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# Musculoskeletal disorder risk as a function of vehicle rotation angle during assembly tasks

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ABSTRACT

Musculoskeletal disorders (MSD) are costly and common problem in automotive manufacturing. The research goal was to quantify MSD exposure as a function of vehicle rotation angle and region during assembly tasks. The study was conducted at the Center for Occupational Health in Automotive Manufacturing (COHAM) Laboratory. Twelve subjects participated in the study. The vehicle was divided into seven regions, (3 interior, 2 underbody and 2 engine regions) representative of work areas during assembly. Three vehicle rotation angles were examined for each region. The standard horizontal assembly condition (0° rotation) was the reference frame. Exposure was assessed on the spine loads and posture, shoulder posture and muscle activity, neck posture and muscle activity as well as wrist posture. In all regions, rotating the vehicle reduced musculoskeletal exposure. In five of the seven regions 45° of vehicle rotation represented the position that reduced MSD exposure most. Two of the seven regions indicated 90° of vehicle rotation had the greatest impact for reducing MSD exposure. This study demonstrated that vehicle rotation shows promise for reducing exposure to risk factors for MDS during automobile assembly tasks.



## 1. Introduction

Musculoskeletal disorders (MSDs) continue to be a common and costly problem (National Research Council, 2001; Dunning et al., 2010) in the manufacturing sector. The auto industry is one of several industries that have high incidence of MSDs (Ulin and Keyserling, 2004). One important risk factor might be the repetitive awkward orientation of the worker relative to the work while trying to access different tasks in auto assembly. Previous studies have shown that awkward postures increase the risk of MSDs (Silverstein et al., 1997; Punnet et al., 2004; Keyserling et al., 2005). Literature reviews of the evidence indicate that reducing workplace exposure to known risk factors including awkward posture results in reduced MSD risk (National Research Council, 2001; Bernard, 1997; Punnet and Wegman, 2004). Thus, effective ergonomic interventions to reduce exposure to awkward postures and other risk factors result in lower risk of MSDs. One potential solution for reducing awkward posture is the rotating auto-body carrier (Rosenheimer Forderanlagen ROFA)™ conveyer system which allows the vehicle to be rotated at a variety of angles during the assembly process. Fig. 1 illustrates the capabilities of a ROFA system to rotate a vehicle. However, it is unknown (from a biomechanical standpoint) if or how much the rotation of the vehicle will influence exposure to MSD risk factors. Thus, the goal of the project was to quantify exposure to MSD risk factors as a function of vehicle rotation angle during assembly tasks.

## 2. Methods

### 2.1. Approach

The vehicle was divided into 9 representative working regions based on vertical height and horizontal reach distance. However, due to space restrictions only seven of the nine regions will be reported. Fig. 2 illustrates the seven regions of the vehicle presented. Regions 1–3 were interior cabin regions of the vehicle. As shown in Fig. 2, region 1 was the high vertical height, edge horizontal reach zone. The edge reach zone may be on either the right or left side of the vehicle and the worker would perform the job from the side of the vehicle where the task was located. Region 2 was the low vertical height, edge horizontal reach zone. Region 3 was the final interior region, in the low vertical height and center horizontal reach. At the zero rotation angle the interior region edge horizontal reach distance was less than 12 inches and center reach distance was approximately 36 inches. These reach distances would change as a function of rotation angle. An interior middle height, edge horizontal reach zone and middle height, middle reach distance were defined but not reported. There were two underbody

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**Fig. 1.** Vehicle body rotated on ROFA system.

regions of the vehicle. Region 4 was underbody edge and region 5 was underbody center. The engine room also had two regions. Region 6 was the engine room firewall region and region 7 was the engine room front fender. The engine room front fender region had to be performed from the front bumper in the standard assembly condition in order for the worker to see the task, however once the vehicle was rotated this no longer held true. One assembly task was performed in each region of the vehicle.

### 2.2. Study participants

Twelve subjects were recruited for the study. Six experienced and six inexperienced workers were in the study. On average the experienced workers had 17 years of auto assembly experience. Ten subjects were male and two were female. The ratio of males to females was intended to match the mix observed at the local auto assembly plant. The average age of the subjects was 35.8 years with a standard deviation of 13.1 years. The average (standard deviation) height and weight of the subjects was 178.5 cm (7.1 cm) and 80.6 kg (10.2 kg), respectively. The inexperienced subjects received three training sessions on all the tasks prior to testing. The experienced subjects also had one day of training in order to familiarize them with the rotated conditions.

### 2.3. Experiment design

#### 2.3.1. Independent measures

There were two independent measures region and rotation angle. Region had seven levels discussed in the approach section. The second measure auto rotation angle and was dependent upon the region of the vehicle. A pilot study was completed examining rotation angles in 15° increments (ie. 0°, 15°, 30°, 45°, 60°, 75° and 90°). The exposure data as well as feasibility of task performance from the pilot study were used to determine the angles for the current study in each of the regions. Interior regions 2 and 3 had vehicle rotation angles of 15° and 45° in addition to the standard zero assembly condition. Interior region 1, and engine room firewall region had rotation angles of zero, 45° and 60°. The two underbody regions and the engine room front fender had rotation angles of zero, 45° and 90°.

#### 2.3.2. Dependent measures

There were 27 dependent measures in several categories including spine, shoulder, neck and wrist. There were six spine variables including load measures of compression at L5/S1, lateral shear at L2/L3 and anterior/posterior shear at L2/L3 (Knapik and Marras, 2009). The spine posture variables included maximum sagittal flexion, maximum lateral bend and maximum twisting posture. There were 8 shoulder measures including right and left normalized muscle activity for the lateral and anterior deltoid muscles. Shoulder posture measures included right and left maximum shoulder flexion and abduction. The dependent measures for the neck were also muscle activity and posture, specifically, the right and left superior trapezius muscle activity, maximum neck flexion, extension and side bend. There were eight wrist posture measures including maximum right and left radial/ulnar and flexion/extension.

### 2.4. Equipment

An automobile rotate carrier conveyor (Rosenheimer Forderanlagen ROFA)™ was used to rotate the vehicle from the standard zero or horizontal assembly-line condition to a maximum of ninety degrees. Fig. 3 illustrates the vehicle rotated at 45° and Fig. 4 illustrates the vehicle at 90°.

