External L5–S1 joint moments when lifting wire mesh screen used to prevent rock falls in underground mines

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ABSTRACT

Bolting large sheets of wire mesh screen (WMS) to the roof of underground mines prevents injuries due to rock falls. However, WMS can be heavy and awkward to lift and transport, and may result in significant spinal loading. Accordingly, six male subjects (mean age = 45.8 years + 7.5 SD) were recruited to lift WMS in a laboratory investigation of the biomechanical demands. Biomechanical modeling was used to estimate external moments about L5–S1 for sixteen lifting tasks, using two sizes of WMS. Full-size WMS involved a two-person lift, while half-size WMS involved a one-person lift. Lifts were performed under 168 cm and 213 cm vertical space. Restriction in vertical space increased the maximum L5–S1 extensor moment from 254 to 274 Nm and right lateral bending moment from 195 to 251 Nm. Lifting full sheets of screen (as opposed to half sheets) resulted in an average 33 Nm increase in L5–S1 extensor moment. The L5–S1 extensor moment was increased by an average of 44 Nm (18%) when lifting screens positioned flat on the floor compared to an upright position.

Relevance to industry: Large flexible materials are commonly lifted in industrial work environments, and may involve the efforts of two or more workers. The current study examines the low back loading associated with lifting large flexible screens and presents recommendations to reduce spine loading.

1. Introduction

Underground coal miners are frequently exposed to poor roof conditions that put them at increased risk of injury due to rock falls. According to data compiled by the Mine Safety and Health Administration (MSHA), for the years 1998–2007 the number of roof fall injuries ranged from a low of 427 per year to a high of 709 per year (MSHA, 2008). A detailed analysis of rock fall injuries for 1997 determined that nearly 100% occurred where the miners could have been protected by roof support (Bauer and Dolinar, 2000). When wire mesh screen (WMS) was installed on the mine roof, on the other hand, analysis of injury data indicated that the number of rock fall injuries was reduced to less than 15% of that experienced prior to its installation (Robertson et al., 2003).

The reason WMS is more effective than other rock fall control techniques is that it covers more surface area of the roof – close to 100% protection can be achieved. However, in the process of achieving increased rock fall protection, musculoskeletal hazards may be introduced due to lifting and handling WMS. WMS handling can be a challenge for operators because it often requires overhead lifts and awkward postures, and the screen is unwieldy due to its large size and flexible nature (Fig. 1). In addition, WMS can be fairly heavy depending on its size, the number of reinforcing wires, and the gage of the steel. Typical full-size sheets of WMS have a mass of about 14.5 kg, but at least one mine in the Western U.S. installs 8-gauge steel sheets that are 6 m long and 1.5 m wide, with a mass of approximately 23 kg (Robertson et al., 2003). Due to the size and weight of WMS, large load moments can be introduced, the magnitude of which will depend on the orientation of the screen.

Given the superior rock fall protection afforded by WMS, the National Institute for Occupational Safety and Health (NIOSH) supports its widespread use in the underground coal mining industry. Recognizing that the biomechanical stresses of handling WMS could negatively impact achievement of this aim, it was considered important to obtain an improved understanding of these stresses so that better handling techniques could be recommended. Accordingly, the purpose of the present exploratory research study was to use a bottom-up biomechanical model to derive moments about the L5–S1 joint during manual lifting of WMS under a variety of conditions. Lifting tasks involved handling two sizes of WMS, various initial and final orientations of the WMS, and different

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Fig. 1. Miners lifting wire mesh screen positioned on the mine floor (A) vs. stored upright against the mine wall, or "rib" (B).

vertical space restrictions, all of which were chosen to simulate WMS handling practices observed in underground coal mines.

2. Methods

2.1. Subjects

Six male subjects (mean age = 45.8 years ± 7.5 SD; mean height = 175.8 cm ± 9.4 SD; mean body mass = 84.0 kg ± 16.2 SD) volunteered to serve as test subjects in this study. Male subjects were used owing to the fact that roof bolters in underground coal mines (workers who would install WMS) are almost exclusively male. Subjects operated under terms of informed consent and were tested in accordance with procedures approved by the National Institute for Occupational Safety and Health (NIOSH) Human Subjects Protection Board. All participants had experience in the underground mining environment, but none had specifically performed WMS lifting in an underground setting. None of the subjects reported a significant history of low back disability (i.e., had experienced no lost-time due to low back pain), and were asymptomatic at the time of testing.

