertion for the lower back; RPE_{WB} = ratings of perceived exertion for the whole body.
Note: Task has five levels (L1G, L1K, L2G, C1 and C2).
Values shown in bold are significant.

focus on alternatives within a given task type. For the small panel, there were main significant effects of mass and task on all risk assessment measures, with two exceptions (Table 3). In general, the heavy condition resulted in higher risk values than the light condition. With regard to task, L2G yielded risk measures comparable with L1G, yet significantly higher than L1K (by 27–164%). The two carrying tasks, C1 and C2, yielded comparable values except for F_X [C2 (1175 (564) N) > C1 (682 (459) N)] and F_Y [C2 (3587 (1125) N) > C1 (2769 (881) N)].

For the medium and large panels, a summary of RANOVA results is presented in Table 4. Significant main effects of mass, size and task affected all three spinal loads, while F_Z was also significantly affected by the size × task interaction. In general, the medium and the heavy conditions increased spinal loads by 16–53% [F_X: 147 N; F_Y: 583 N] and 4–11% [F_X: 41 N; F_Y: 330 N] respectively, compared with the large and the light conditions. However, only E1GTop, E1GSide and E1KSide yielded higher F_Z values for the medium vs. large panels. Across the different tasks, comparisons of F_X values indicated E1GSide ≈ E1GTop ≈ E1KSide > E1KTop, and F_Y values indicated E1GTop ≈ E1GSide > E1KSide > E1KTop.

Mass, task and their interaction significantly affected P_{Risk} and REBA. E1GTop and E1GSide yielded comparable P_{Risk} and REBA values between the mass conditions, and 98–240% and 51–105% higher values respectively, compared with E1KSide and E1KTop. Further, P_{Risk} was higher for E1KSide vs. E1KTop in the light condition, yet E1KSide = E1KTop in the heavy condition. Slightly higher REBA scores were found for E1KSide than for E1KTop. RPE_{LB} and RPE_{WB} were significantly affected by mass (heavy > light) and task (RPE_{LB}: E1GSide ≈ E1KSide ≈ E1GTop > E1KTop; RPE_{WB}: E1KSide ≈ E1GSide > E1GTop > E1KTop).

4. Discussion

In support of a proactive assessment of risks involved with panel erection tasks and alternative design approaches, it was hypothesised that panel design factors, specifically panel mass and size, would influence imposed risk levels during common panel erection tasks and that these influences would vary between tasks. Note that in an actual workplace the number of workers involved in a given task varies with these same design factors. Thus, to provide more practically relevant results, the number of workers for each task was adjusted based on field observations. Overall, panel mass, size and erection task had main and interaction effects on the set of risk measures, although to varying degrees (e.g. Table 2). The effects of panel mass were quite straightforward and consistent with initial expectations, in that spinal loads, LI values and RPE scores increased in the heavy vs. light condition. For most of the tasks, however, risk levels were comparable between the three fairly divergent panel sizes.

The effects of panel mass are consistent with earlier findings, specifically that handling heavy objects and/or heavy tasks are injury risk factors among residential carpenters and labourers (Lipscomb *et al.* 2003b, Spielholz *et al.* 2006). In this study, the respective mass differences between the light and heavy conditions were 23 kg (77%), 43 kg (97%) and 54 kg (100%) for the small, medium and large panels respectively. The heavy condition caused increases of 12–18% in peak spinal loads, 19–46% in LI values and approx. 36% in RPE scores and thus represent effect sizes of apparent practical relevance. However, P_{Risk} values and REBA scores for a given task were essentially insensitive to the mass condition (Figures 3 and 4). Both the lumbar risk model and REBA primarily consider body kinematics, suggesting that body movements do not differ enough between the mass conditions to yield

Table 4. Repeated measures ANOVA results [*F* value (*p*)] for effects of mass (M), size (S) and task (T) on risk measures for the medium and large panels.