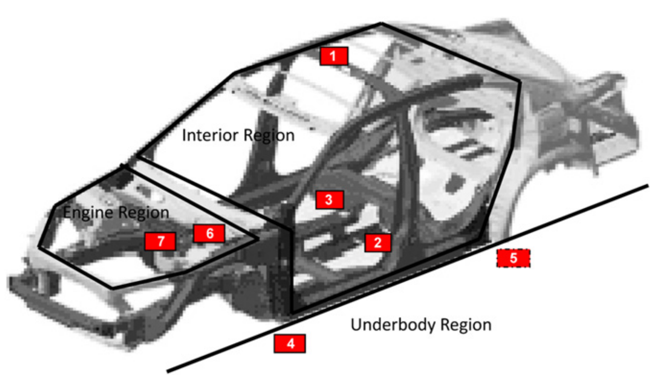


**Fig. 2.** Regions of the vehicle.

**Fig. 3.** Vehicle rotated at 45° and fully instrumented subject.

**Fig. 4.** Vehicle rotated at 90° and fully instrumented subject.

The lumbar motion monitor (LMM) was used to measure low back posture as illustrated in Figs. 3 and 4. The LMM, a tri-axial electrogoniometer, measures position, velocity and acceleration in all three planes of the body and has been previously validated (Marras et al., 1992).

A wired electromyography (EMG) system (Delsys, Boston MA) was used to measure muscle activity of the latissimus dorsi, erector spinae, rectus abdominus, external obliques, internal obliques, lateral deltoid, anterior deltoid, and superior trapezius muscle. All surface EMGs were collected on both the right and left side. The electrodes were applied using standard placement procedures (Solderberg, 1992).

Nine magnetic/gravitational sensors (Xsens Technologies,™ Enschede, The Netherlands) were placed on the torso, upper and lower legs, upper arm and neck in order to track body posture during the experimental conditions.

Finally, goniometers were used to measure elbow and wrist motion. Figs. 3 and 4 show a fully instrumented subject performing the task in engine room front bumper region at 45° and 90°, respectively.

### 2.5. Procedure

Upon arrival to the testing facility, subjects signed the university's internal review board (IRB) consent form. Surface electrodes were then placed on all the muscles of interest in the standard locations. Maximum exertions were performed for each muscle. After this, the lumbar motion monitor was placed on the subject. The subject then performed a set of standard lifting conditions. Muscle gains (required for the biomechanical model)

**Table 1**
Means (standard deviation) for dependent measures during assembly in region 1 the interior process high height, edge reach.

| | Auto | Rotation | Angles | *P*-values |
|---|---|---|---|---|
| | Horizontal (0°) | Forty-five (45°) | Sixty (60°) | |
| Dependent measures | | | | |
| *Spine loads (N)* | | | | |
| Compression (L5/S1) | 1202.58 (251.40)$^{A}$ | 901.80 (255.34)$^{B}$ | 908.32 (310.92)$^{B}$ | 0.0001* |
| Lateral shear (L2/L3) | 267.06 (140.71) | 215.58 (59.62) | 221.34 (53.27) | 0.3083 |
| A/P shear (L2/L3) | 770.50 (191.34)$^{A}$ | 648.04 (200.80)$^{B}$ | 653.46 (233.73)$^{B}$ | 0.0047* |
| *Spine posture (degrees)* | | | | |
| Maximum flexion | 32.62 (12.50)$^{A}$ | 13.48 (5.64)$^{B}$ | 12.19 (5.42)$^{B}$ | 0.0001* |
| Maximum lateral bend | 12.13 (7.08) | 10.85 (2.86) | 10.91 (2.67) | 0.4931 |
| Maximum twist | 12.43 (5.16)$^{A}$ | 9.48 (2.92)$^{B}$ | 8.40 (2.96)$^{B}$ | 0.0091* |
| *Shoulder normlized EMG* | | | | |
| Right lateral deltoid | 0.26 (0.15)$^{A}$ | 0.11 (0.08)$^{B}$ | 0.14 (0.07)$^{B}$ | 0.0032* |
| Left lateral deltoid | 0.13 (0.05) | 0.12 (0.07) | 0.11 (0.04) | 0.5516 |
| Right anterior deltoid | 0.36 (0.16)$^{A}$ | 0.19 (0.05)$^{B}$ | 0.20 (0.06)$^{B}$ | 0.0002* |
| Left anterior deltoid | 0.30 (0.11) | 0.25 (0.12) | 0.23 (0.08) | 0.2264 |
| *Shoulder posture (degrees)* | | | | |
| Max right shoulder flexion | 88.74 (28.74)$^{A}$ | 59.31 (23.15)$^{B}$ | 54.40 (16.72)$^{B}$ | 0.0003* |
| Max left shoulder flexion | 65.41 (24.41) | 80.75 (22.34) | 80.91 (20.45) | 0.0970 |
| Max right shoulder abduction | 22.62 (21.79) | 18.16 (21.79) | 33.05 (30.67) | 0.3332 |
| Max left shoulder abduction | 20.03 (34.98) | 25.48 (30.26) | 27.05 (25.51) | 0.7715 |
| *Neck normalized EMG* | | | | |
| Right superior trapezius | 0.40 (0.20) | 0.33 (0.14) | 0.39 (0.18) | 0.1580 |
| Left superior trapezius | 0.30 (0.15) | 0.32 (0.18) | 0.40 (0.18) | 0.0583 |
| *Neck posture (degrees)* | | | | |
| Maximum flexion | 21.22 (26.48) | 11.43 (18.07) | 20.94 (26.95) | 0.2562 |
| Maximum extension | −11.19 (24.28) | −20.23 (17.85) | −15.31 (18.89) | 0.4010 |
| Maximum right side bend | 14.77 (21.84) | 11.54 (11.08) | 16.20 (19.22) | 0.4572 |
| *Wrist posture (degrees)* | | | | |
| Maximum right radial | 8.30 (9.18) | 6.87 (9.74) | 5.41 (9.69) | 0.5237 |
| Maximum right ulnar | 33.42 (11.40) | 40.86 (9.15) | 38.38 (8.74) | 0.1498 |
| Maximum left radial | 8.34 (8.90) | 6.58 (10.54) | 10.90 (11.54) | 0.1224 |
| Maximum left ulnar | 23.74 (9.54)$^{B}$ | 36.44 (10.31)$^{A}$ | 36.46 (9.11)$^{A}$ | 0.0013* |
| Maximum right flexion | 12.94 (16.32) | 16.62 (14.44) | 18.74 (13.60) | 0.3884 |
| Maximum right extension | 39.84 (9.28) | 33.27 (12.43) | 29.47 (13.81) | 0.2211 |
| Maximum left flexion | 6.74 (18.19)$^{B}$ | 26.45 (22.01)$^{A}$ | 30.44 (16.17)$^{A}$ | 0.0001* |
| Maximum left extension | 41.54 (15.40) | 39.71 (16.90) | 39.20 (10.51) | 0.2977 |