2.2. Experimental design

A completely randomized within-subjects experimental design was used to evaluate the biomechanical demands of lifting full-size and half-size WMS. Lifting was performed under two vertical workspace conditions (168 cm and 213 cm). These vertical workspace conditions were chosen to evaluate the effects of lifting in high-seam (>183 cm) coal mine conditions as opposed to a vertical height more characteristic of a mid-seam (122–183 cm) coal mine where stooping would be required. Two sizes of the wire mesh screen were tested. These included full-size WMS (4 m × 1.53 m, 8-gage steel wire, 14.5 kg) and half-size WMS (1.5 × 1.5 m, 8-gage steel wire, 6 kg). Examples of lifting WMS in the motion analysis laboratory can be seen in Fig. 2. As shown in Fig. 2A, the subject lifted one side of the screen while other side was lifted by a member of the research team (always the same member) when lifting full-size WMS. The half-size WMS was performed as a one-person lift (Fig. 2B). Dependent measures consisted of minimum, average and peak three-dimensional external moments (for X, Y, and Z axes) about the L5–S1 joint based upon calculations derived from a biomechanical model described in detail below.

A priori orthogonal contrasts were developed to test effects of interest for sixteen lifting conditions. Contrasts are identified in Table 1. Each of these contrasts sum to zero and each contains a unique piece of information regarding the data collected. As an example of how such contrasts are analyzed, the first row in the table represents a comparison representing the effect of different seam heights (168 cm vs. 213 cm) on L5–S1 external moments. Since there are 6 trials at the 168 cm height and 10 at the 213 cm height, values are multiplied by 5 (168 cm) or −3 (213 cm) to provide a fair comparison regarding the effect of seam height. As these contrasts were established before data collection, t-tests were computed using a *per contrast* Type I error = 0.05 (Kirk, 1995). All t-tests reported below have 75 degrees of freedom.

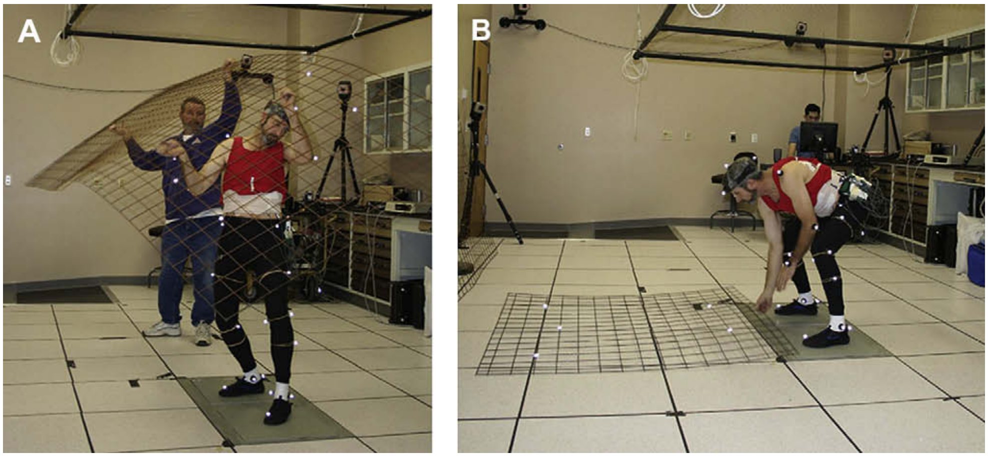

Fig. 2. Examples of lifting wire mesh screen in the Motion Analysis Laboratory. (A) Shows an overhead lift of a full-size WMS, while (B) shows subject lifting a half-size WMS from the floor.

Table 1

A priori orthogonal contrasts used to analyze data from the experiment. [Note: Seam height represents vertical space constraints, FLR = WMS laying flat on floor at start of lift, RIB = WMS leaning against wall (rib) at start of lift, L = subject facing screen and lifting left side of full-size WMS, R = subject facing screen and lifting right side of full-size WMS, OV = Lifting full-size WMS to an overhead-carry position, SI = lifting full-size WMS to side-carry position].

	168 cm seam height						213 cm seam height									
	Half-size WMS		Full-size WMS				Half-size WMS		Full-size WMS							
	FLR	RIB	FLR		RIB		FLR	RIB	FLR				RIB			
			L	R	L	R			L		R		L		R	
									OV	SI	OV	SI	OV	SI	OV	SI
168 cm vs. 213 cm	5	5	5	5	5	5	−3	−3	−3	−3	−3	−3	−3	−3	−3	−3
Half-size WMS vs. Full-size WMS	4	4	−2	−2	−2	−2	4	4	−1	−1	−1	−1	−1	−1	−1	−1
FLR vs. RIB	1	−1	1	1	−1	−1	1	−1	1	1	1	1	−1	−1	−1	−1
Seam Height × FLR/RIB	5	−5	5	5	−5	−5	−3	3	−3	−3	−3	−3	3	3	3	3
Left side vs. Right side (Full-size WMS)	0	0	1	−1	1	−1	0	0	1	1	−1	−1	1	1	−1	−1
Overhead Lift vs. Side Lift (Full-size WMS)	0	0	0	0	0	0	0	0	1	−1	1	−1	1	−1	1	−1
Left/Right × Overhead/Side (Full-size WMS)	0	0	0	0	0	0	0	0	1	−1	−1	1	1	−1	−1	1
Left/Right × FLR/RIB (Full-size WMS)	0	0	1	−1	−1	1	0	0	1	1	−1	−1	−1	−1	1	1