	Mass	Size	Task	M × S	M × T	S × T	M × S × T
AP shear force (F_X)	**6.40 (0.012)**	**4.66 (0.032)**	**9.45 (<0.0001)**	1.45 (0.23)	0.087 (0.97)	0.89 (0.44)	1.50 (0.22)
Compression force (F_Y)	**11.13 (0.001)**	**15.70 (0.0001)**	**15.69 (<0.0001)**	1.07 (0.30)	0.31 (0.82)	1.03 (0.38)	1.11 (0.34)
Lat. shear force (F_Z)	**4.63 (0.032)**	**15.95 (0.0001)**	**12.90 (<0.0001)**	3.33 (0.069)	0.81 (0.49)	**3.26 (0.022)**	0.22 (0.89)
P_{Risk}	**21.72 (<0.0001)**	3.79 (0.0529)	**331.97 (<0.0001)**	0.17 (0.68)	**8.19* (<0.0001)**	0.86 (0.46)	1.27 (0.29)
REBA	**18.67 (<0.0001)**	0.58 (0.45)	**422.92 (<0.0001)**	**4.62 (0.0327)**	**5.05* (0.0021)**	0.29 (0.83)	**3.17 (0.025)**
RPE_{LB}	**17.85 (<0.0001)**	0.78 (0.38)	**4.07 (0.0094)**	1.25 (0.27)	0.19 (0.90)	0.51 (0.67)	0.28 (0.84)
RPE_{WB}	**35.87 (<0.0001)**	0.17 (0.68)	**7.87 (0.0001)**	0.018 (0.89)	0.58 (0.63)	1.82 (0.15)	0.77 (0.51)

AP = antero–posterior; P_{Risk} = probability of membership in a group at high risk; LI = lifting index; REBA = Rapid Entire Body Assessment; RPE_{LB} = ratings of perceived exertion for the lower back; RPE_{WB} = ratings of perceived exertion for the whole body.
*Effects of size are significant for all tasks except E1GSide and E1GTop.
Note: Task has four levels (E1GTop, E1GSide, E1KTop, and E1KSide).
Values shown in bold are significant.

different P_{Risk} values and REBA scores. Preliminary analyses of trunk kinematics support this, since differences in panel mass within a given task yielded only 0.1–6° differences in maximum trunk angles (Kim *et al.* 2009). For a given task, the effect of panel size was either small or inconsistent (Figures 3, 4 and 5), depending on the specific assessment tool. Note that this study did not aim to assess the 'true' effects of size, but rather to assess risk levels during panel erection tasks with levels of panel design factors commonly used in practice.

Initial vertical panel placement affected risk levels. These levels were higher for a given task if the panel was placed initially on the ground vs. knuckle height, which agrees with existing studies (Ferguson *et al.* 2002, Lavender *et al.* 2003, Faber *et al.* 2009). Tasks originating from ground level (E1GSide, E1GTop, L1G and L2G) resulted in $P_{Risk} > 88\%$ and REBA scores > 10 (high risk level), whereas tasks starting at knuckle height (E1KSide, E1KTop and L1K) had $P_{Risk} < 45\%$ and REBA scores < 7 (medium risk level). This effect of initial height was less pronounced on spinal loads, the revised NIOSH equation and RPE, which is potentially attributable to a differential focus of each tool on risk.

Considering the magnitude of the effects of mass and size, the results suggest that panel mass is an important design factor and one that could have a substantial impact on work-related musculoskeletal disorder (WMSD) risk levels among workers performing common panel erection tasks. In this study, using unsheathed (light) panels, which decreased panel mass by 23–54 kg, yielded approx. 12–46% decreases in risk assessment measures across a range of panel erection tasks. A review of intervention studies suggests that $\geqslant 14\%$ reduction in mechanical exposure likely leads to a concomitant improvement in musculoskeletal health (Lötters and Burdof 2002). Hence, panel designers could be encouraged to take the total mass of a panel into consideration, such as when deciding upon panel component materials and how to 'break up' or panelise the walls for a given floor plan. In addition, there may be value in minimising the total number of sheathed panels, with sheathing instead installed, at least partially, on site rather than in the factory. However, simply reducing panel mass by these approaches does not guarantee a reduction in overall exposures, since the overall panel erection process would change and could result in increased overall exposures. More importantly, any change in the overall panel erection process could compromise on-site productivity. These concerns regarding overall exposures and productivity emphasise the necessity for a system that can collectively consider physical demands and productivity and allow panel designers to assess the compromises involved.