NOTE: *p*-values in differences among angles, * indicates statistical significance at alpha = 0.05. Letter (A,B,C) indicate statically significant different exposure among the angle.

**Table 2**
Means (standard deviation) and *p*-values for dependent measures during assembly in the interior low height, edge reach region.

| | Auto | Rotation | Angles | *P*-values |
|---|---|---|---|---|
| | Horizontal (0°) | Fifteen (15°) | Forty-five (45°) | |
| Dependent measures | | | | |
| *Spine loads (N)* | | | | |
| Compression (L5/S1) | 1911.86 (579.13)$^A$ | 1532.05 (605.21)$^B$ | 1422.37 (481.77)$^B$ | 0.0001* |
| Lateral shear (L2/L3) | 534.46 (194.22)$^A$ | 447.55 (174.71)$^B$ | 271.53 (122.46)$^C$ | 0.0001* |
| A/P shear (L2/L3) | 768.85 (330.07) | 866.20 (290.36) | 818.16 (282.14) | 0.1932 |
| *Spine posture (degrees)* | | | | |
| Maximum flexion | 47.51 (9.16)$^A$ | 20.89 (8.58)$^C$ | 28.53 (8.55)$^B$ | 0.0001* |
| Maximum lateral bend | 18.77 (3.60)$^A$ | 18.63 (2.64)$^A$ | 13.33 (3.02)$^B$ | 0.0001* |
| Maximum twist | 5.69 (3.31) | 6.35 (2.86) | 5.71 (3.17) | 0.4088 |
| *Shoulder normlized EMG* | | | | |
| Right lateral deltoid | 0.28 (0.13)$^A$ | 0.21 (0.15)$^B$ | 0.16 (0.11)$^B$ | 0.0039* |
| Left lateral deltoid | 0.27 (0.15)$^B$ | 0.42 (0.19)$^A$ | 0.26 (0.18)$^B$ | 0.0010* |
| Right anterior deltoid | 0.44 (0.18)$^A$ | 0.31 (0.14)$^B$ | 0.21 (0.11)$^C$ | 0.0001* |
| Left anterior deltoid | 0.18 (0.12) | 0.25 (0.17) | 0.22 (0.22) | 0.1381 |
| *Shoulder posture (degrees)* | | | | |
| Max right shoulder flexion | 90.13 (22.83)$^A$ | 65.07 (13.06)$^B$ | 54.96 (16.12)$^C$ | 0.0001* |
| Max left shoulder flexion | 43.40 (31.18) | 34.28 (33.96) | 36.97 (25.08) | 0.3437 |
| Max right shoulder abduction | 16.59 (22.14) | 26.93 (22.67) | 24.67 (19.14) | 0.1059 |
| Max left shoulder abduction | 55.36 (24.90)$^B$ | 71.20 (13.89)$^A$ | 47.60 (14.25)$^B$ | 0.0005* |
| *Neck normalized EMG* | | | | |
| Right superior trapezius | 0.30 (0.20)$^B$ | 0.41 (0.23)$^A$ | 0.29 (0.15)$^B$ | 0.0066* |
| Left superior trapezius | 0.34 (0.21) | 0.36 (0.19) | 0.33 (0.23) | 0.7611 |
| *Neck posture (degrees)* | | | | |
| Maximum flexion | 21.55 (12.00)$^B$ | 41.58 (8.71)$^A$ | 43.08 (10.77)$^A$ | 0.0001* |
| Maximum extension | 8.86 (11.79)$^B$ | 25.76 (9.95)$^A$ | 22.96 (14.58)$^A$ | 0.0002* |
| Maximum right side bend | 3.07 (14.35) | 3.99 (11.93) | 4.83 (14.14) | 0.9059 |
| *Wrist posture (degrees)* | | | | |
| Maximum right radial | 0.04 (8.83) | 3.97 (12.87) | 1.33 (16.04) | 0.4193 |
| Maximum right ulnar | 24.74 (8.31) | 29.45 (11.15) | 28.80 (10.30) | 0.0754 |
| Maximum left radial | 5.37 (11.30) | 7.83 (12.87) | 6.32 (14.36) | 0.6258 |
| Maximum left ulnar | 23.36 (11.23)$^C$ | 26.65 (10.72)$^B$ | 34.33 (10.54)$^A$ | 0.0001* |
| Maximum right flexion | 35.04 (20.12) | 39.06 (19.23) | 30.16 (18.06) | 0.0520 |
| Maximum right extension | 19.10 (15.32) | 12.29 (17.18) | 15.66 (17.64) | 0.3014 |
| Maximum left flexion | 44.96 (11.09)$^A$ | 48.99 (8.61)$^A$ | 33.52 (13.74)$^B$ | 0.0001* |
| Maximum left extension | 1.89 (21.13)$^B$ | 15.63 (29.20)$^A$ | 22.51 (26.22)$^A$ | 0.0001* |

NOTE: *p*-values in differences among angles, * indicates statistical significance at alpha = 0.05. Letter (A,B,C) indicate statically significant different exposure among the angle.

were set using the standard lifting exertions (Fathallah et al., 1997) in conjunction with an optimization testing scheme (Prahbu, 2005). Finally, the Xsens sensors and goniometers were placed on the subject and data collection began. Data were collected at 1000 Hz via hard wire cable using custom laboratory software.