2.3. Motion analysis system/force plates

A ten-camera motion analysis system (Motion Analysis Corporation, Santa Rosa, California) was used to obtain kinematics of subjects performing the lifting tasks. Reflective markers were attached using a modified (i.e., no markers on the greater trochanters) Helen Hayes marker set, as depicted in Fig. 3 (Davis et al., 1991). Motion data were recorded at a rate of 60 frames/s using digital video cameras. A set of five reflective markers was placed on each of the wire mesh screens to track the motion of the object as it was lifted. Analog data from a pair of force plates (Advanced Mechanical Technology (AMTI), Inc., Watertown, MA) were collected synchronously with the motion data and stored in the motion capture data files, as was a digital video representation of the lifting sequence. All subjects started in a standardized position (a “T-pose”, standing up with arms held out to the side), facing the same direction, prior to the start of data collection.

2.4. Biomechanical model

Biomechanical models employing both bottom-up and top-down approaches were used in to analyze the data. However, the

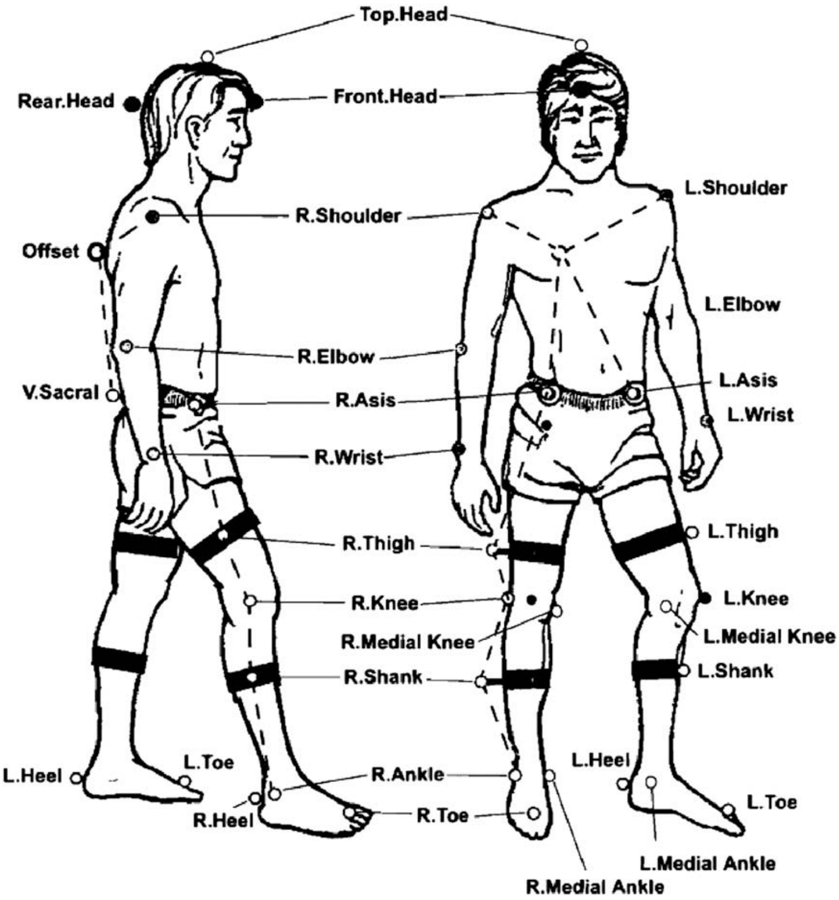

Fig. 3. Modified Helen Hayes marker set used to obtain motion data in the study.