Eventual use of this DSS will allow panel design factors to be considered not only to determine panel specifications, but also to address the panel stacking order and build-sequence problems. The current results suggest potential 'rules' to be used by the system, as well as more general practical guidance for panel manufacturers and builders, some of which are also applicable to the traditional wall-building process. For example, heavy panels could be stacked close to knuckle height to raise the initial panel height. However, the design and construction plans should allow for the minimisation or elimination of multiple handing, particularly of larger and heavier panels. In other words, workers would be exposed to potentially avoidable exposures and risk if they needed to sort through a stack of panels to get to the next one needed. Further, carrying tasks resulted in relatively high risk levels; panel stacks should thus be located on the worksite to minimise carrying distances. Since spinal loads (F_X and F_Y) were higher for C2 than C1, there may be value in encouraging (or training) workers to carry panels in a horizontal orientation. For tasks involving erecting a panel from knuckle height, workers could benefit by alternating between standing at the panel side and top-plate since risk levels were higher for E1KSide than E1KTop. In addition to these recommendations, alternative work processes, such as using assistive devices for panel erection tasks, might be introduced. Care would be needed, however, to ensure that productivity is not compromised. Assistive devices such as pneumatic lifts have exhibited such adverse effects on productivity, depending on the characteristics of a panel (Mirka *et al.* 2003).

A few limitations of this study should be acknowledged. First, the participants had no formal experience in panel erection tasks, although some participants had experienced general carpentry. All participants observed video recordings of panel erection tasks during the preliminary session and had opportunities to practise each task during data collection sessions. Physical competency and perceptions of the participants, however, could differ from those of experienced carpenters. Indeed, this, and the fact that the tasks were not simulated over the typical duration of a working day, may explain the relatively low reported levels of perceived exertion. It is also assumed that the risks reported here are conservative and that any designs or approaches that reduce them will also benefit actual workers. Second, due to constraints in the laboratory equipment, participants' movements were somewhat restrained and they were asked to keep their hands on load cells attached to the panels. Although efforts were taken to avoid discomfort and to provide sufficient familiarisation, limitations such as these may nonetheless limit external validity. Third, inputs to the multiple logistic regression model (Marras *et al.* 1993) were obtained here using a set of passive markers, while the model was developed using different technology [i.e. lumbar motion monitor (LMM)]. However, presuming rigid body motion of the thorax, the current use of individual markers and marker cluster was expected to provide information comparable to a LMM, in particular related to angular velocities (to which the risk estimation model is more sensitive vs. orientations). The difference in technology, however, still may have biased estimated P_{Risk} values. Fourth, suboptimal working conditions were not considered, such as a reduced crew size or unstable, uneven or slippery surfaces. Fifth, quantitative descriptions of risks were not determined in other (more extreme) situations, such as when handling smaller or larger panels; only the most common situations were assessed.

The present work estimated WMSD risks resulting from common panel erection tasks under conditions of different panel masses and sizes. It should be noted that the set of risk measures suggests that many common panel erection tasks impose a high risk on workers while handling panels, independent of or dependent upon panel mass and size. Although there are some inconsistencies in predicted risk levels among the risk assessment tools, there was consistent evidence that a reduction in panel mass can lead to a decrease in spinal loads, LI values and perceived exertion and that manipulating panels from the ground results in higher risk levels. Some practical guidance was suggested based on the results. In addition, given the existence of centralised designers in off-site panel production, the current information on risk levels can be exploited by a system such as the DSS to proactively control WMSD risks during the entire panel erection process. To enhance the likelihood that such an approach is used, it will be necessary to ensure that rules or recommendations improve (or at least do not compromise) on-site productivity.

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