### 2.6. Testing

The order of the regions was completely randomized using a random number generator and each region had one installation task for the subjects to perform. The installation tasks were side airbag install, seat belt install, wiring harness install, wheel well liner install, fuel canister install, wiper motor install and brake-line install, for region 1–7, respectively. All tasks were actual assembly tasks simulated for the study and all subjects performed all trials. Time markers were used during the trial to indicate when the worker/subject was performing the task. The study took place at the Center for Occupational Health in Automotive Manufacturing (COHAM), a laboratory at The Ohio State University. The installation tasks required 25–55 s depending on the task. Both the experienced and inexperienced subjects had to complete the task within the time given for that task. The rotation angles were randomized for each region and three repetitions of each trial were collected. Subjects began and ended each trial standing erect with their hands at their sides in order to record a neutral reference. There were usually a couple minutes between trials of the same task and several minutes between regions. The testing session required a complete 8 h day with set up time and lunch break.

### 2.7. Data analysis

The raw EMG signals were pre-amplified, high pass filtered at 15 Hz and low pass filtered at 1000 Hz, rectified, and then processed with a 20 ms sliding window. The normalized EMG and kinematic data were imported into the EMG-assisted model using MSC.ADAMS software (MSC Software, 2008). The EMG-assisted biomechanical model was used to estimate the spine forces resulting during the assembly tasks (Marras and Sommerich 1991a,b; Granata and Marras 1993; Granata and Marras 1995; Marras and Granata 1995, 1997a,b; Davis, Marras et al., 1998; Knapik and Marras 2009. Shoulder, neck and wrist angles were calculated using cardan angles (Tupling and Pierrynowski, 1987). All shoulder and neck emg data was normalized to maximum exertions for that muscle.

### 2.8. Statistical analysis

General linear models were developed (SAS Institute, Cary, NC) for each dependent measure to determine if there was a statistically significant change due to angle. Test statements were used to specify the error term also post hoc Ryan–Einot–Gabriel–Welsch multiple range tests were employed to determine significant

**Table 3**
Means (standard deviation) and *p*-values for dependent measures during assembly in the interior low height, center reach region.

| | Auto | Rotation | Angles | *P*-values |
|---|---|---|---|---|
| | Horizontal (0°) | Fifteen (15°) | Forty-five (45°) | |
| Dependent measures | | | | |
| *Spine loads (N)* | | | | |
| Compression (L5/S1) | 1820.26 (641.96)$^A$ | 1706.91 (422.84)$^A$ | 1325.17 (407.07)$^B$ | 0.0002* |
| Lateral shear (L2/L3) | 274.90 (150.61) | 295.51 (103.37) | 267.28 (89.26) | 0.7489 |
| A/P shear (L2/L3) | 770.05 (387.36)$^B$ | 941.56 (279.01)$^A$ | 843.44 (276.23)$^{AB}$ | 0.0193* |
| *Spine posture (degrees)* | | | | |
| Maximum flexion | 47.83 (7.56)$^A$ | 25.48 (6.44)$^B$ | 14.16 (6.20)$^C$ | 0.0001* |
| Maximum lateral bend | 10.35 (4.07) | 9.83 (3.51) | 10.31 (4.58) | 0.6082 |
| Maximum twist | 8.43 (3.97) | 9.11 (3.63) | 9.87 (2.91) | 0.6050 |
| *Shoulder normlized EMG* | | | | |
| Right lateral deltoid | 0.62 (0.17)$^A$ | 0.56 (0.15)$^{AB}$ | 0.49 (0.17)$^B$ | 0.0125* |
| Left lateral deltoid | 0.30 (0.17)$^A$ | 0.33 (0.15)$^A$ | 0.22 (0.13)$^B$ | 0.0081* |
| Right anterior deltoid | 0.38 (0.15) | 0.40 (0.13) | 0.33 (0.11) | 0.0861 |
| Left anterior deltoid | 0.29 (0.13) | 0.32 (0.13) | 0.29 (0.09) | 0.4088 |
| *Shoulder posture (degrees)* | | | | |
| Max right shoulder flexion | 121.49 (21.26)$^A$ | 110.72 (20.94)$^{AB}$ | 105.30 (27.35)$^B$ | 0.0232* |
| Max left shoulder flexion | 99.38 (16.94)$^A$ | 97.18 (12.10)$^A$ | 85.38 (16.43)$^B$ | 0.0036* |
| Max right shoulder abduction | 40.77 (15.79) | 48.32 (17.01) | 50.65 (20.59) | 0.1417 |
| Max left shoulder abduction | 28.94 (21.54)$^B$ | 43.57 (19.68)$^A$ | 43.96 (18.94)$^A$ | 0.0211* |
| *Neck normalized EMG* | | | | |
| Right superior trapezius | 0.28 (0.15) | 0.32 (0.16) | 0.28 (0.13) | 0.1406 |
| Left superior trapezius | 0.18 (0.10)$^B$ | 0.27 (0.14)$^A$ | 0.22 (0.12)$^B$ | 0.0058* |
| *Neck posture (degrees)* | | | | |
| Maximum flexion | −9.36 (13.39)$^A$ | 14.45 (11.49)$^B$ | 24.26 (13.82)$^C$ | 0.0001* |
| Maximum extension | −40.03 (14.55)$^A$ | −26.20 (10.57)$^B$ | −21.76 (8.81)$^B$ | 0.0001* |
| Maximum right side bend | 11.26 (17.47) | 12.98 (17.47) | 16.85 (9.69) | 0.3694 |
| *Wrist posture (degrees)* | | | | |
| Maximum right radial | 13.08 (6.66) | 10.95 (7.75) | 10.94 (6.25) | 0.3768 |
| Maximum right ulnar | 28.29 (7.55) | 29.03 (6.54) | 30.77 (7.22) | 0.1583 |
| Maximum left radial | 12.81 (10.87) | 11.57 (8.00) | 11.96 (8.68) | 0.8466 |
| Maximum left ulnar | 24.88 (11.78) | 26.41 (10.18) | 26.06 (9.02) | 0.6765 |
| Maximum right flexion | 23.48 (13.56)$^B$ | 29.78 (12.55)$^A$ | 33.86 (11.45)$^A$ | 0.0057* |
| Maximum right extension | 51.23 (14.03) | 45.06 (12.11) | 46.37 (9.86) | 0.1183 |
| Maximum left flexion | 22.72 (20.63)$^B$ | 45.60 (15.13)$^A$ | 26.75 (13.96)$^B$ | 0.0001* |
| Maximum left extension | 45.19 (16.20) | 46.72 (11.85) | 49.89 (10.10) | 0.4402 |

NOTE: *p*-values in differences among angles, * indicates statistical significance at alpha = 0.05. Letter (A,B,C) indicate statically significant different exposure among the angle.

differences among the three rotation angles. The goal of the project was to evaluate differences due to rotation angle not to examine differences among the regions therefore no analyses were performed among the different regions of the vehicle. There was also no analysis between experience and inexperience.