bottom-up approach was considered superior due to the fact that hand forces on the WMS were not captured and had to be assumed to be equal, which was difficult to justify. Only results from the bottom-up analysis are presented. The 14 body segments and local coordinate system for L5–S1 are shown in Fig. 4. Mass distributions for each body segment were based upon data provided by Dempster (1955), as corrected for fluid loss by Clauser et al. (1969). Three-dimensional forces, moments, and center of pressure data were obtained from AMTI force plates and were used to calculate moment estimates for L5–S1. Axes established for the force plates used the "right hand" rule and are illustrated in Fig. 5. The position estimate for L5–S1 was operationally defined as a point lying 40% of the distance (posterior to anterior) from sacral motion analysis marker (V.SACRAL) to a point bisecting the line connecting markers on the right and left anterior superior iliac spines (R.ASIS and L.ASIS). Moments about L5–S1 were calculated based on the ground reaction forces and the positions of force application and the position of L5–S1 were corrected by subtracting moments about the left and right thighs, shanks, and feet. The total force (including calculated inertial forces for each body segment) of these segments was used in this correction. Inertial forces were calculated using a dynamic model described by Huston et al. (1976). Equation (1) demonstrates the bottom-up model used to calculate M_Y (extension moment) at L5–S1:

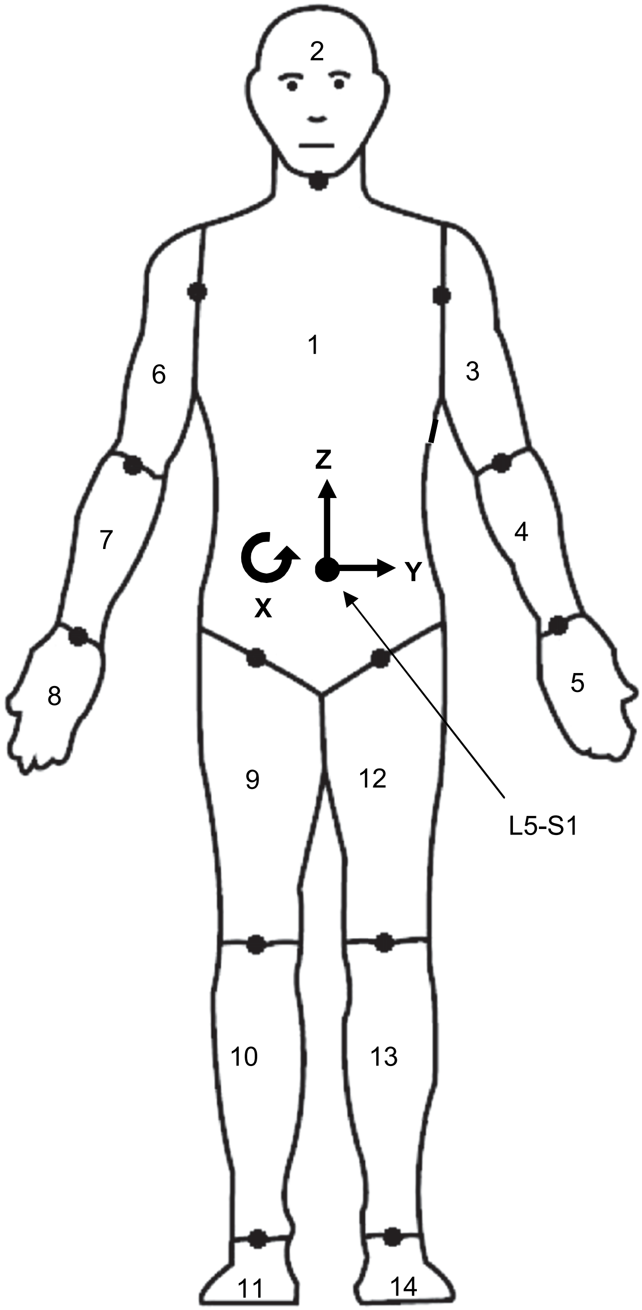

Fig. 4. Fourteen body segments used in link segment model and orientation of local coordinate system for L5–S1.

$$
\begin{aligned}
M_{Y\ \mathrm{L5-S1}} = {} & \left(x_{\mathrm{fp1}} - x_{\mathrm{L5-S1}}\right) \times fz_{fp1} + \left(x_{\mathrm{fp2}} - x_{\mathrm{L5-S1}}\right) \times fz_{\mathrm{fp2}} \\
& - \left(z_{\mathrm{L5-S1}} \times fx_{\mathrm{fp1}}\right) - \left(z_{\mathrm{L5-S1}} \times fx_{\mathrm{fp2}}\right) - M_{Y\ \mathrm{r.thigh}} \\
& - M_{Y\ \mathrm{r.shank}} - M_{Y\ \mathrm{r.foot}} - M_{Y\ \mathrm{l.thigh}} - M_{Y\ \mathrm{l.shank}} \\
& - M_{Y\ \mathrm{l.foot}}
\end{aligned}
\tag{1}
$$