## 3. Results

The means and standard deviations for all dependent measures in all regions are listed in Tables 1–7. The tables also list *p*-values with a significance indicator. Letters indicate significant differences for each dependent measure among the three rotation angles. It should be noted that the spine loading model generates spine loads from L5/S1 to L1/T12 however in the interest of space and to present whole body results only one spine level was presented here.

### 3.1. Interior regions

#### 3.1.1. Region 1: interior high height, edge reach

Table 1 shows there were significant differences between the standard task and the rotate angles in spine loads, spine posture, right shoulder muscle activity and right shoulder flexion. Four of the six (67%) spine measures showed significant differences. Spine compression decreased by approximately 300 N and anterior/posterior shear decreased by approximately 100 N as the vehicle was rotated from standard horizontal position to 45° or 60°. Normalized right shoulder muscle activity decreased by nearly half in both the lateral and anterior deltoid. It should be noted that there were no differences in neck muscle activity or neck posture among the conditions. Left wrist flexion and ulnar motion increased as the vehicle was rotated. Note that there were no significant differences between 45° and 60° conditions for any of the dependent measures.

#### 3.1.2. Region 2: interior low height, edge reach

Four of the six (67%) spine measures were significantly influenced by vehicle rotation as indicated in Table 2. Lateral shear load was significantly reduced as the vehicle was rotated from 0° to 15° and again from 15° to 45°. Right shoulder flexion posture also decreased significantly as the vehicle was rotated from 0° to 15° and again from 15° to 45°. Neck posture however showed a significant increase in flexion as the vehicle was rotated from 0° to 15° degrees and no change with further rotation to 45°.Also, the positive numbers in the neck extension indicate that the neck was in flexion during the task and not extension. There were significant changes in the left wrist posture but not the right wrist posture.

#### 3.1.3. Region 3: interior low height, center reach

The means (standard deviations) and *p*-values indicating significant differences among the three rotations angles of assembly are listed in Table 3. Three of the six (50%) spine measures showed

**Table 4**
Means (standard deviation) and *p*-values for dependent measures during assembly in the underbody edge region.

| | Auto | Rotation | Angles | *P*-values |
|---|---|---|---|---|
| | Horizontal (0°) | Forty-five (45°) | Ninety (90°) | |
| Dependent measures | | | | |
| *Spine loads (N)* | | | | |
| Compression (L5/S1) | 975.01 (403.98) | 948.73 (309.51) | 869.39 (304.44) | 0.1208 |
| Lateral shear (L2/L3) | 202.15 (127.91)$^{A}$ | 126.95 (37.96)$^{B}$ | 116.71 (43.04)$^{B}$ | 0.0082* |
| A/P shear (L2/L3) | 717.08 (262.07)$^{A}$ | 652.04 (201.64)$^{B}$ | 612.70 (196.15)$^{B}$ | 0.0242* |
| *Spine posture (degrees)* | | | | |
| Maximum flexion | 15.23 (4.34)$^{A}$ | 13.97 (7.13)$^{A}$ | 8.10 (3.67)$^{B}$ | 0.0011* |
| Maximum lateral bend | 10.00 (4.03)$^{A}$ | 7.60 (3.27)$^{B}$ | 6.22 (2.64)$^{B}$ | 0.0002* |
| Maximum twist | 10.66 (3.88)$^{A}$ | 9.11 (3.30)$^{B}$ | 7.55 (2.80)$^{C}$ | 0.0005* |
| *Shoulder normlized EMG* | | | | |
| Right lateral deltoid | 0.32 (0.22)$^{A}$ | 0.15 (0.10)$^{B}$ | 0.18 (0.13)$^{B}$ | 0.0010* |
| Left lateral deltoid | 0.08 (0.06) | 0.06 (0.03) | 0.05 (0.03) | 0.0827 |
| Right anterior deltoid | 0.58 (0.26)$^{A}$ | 0.39 (0.17)$^{B}$ | 0.36 (0.18)$^{B}$ | 0.0166* |
| Left anterior deltoid | 0.28 (0.20)$^{A}$ | 0.24 (0.18)$^{AB}$ | 0.19 (0.10)$^{B}$ | 0.0140* |
| *Shoulder posture (degrees)* | | | | |
| Max right shoulder flexion | 92.77 (30.75)$^{A}$ | 68.53 (20.36)$^{B}$ | 68.19 (17.34)$^{B}$ | 0.0001* |
| Max left shoulder flexion | 70.08 (23.55)$^{A}$ | 50.73 (21.34)$^{B}$ | 44.18 (19.80)$^{B}$ | 0.0001* |
| Max right shoulder abduction | 39.21 (26.84) | 20.60 (10.47) | 24.37 (11.91) | 0.0607 |
| Max left shoulder abduction | 21.55 (24.32) | 14.57 (11.92) | 20.76 (17.98) | 0.1455 |
| *Neck normalized EMG* | | | | |
| Right superior trapezius | 0.26 (0.16)$^{A}$ | 0.17 (0.09)$^{B}$ | 0.17 (0.09)$^{B}$ | 0.0210* |
| Left superior trapezius | 0.12 (0.08) | 0.10 (0.07) | 0.10 (0.08) | 0.2417 |
| *Neck posture (degrees)* | | | | |
| Maximum flexion | 27.04 (15.29) | 35.88 (15.93) | 28.60 (11.94) | 0.0659 |
| Maximum extension | −31.36 (14.27)$^{A}$ | −0.47 (14.87)$^{B}$ | −2.26 (13.19)$^{B}$ | 0.0001* |
| Maximum right side bend | 19.36 (9.8) | 15.10 (11.26) | 14.11 (10.43) | 0.2168 |
| *Wrist posture (degrees)* | | | | |
| Maximum right radial | 12.89 (7.10)$^{A}$ | 13.78 (8.84)$^{A}$ | 8.82 (8.54)$^{B}$ | 0.0058* |
| Maximum right ulnar | 28.46 (7.98)$^{B}$ | 29.45 (8.96)$^{B}$ | 32.22 (8.55)$^{A}$ | 0.0029* |
| Maximum left radial | 11.24 (7.67) | 14.14 (10.26) | 10.18 (11.02) | 0.1590 |
| Maximum left ulnar | 25.24 (7.50) | 24.05 (7.59) | 25.04 (7.23) | 0.3279 |
| Maximum right flexion | 11.68 (8.93) | 11.72 (10.33) | 12.42 (8.39) | 0.8782 |
| Maximum right extension | 67.85 (12.70) | 68.32 (14.21) | 61.90 (14.13) | 0.0514 |
| Maximum left flexion | 12.67 (11.25) | 11.25 (11.84) | 10.21 (13.08) | 0.8979 |
| Maximum left extension | 53.08 (14.80) | 52.05 (15.30) | 49.42 (15.77) | 0.1258 |