In this equation, $M_{Y\,\mathrm{L5-S1}}$ is the extension moment about L5–S1, x_{fp} is the location of the center of pressure for force plates 1 or 2 (per subscripts) in the x direction, $x_{\mathrm{L5-S1}}$ is the x coordinate of the calculated position of L5–S1, fz_{fp} is the measured force in the z axis for force plates 1 or 2 (per subscripts), $z_{\mathrm{L5-S1}}$ is the z coordinate of L5–S1, fx_{fp} is the measured force in the x axis from force plate 1 or 2 (per subscripts), and $M_{Y\,\mathrm{r.thigh}}$, $M_{Y\,\mathrm{r.shank}}$, $M_{Y\,\mathrm{r.foot}}$, $M_{Y\,\mathrm{l.thigh}}$, $M_{Y\,\mathrm{l.shank}}$, $M_{Y\,\mathrm{l.foot}}$ are moments about the Y axis of the specified segments of the lower extremities. Similar equations were developed to determine M_x and M_Z for L5–S1. Since subjects pivoted from a positive X facing position to a positive Y facing position (as they would to begin carrying the screen), moments about L5–S1 were rotated based on the position of the markers L.ASIS and R.ASIS so that consistent moment estimates about the local coordinate system at L5–S1 could be maintained.

2.5. Procedure

Upon arrival at the laboratory, subjects were explained the purpose of the study, read and signed the informed consent form and a standard photo release form. Subjects were asked to change into clothes appropriate for the motion analysis study and were fitted with the motion analysis markers. Calibration of the motion analysis system capture volume was performed at the beginning of each day of testing, and was repeated if necessary. Subjects were instructed as to how the lifting tasks should be performed and were

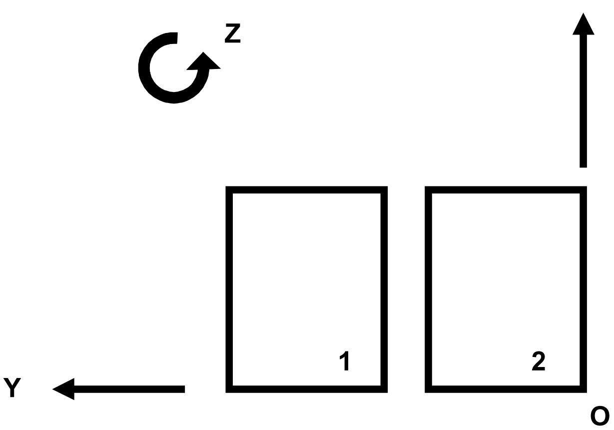

Fig. 5. Orientation of axes with respect to force plates. Subjects were facing in the positive X direction when the lift was initiated.

allowed to practice until they felt comfortable with the tasks. Data were obtained on 16 WMS lifting conditions for each subject. A two-man lift was used for the full-size WMS, with data collected on only one subject. For any given lifting condition, the subject would perform one or more trials until the task was deemed to have been performed successfully (i.e., subject remained on force plates throughout the task, no difficulties encountered during the lift, etc.). At the start of the lifting tasks, subjects stood on the two AMTI force plates, with one foot on each plate facing in the positive *X* direction (Fig. 5). Lifts started with the screen either flat on the floor or at a near vertical orientation (as if leaning against a mine "rib"). Vertical space constraints (simulated mine seam heights) were controlled by way of an adjustable roof that was raised or lowered as necessary. Lifts of full-size screens in the 213-cm vertical space consisted of lifting the screen to either an overhead-carry position or to a side-carry position. In the limited 168-cm vertical space, only a lift to the side-carry position was possible. Subjects alternated lifting on the right vs. left side of the screen for full-size WMS. For half-size screens, lifts to only a side carry were examined, as these screens are not observed to be carried overhead in the mining environment. Starting positions for half-size WMS also consisted of lying flat on the floor or leaning against a rib. Other than the constraints listed above, the subject was free to use his own lifting technique. The reader is referred to Table 1 for a full representation of the lifting conditions. The order of presentation of the 16 lifting conditions was completely randomized on a within-subjects basis. Subjects were given two minutes rest between each trial (Caldwell et al., 1974).

3. Results

Table 2 provides a summary of the external L5–S1 peak joint moments observed for the "main effect" contrasts examined in this study. Other significant results, involving interactive effects and other joint moment measures are detailed below.

3.1. Effect of vertical space restriction

Compared to the 213 cm vertical space, restricted vertical space (e.g., the 168 cm simulated mine seam height) was associated with an increase in the peak L5–S1 extensor moment from 254 to 274 Nm ($t = 2.77$, $p < 0.01$) and an increase in the average peak right lateral bending moment from 195 to 251 Nm ($t = 5.54$, $p < 0.001$). The minimum L5–S1 extensor moment in the 168 cm vertical workspace was 63 Nm greater than in the less restricted space ($t = 4.24$, $p < 0.001$).

3.2. Effect of WMS size

The difference in mass expected to be handled by the subject for full-size WMS (two-person lift of a 14.5 kg WMS) and half-size WMS (one-person lift of a 6 kg WMS) would be expected to average 1.25 kg. However, full-size WMS was associated with a peak L5–S1 extensor moment that was 26 Nm greater than the half-size WMS, on the average ($t = 3.66$, $p < 0.001$). The peak right lateral bending moment was increased 7 percent (205.1 vs. 219.6 Nm) when lifting the full-size WMS ($t = 2.14$, $p < 0.05$).

3.3. Effects of initial WMS orientation

Lifting WMS from a floor-lying orientation significantly increased both peak ($t = 6.19$, $p < 0.001$) and average ($t = 7.74$, $p < 0.001$) extensor moments compared to when the screens were oriented vertically. Table 2 provides the increased peak extensor moment observed when lifting from the floor vs. the rib. The L5–S1 peak extensor moment exhibited an increase of 44 Nm (18% increase) when lifting the screen from the floor. The average extensor moment was 32% higher (95 vs. 125 Nm) when the WMS was lifted from the floor.

Table 2
Averaged peak external L5–S1 joint moments (Nm) and standard errors for specified contrasts. (Note: * $p < 0.05$, *** $p < 0.001$.)

Contrast	M_X	M_Y	M_Z
168 cm vs.	$251.1 \pm 13.2^{***}$	$274.5 \pm 12.7^{***}$	30.1 ± 2.4
213 cm	194.9 ± 6.9	254.2 ± 8.7	25.3 ± 1.7
HALF-SIZE WMS vs.	$205.2 \pm 14.1^{*}$	$242.0 \pm 13.2^{***}$	26.3 ± 2.3
FULL-SIZE WMS	219.6 ± 8.1	268.4 ± 8.4	27.3 ± 1.7
FLOOR vs.	216.3 ± 8.8	$283.8 \pm 7.6^{***}$	28.4 ± 1.9
RIB	215.7 ± 11.2	239.8 ± 11.6	25.8 ± 2.1
RIGHT vs.	230.6 ± 13.1	281.5 ± 12.5	29.4 ± 2.3
LEFT	208.5 ± 9.8	255.2 ± 11.3	25.3 ± 2.6
OVERHEAD vs.	192.3 ± 9.3	275.2 ± 13.4	26.7 ± 2.9
SIDE	206.0 ± 12.6	245.0 ± 14.2	25.1 ± 2.9

3.4. Interaction contrasts

Three contrasts tested for significant interactions, as specified in Table 1. Only one interaction contrast was found to have a significant effect on the peak extensor moment. Specifically, the interaction between Overhead/Side lift by Left/Right side positioning of the subject during the lift was found to be significant ($t = 2.46$, $p < 0.05$). Fig. 6 shows the nature of the interaction, which appeared to be the result of a smaller disparity between Overhead and Side lifts when the subject was located on the right side of the full-size WMS compared to when the subject was positioned on the left.

4. Discussion

Wire mesh screens provide an effective method with which to prevent falls of rock in a mine. However, these screens are large, awkward, and bendable loads, complicating manual handling activities. The difficulties associated with handling such a large flexible load are apparently exacerbated by restrictions in vertical space, commonly encountered in underground coal mines. Prior

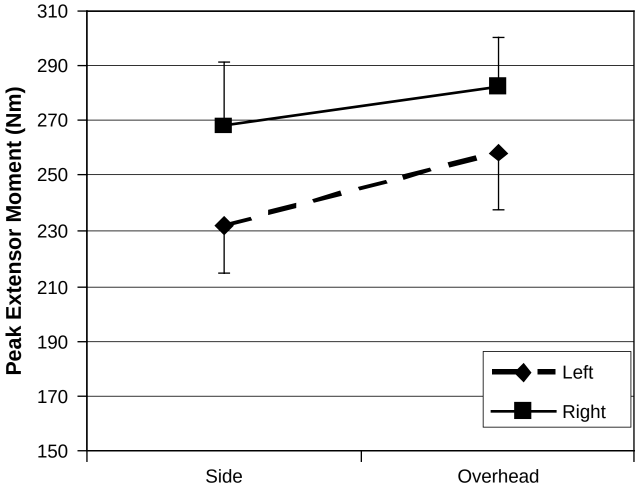

Fig. 6. Interaction between lifting to an overhead vs. side-carry position and being positioned on the left vs. right side of the full-size WMS on the peak extensor moment about L5–S1. Error bars represent the standard error of the mean.