NOTE: *p*-values in differences among angles, * indicates statistical significance at alpha = 0.05. Letter (A,B,C) indicate statically significant different exposure among the angle.

significant differences. Compression decreased significantly from 15° to 45°. Anterior/posterior shear increased significantly from zero to 15°. Review of the video showed that this was due to the worker's supporting their trunk at zero with their arm on the floor of the vehicle. Sagittal flexion decreased significantly from 0° to 15° and again from 15° to 45°. Shoulder muscle activity significantly decreased at 45° compared to the standard zero condition. Shoulder flexion significantly decreased at 45° as well however, left shoulder abduction increased significantly at 45°. The neck posture results showed a significant change in neck flexion and extension toward less neck extension and greater neck flexion as the car was rotated from zero to 45°. The right and left wrist flexion measures both significantly changed among the three rotation angles. The right wrist was flexed significantly more during rotated conditions compared to the horizontal condition. The left wrist had significantly greater flexion at 15° of vehicle rotation but showed no difference between the standard horizontal and 45° condition.

### 3.2. Underbody regions

#### 3.2.1. Region 4: underbody, edge

Table 4 lists the means, standard deviations and *p*-values for significant difference among the three assembly conditions. Table 4 indicates that five of the six (83%) spine measures changed significantly as a function of the rotation angle. The means show that the 90° condition had the lowest exposure values for all spine measures. Five of the eight (62%) shoulder measures changed significantly as the vehicle rotated from zero to 45°. Right lateral deltoid muscle activity decreased by half as the vehicle was rotated from 0° to 45°. Right and left shoulder flexion decreased by approximately 25° as the vehicle was rotated from 0° to 45°. There was no significant change between 45° and 90° for shoulder measures. Neck extension and right superior trapezius muscle activity were significantly reduced when the vehicle was rotated from 0° to 45° degrees. Right radial/ulnar wrist motion changed significantly as the vehicle was rotated from 45° to 90°. There was a decrease in radial motion and an increase in ulnar motion indicating a trade-off in motion of the wrist between radial and ulnar motion.

#### 3.2.2. Region 5: underbody, center

Table 5 lists the means, standard deviations and *p*-values for all the spine, shoulder, neck and wrist exposure measures during the underbody center assembly task. Three of the six (50%) spine measures changed significantly as the vehicle rotated. Lateral shear, maximum flexion and lateral bending significantly decreased as the vehicle was rotated from the standard to 45°. There were no significant differences in spine measures between the two rotated conditions. Six of the eight (75%) shoulder measures were significantly influenced by the vehicle rotation. Right and left lateral and

**Table 5**
Means (standard deviation) and *p*-values for dependent measures during assembly in the underbody center region.