work has shown that increasingly restrictive vertical workspaces result in a progressive increase in peak L5–S1 extensor moments on the low back (Gallagher et al., 2001). The current study, which imposed a relatively modest restriction in vertical space compared to the previous study, demonstrated a similar result in terms of both peak and average L5–S1 extensor moments. The average extensor moment was at least partially due to a higher minimum moment, as subjects began the task in a partial stoop, rather than standing upright. As vertical workspace diminishes, of course, the trunk is forced to bend forward. Flexion of the trunk will cause the center of mass of the upper body to move anterior with respect to L5–S1, increasing the forward bending moment about this joint. This effect would be present even without any load in the hands, and adding a load will only magnify the extensor moment.

The effects of restricted space on spinal loading do not appear confined to a single plane. Lateral bending moments were also significantly affected by lower working heights. Specifically, subjects in this study exhibited higher right lateral bending moments when exposed to reduced headroom. When considered in conjunction with the increased extensor moment described above, the combined loading effect associated with restricted space appears to be a combination that generates particularly high stress concentrations in the lateral and posterior annulus fibrosus (Adams et al., 2006). These stress concentrations are thought to be linked with the disc's susceptibility to prolapse under the combined influence of bending and compression (McNally et al., 1993). It is conceivable that repetitive handling of loads that produce such stress concentrations (as would be experienced in installing WMS) might increase the chances of disc prolapse as a consequence of fatigue failure of tissues in the posteriolateral aspect of the disc (Adams et al., 2006).

Lifting full-size WMS is challenging for several reasons. These include the fact that a two-person lift is required, the load is quite flexible, and the load is an awkward size and shape. It is notable, for instance, that though the mass handled by a subject when lifting full-size WMS would be slightly greater compared to the half-size WMS (1.25 kg on average); the L5–S1 peak extensor moment was approximately 26 Nm higher, and the right lateral bending was also significantly higher. There may be several possible explanations for this result. For example, it is understandable that in a two-person lift, it is quite possible for one person to assume a greater portion of the load at certain times since it is practically impossible to coordinate such a lift equally (Dennis and Barrett, 2003). This would be true with a rigid object; however, the disparity in loading may be magnified when lifting an object that is flexible and which is likely to sag and experience oscillations along its length. In this regard, it should be noted that it would be difficult (if not impossible) to control the load distribution of such a large and flexible material in a two-person lift. While we always had the same person lift the side of the screen not lifted by the subject, differences in stature may have led to some differences in loading between subjects. It should be noted, however, that contrast effects were determined on a within-subjects basis which should minimize the impact of any such between-subjects difference. The two-person lift of the full-size WMS was generally observed to take increased time to accomplish than the single-person lift of the half-size WMS.

In contrast to the combined loading associated with restricted space, lifting from the floor was found to influence only the extensor moment about L5–S1. On the other hand, lifting the screen from the floor produced the highest observed extensor moments of any contrasts studied. The fact that extensor moments averaged 45 Nm lower when WMS is oriented vertically suggests that storage of WMS on the floor is not recommended, unless subsequent moves are made using mechanical assistance. If manual lifts will be performed, WMS should be stored against the rib (as shown in Fig. 1B).

The results of this study can be compared with other research on biomechanical demands of manual lifting involving awkwardly shaped or atypical loads in mining. A study by Plamondon et al. (2006) involved lifting large drill rods for in-the-hole drilling tasks. Results of this lifting tasks indicated peak resultant moments ranging from approximately 185 Nm to 275 Nm depending on the foot position and height of the drill rod at the beginning of the lift. Peak asymmetrical moments for this task averaged about 75 Nm. Studies involving lifts of heavy electrical cable have estimated L5–S1 resultant moments ranging from 200 to 315 Nm depending on the posture and seam height when performing the lift, with a stooping posture generally associated with higher extensor moments (Gallagher et al., 2001, 2002). In the current study, the peak extensor moments about L5–S1 ranged from 188 Nm to 315 Nm, and peak lateral bending moments ranged from 170 Nm to 270 Nm. Thus, lifting WMS resulted in spinal loads that were of a similar range in terms of extensor moments compared to the above mining tasks; however, the asymmetric moments were higher in the current study. This may be the result of the fact that the WMS was often brought to a side-carry position (which would increase the lateral bending moment), and lifting the screen overhead (as in Fig. 2A) also created significant lateral bending moments about L5–S1. Overall, the spine moments observed in this study were in a range similar to previously studied high-risk mining tasks (Gallagher et al., 2001; Plamondon et al., 2006).