| | Auto | Rotation | Angles | *P*-values |
|---|---|---|---|---|
| | Horizontal (0°) | Forty-five (45°) | Ninety (90°) | |
| Dependent measures | | | | |
| *Spine loads (N)* | | | | |
| Compression (L5/S1) | 1619.87 (808.07) | 1219.31 (368.12) | 1310.57 (365.63) | 0.1508 |
| Lateral shear (L2/L3) | 300.60 (149.66)$^{A}$ | 178.14 (52.86)$^{B}$ | 193.99 (59.24)$^{B}$ | 0.0014* |
| A/P shear (L2/L3) | 1075.69 (412.61) | 852.67 (257.49) | 872.61 (274.46) | 0.0634 |
| *Spine posture (degrees)* | | | | |
| Maximum flexion | 22.39 (9.82)$^{A}$ | 15.43 (7.76)$^{B}$ | 13.08 (7.57)$^{B}$ | 0.0094* |
| Maximum lateral bend | 12.06 (4.47)$^{A}$ | 9.88 (3.24)$^{B}$ | 9.24 (2.64)$^{B}$ | 0.0326* |
| Maximum twist | 7.22 (3.01) | 7.47 (2.92) | 7.33 (2.95) | 0.9147 |
| *Shoulder normlized EMG* | | | | |
| Right lateral deltoid | 0.25 (0.15)$^{A}$ | 0.15 (0.08)$^{B}$ | 0.11 (0.07)$^{B}$ | 0.0005* |
| Left lateral deltoid | 0.17 (0.10)$^{A}$ | 0.08 (0.05)$^{B}$ | 0.07 (0.05)$^{B}$ | 0.0001* |
| Right anterior deltoid | 0.46 (0.19)$^{A}$ | 0.34 (0.17)$^{B}$ | 0.26 (0.06)$^{C}$ | 0.0001* |
| Left anterior deltoid | 0.58 (0.19)$^{A}$ | 0.37 (0.14)$^{B}$ | 0.31 (0.11)$^{B}$ | 0.0001* |
| *Shoulder posture (degrees)* | | | | |
| Max right shoulder flexion | 93.55 (23.77)$^{A}$ | 66.18 (9.89)$^{B}$ | 54.27 (13.89)$^{C}$ | 0.0001* |
| Max left shoulder flexion | 85.27 (25.59)$^{A}$ | 53.27 (14.48)$^{B}$ | 45.88 (6.40)$^{B}$ | 0.0001* |
| Max right shoulder abduction | 18.58 (25.74) | 7.05 (10.19) | 9.60 (11.91) | 0.0968 |
| Max left shoulder abduction | 1.76 (12.53) | 3.82 (15.35) | 6.08 (10.21) | 0.0752 |
| *Neck normalized EMG* | | | | |
| Right superior trapezius | 0.23 (0.10)$^{A}$ | 0.19 (0.10)$^{B}$ | 0.17 (0.08)$^{B}$ | 0.0082* |
| Left superior trapezius | 0.20 (0.12) | 0.17 (0.14) | 0.17 (0.09) | 0.3002 |
| *Neck posture (degrees)* | | | | |
| Maximum flexion | −14.86 (11.94)$^{A}$ | 5.59 (12.56)$^{B}$ | 9.41 (8.75)$^{B}$ | 0.0001* |
| Maximum extension | −39.96 (10.02)$^{A}$ | −21.17 (9.45)$^{B}$ | −11.58 (11.00)$^{C}$ | 0.0001* |
| Maximum right side bend | 12.00 (12.43) | 13.94 (10.20) | 16.11 (7.31) | 0.4745 |
| *Wrist posture (degrees)* | | | | |
| Maximum right radial | 16.80 (7.52)$^{A}$ | 13.58 (4.90)$^{B}$ | 10.02 (5.33)$^{C}$ | 0.0006* |
| Maximum right ulnar | 12.75 (11.48) | 11.72 (10.40) | 13.34 (8.44) | 0.8723 |
| Maximum left radial | 23.03 (9.44)$^{A}$ | 18.24 (11.19)$^{B}$ | 14.43 (11.89)$^{C}$ | 0.0001* |
| Maximum left ulnar | 9.97 (15.57)$^{C}$ | 16.86 (10.92)$^{B}$ | 28.63 (13.20)$^{A}$ | 0.0001* |
| Maximum right flexion | 21.75 (21.90) | 19.58 (16.28) | 15.31 (14.24) | 0.1369 |
| Maximum right extension | 69.84 (10.25)$^{A}$ | 61.22 (11.85)$^{B}$ | 55.32 (9.80)$^{C}$ | 0.0001* |
| Maximum left flexion | 14.90 (17.05)$^{A}$ | 5.91 (20.19)$^{B}$ | 3.32 (12.23)$^{B}$ | 0.0325* |
| Maximum left extension | 61.51 (10.77)$^{A}$ | 56.04 (11.24)$^{B}$ | 47.03 (9.49)$^{C}$ | 0.0001* |

NOTE: *p*-values in differences among angles, * indicates statistical significance at alpha = 0.05. Letter (A,B,C) indicate statically significant different exposure among the angle.

anterior deltoid muscle activity decreased significantly as the vehicle rotated from 0° to 45°. The right anterior deltoid also had a significant decrease in muscle activity level as the vehicle was rotated from 45° to 90°. Right and left shoulder flexion decreased by approximately 30° as the vehicle was rotated and had the lowest exposure at 90° of vehicle rotation. Neck extension decreased significantly from nearly 40° at the standard assembly condition to just 11° at the 90° vehicle rotation angle. In the standard horizontal assembly condition the neck is actually in extension and not flexion as indicated by the maximum neck position of −14.86°. Six of the eight wrist measures were significantly influenced by vehicle rotation. All four left wrist measures were significantly influenced where as only two of the right wrist measures were influenced by vehicle rotation. The wrist extension and radial position (both left and right) decreased significantly as the vehicle rotated from 0° to 45° and from 45° to 90°. The left wrist had a significant increase in ulnar motion as the vehicle rotated from 0° to 45° and from 45° to 90°.

## 3.3. Engine regions

### 3.3.1. Region 6: engine room, firewall

The means, standard deviation and *p*-values indicating significant differences among the assembly rotation angles for the engine room firewall region are listed in Table 6. Table 6 shows numerous significant differences among the spine, shoulder, neck and wrist measures. In all musculoskeletal risk measures the pattern of significant differences was similar. There was a significant reduction in exposure as the vehicle was rotated from zero to 45° but no change in exposure as the car was rotated from 45° to 60°.

### 3.3.2. Region 7: engine room, front bumper

The standard assembly process in the engine room front bumper region must be performed with the worker standing in front of the vehicle, in order to see the process, however once the vehicle was rotated this is not necessary. Table 7 lists the means, standard deviations, and *p*-values for differences among the three vehicle rotation angles. Five of the six (83%) spine measures were significantly influenced by vehicle rotation angle. Spine compression, lateral shear and spine flexion all showed a significant decrease from 0° to 45° and from 45° to 90°. Seven of the eight (88%) shoulder measures had a significant change due to vehicle rotation angle. All four shoulder muscles as well as shoulder flexion (right and left) decreased significantly as the vehicle was rotated from 0° to 45° but no change from 45° to 90°. The means show that right shoulder flexion decreased by more than 50° in the ninety degree assembly condition compared to the standard horizontal condition. Four of the five neck measures were significantly influenced by vehicle rotation. Both right and left superior trapezius muscle activity levels decreased significantly and at the 90° assembly condition muscle activity level

**Table 6**
Means (standard deviation) and *p*-values for dependent measures during assembly in the engine room firewall, side fender region.