In the study by Gallagher et al. (2002), an extensor moment of 315 Nm was associated with an L5–S1 compressive force of approximately 6 kN, while an extensor moment of 200 Nm was associated with a compressive force averaging approximately 3.4 kN. These values are close to the NIOSH Maximum Permissible Limit (6.4 kN) and Action Limit (3.4 kN), respectively (Waters et al., 1993). These compressive loads are also very near the reported range of 6.1–10.2 kN average ultimate strength of vertebral endplates for males aged 20–50 years (Adams et al., 2006). Assuming that similar moments lead to similar compressive loads, this finding would suggest that some of the more difficult lifting conditions in the current study might result in compressive loads that could cause fractures in the endplates of those performing such a lift. When considering the fact that this lifting task is repetitive in nature, it is very likely that fatigue failure of vertebral endplates would occur with a sufficient number of loading cycles at such a load magnitude (Brinckmann et al., 1988; Gallagher et al., 2007). The number of loading cycles necessary would be a function of both the magnitude of the applied load and the strength of an individual's lumbar spine. In cadaver fatigue failure studies, it has been found that 73% of lumbar motion segments survived 5000 loading cycles when loaded at 30–40% of a spine's predicted ultimate stress. When loaded at 60–70% of the ultimate stress, almost two-thirds of lumbar motion segments tested lasted less than 100 loading cycles (Brinckmann et al., 1988). Thus, it is important to consider methods that can reduce the spinal load when handling WMS so that the risk of injury is reduced. Such methods may include use of mechanical handling devices such as winches, reducing the magnitude of the load on the spine, and reducing the frequency of lifting.

The data from this study can be used as a starting point for recommending practices that might reduce low back loading and musculoskeletal risk during manual handling of WMS. Additionally, it may be helpful to consider additional methods of storing and handling screen that might be useful in reducing low back injury risk. Currently, the most common method of delivering roof screen to the area being roof bolted is to drag them using a chain to the active section of the mine, then lift the screens up, one or two at a time, and either lean them against the rib or leave them lying on the mine floor. Data from this study clearly show that leaning the screens against the rib is preferable. Putting the screens in an

Fig. 7. Roof bolter with rails for storage of roof screen (Compton et al., 2007).

upright orientation greatly reduces the biomechanical load on the low back during lifting, and has the additional benefit of keeping the screens out of a potentially muddy floor and reduces the chances that the screens will present a tripping hazard. Broken, bent and muddy screen is much more difficult to handle and install. As discussed earlier, handling screen in mines with restricted vertical space resulted in significantly increased low back loading in the current study. This suggests the need to find methods to increase mechanical handling of screen when restricted headroom is present.

One supply method that may be helpful in both low- and high-seam mines is the use of racks or rails (Fig. 7) installed on the bolting machine. These racks are capable of holding enough sheets of WMS to complete the bolting of roof exposed from a newly mined section. Keeping WMS on the roof bolter is both efficient (reducing the need to walk back to retrieve sheets of screen) and can greatly reduce the lifting demands on the worker. Some mines have found that they can use a winch to load the roof screen on the rails, eliminating the need to manually handle screens until they need to be moved just prior to the bolting process. Furthermore, a more extensive rail system has been tested that facilitates sliding full sheets of WMS using rails all the way up to the front of the bolter, eliminating the lifting requirement altogether (Compton et al., 2007). Development of methods to improve efficiency and reduce musculoskeletal demands are important considerations that may help roof screen achieve its potential to prevent serious injuries caused by the fall of small rocks in underground mines.

As with all studies, limitations associated with the current work must be addressed. One limitation that must be noted is that the subjects in this experiment were not experienced with lifting roof screen, and this limitation may affect the external validity of the current analysis. However, the performance of the lifting tasks was considered realistic by a former roof bolter who was part of the research team. In addition, the sample size was also somewhat small; however, the finding of numerous significant results suggests that statistical power was more than adequate for the measures studied.

5. Conclusions

The following conclusions are drawn from the present study:

1. Restricted vertical space increases both L5–S1 extensor moments and increased lateral bending moments when handling wire mesh screen.
2. In contrast to the effects of vertical space restriction, lifting screen from flat on the floor (as opposed to a vertical orientation) significantly affected only the extensor moments for L5–S1.
3. Lifting of full-size WMS (a two-person lift) resulted in a 26 Nm increase in the L5–S1 extensor moment compared to lifting the half-size WMS (one-person lift), though the average difference in the load being lifted was approximately 1 kg.
4. Methods of storing, lifting, and carrying WMS can have a significant effect on the biomechanical stresses experienced by workers handling this material, and results suggest that simple steps (i.e., storing WMS upright against the mine "rib") can reduce the loading experienced by miners handling screens.

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