| | Auto Horizontal (0°) | Rotation Forty-five (45°) | Angles Sixty (60°) | *P*-values |
|---|---|---|---|---|
| Dependent measures | | | | |
| *Spine loads (N)* | | | | |
| Compression (L5/S1) | 1765.28 (691.17)$^{A}$ | 1159.06 (464.33)$^{B}$ | 1087.23 (442.75)$^{B}$ | 0.0001* |
| Lateral shear (L2/L3) | 329.91 (134.03)$^{A}$ | 148.84 (72.18)$^{B}$ | 144.23 (96.36)$^{B}$ | 0.0001* |
| A/P shear (L2/L3) | 1057.54 (383.66)$^{A}$ | 728.66 (281.97)$^{B}$ | 689.33 (274.48)$^{B}$ | 0.0001* |
| *Spine posture (degrees)* | | | | |
| Maximum flexion | 18.72 (6.47) | 19.09 (7.29) | 15.76 (9.24) | 0.1901 |
| Maximum lateral bend | 11.66 (2.78)$^{A}$ | 8.05 (3.46)$^{B}$ | 7.16 (3.57)$^{B}$ | 0.0001* |
| Maximum twist | 10.83 (4.86)$^{A}$ | 5.70 (2.04)$^{B}$ | 5.13 (2.45)$^{B}$ | 0.0003* |
| *Shoulder normlized EMG* | | | | |
| Right lateral deltoid | 0.31 (0.15)$^{A}$ | 0.13 (0.08)$^{B}$ | 0.11 (0.06)$^{B}$ | 0.0001* |
| Left lateral deltoid | 0.37 (0.25)$^{A}$ | 0.07 (0.06)$^{B}$ | 0.07 (0.04)$^{B}$ | 0.0001* |
| Right anterior deltoid | 0.29 (0.08)$^{A}$ | 0.17 (0.06)$^{B}$ | 0.17 (0.07)$^{B}$ | 0.0001* |
| Left anterior deltoid | 0.51 (0.21)$^{A}$ | 0.26 (0.10)$^{B}$ | 0.29 (0.15)$^{B}$ | 0.0001* |
| *Shoulder posture (degrees)* | | | | |
| Max right shoulder flexion | 96.28 (23.43)$^{A}$ | 51.25 (10.79)$^{B}$ | 56.30 (17.83)$^{B}$ | 0.0001* |
| Max left shoulder flexion | 94.86 (25.30)$^{A}$ | 56.84 (11.31)$^{B}$ | 54.45 (10.87)$^{B}$ | 0.0001* |
| Max right shoulder abduction | 45.37 (30.87)$^{A}$ | 18.65 (11.02)$^{B}$ | 22.39 (14.50)$^{B}$ | 0.0001* |
| Max left shoulder abduction | 51.50 (29.92)$^{A}$ | 14.52 (9.39)$^{B}$ | 14.62 (10.06)$^{B}$ | 0.0001* |
| *Neck normalized EMG* | | | | |
| Right superior trapezius | 0.36 (0.21)$^{A}$ | 0.15 (0.08)$^{B}$ | 0.18 (0.11)$^{B}$ | 0.0001* |
| Left superior trapezius | 0.44 (0.23)$^{A}$ | 0.15 (0.07)$^{B}$ | 0.16 (0.08)$^{B}$ | 0.0001* |
| *Neck posture (degrees)* | | | | |
| Maximum flexion | 12.90 (11.86)$^{A}$ | 26.03 (10.42)$^{B}$ | 26.71 (10.46)$^{B}$ | 0.0002* |
| Maximum extension | −23.17 (13.39)$^{A}$ | 0.25 (8.66)$^{B}$ | 1.80 (6.94)$^{B}$ | 0.0001* |
| Maximum right side bend | 5.03 (6.17) | 5.76 (8.99) | 3.58 (7.13) | 0.3851 |
| *Wrist posture (degrees)* | | | | |
| Maximum right radial | 7.99 (10.34) | 9.89 (7.38) | 11.56 (5.91) | 0.4012 |
| Maximum right ulnar | 26.38 (8.99) | 26.88 (6.14) | 29.55 (8.49) | 0.1805 |
| Maximum left radial | 7.09 (20.21) | 11.36 (11.80) | 12.37 (10.77) | 0.1572 |
| Maximum left ulnar | 27.37 (14.01) | 28.51 (10.93) | 30.88 (10.83) | 0.1807 |
| Maximum right flexion | 26.74 (14.18)$^{A}$ | 9.42 (16.93)$^{B}$ | 11.01 (18.02)$^{B}$ | 0.0003* |
| Maximum right extension | 41.48 (15.69)$^{A}$ | 48.91 (19.74)$^{B}$ | 50.17 (17.91)$^{B}$ | 0.0016* |
| Maximum left flexion | 23.86 (20.67)$^{A}$ | 12.81 (17.07)$^{B}$ | 15.93 (19.81)$^{AB}$ | 0.0456* |
| Maximum left extension | 16.38 (18.94)$^{A}$ | 39.96 (7.90)$^{B}$ | 42.95 (10.29)$^{B}$ | 0.0001* |

NOTE: *p*-values in differences among angles, * indicates statistical significance at alpha = 0.05. Letter (A,B,C) indicate statically significant different exposure among the angle.

were less than 10% of maximum. Six of the eight (75%) wrist measures were significantly influence by vehicle rotation angle. Right wrist extension decreased by more than half as the vehicle was rotated from the standard assembly condition to either of the rotated conditions. Review of the video showed that workers supported their body with the right arm during the standard condition resulting in extreme wrist extension and in the rotated assembly conditions this was not necessary.

## 4. Discussion

This was the first study to examine the rotate carrier intervention tool. In general the rotate body conditions reduced the musculoskeletal demand compared to the standard assembly condition. Tables 1–7 showed statistically significant reductions in exposure measures due to rotation of the vehicle. However, the question remains whether the reduction in exposure was enough or does more need to be done to reduce the risk of specific MSDs.

The spine loads in Tables 1–7 may be compared to known risk values of spine loading. For compressive spine load, 3400 N is the known risk level at which microfactures can begin to occur. In all regions regardless of rotation angle the compressive load is below the 3400 N limit. Shear loads greater than 1000 N cause injury with cyclic loading as would occur in automotive assembly tasks (McGill, 2002). Lateral shear does not reach the 1000 N limit in any of the region. The mean anterior/posterior shear exceeds the 1000 N threshold in two regions during the standard assembly task. These regions are regions 5 underbody, center; and region 6 engine room, firewall. Vehicle rotation reduced the anterior/posterior mean shear loads to below the 1000 N threshold in these two regions. Thus, the rotate carrier appears to be an effective intervention tool for reducing spine loads and has the potential to reduce the risk of low back injury during certain assembly tasks.

The risk of MSDs to the shoulder was evaluated using shoulder posture as well as muscle activation levels. In all regions, at least one of the four shoulder muscles evaluated showed significant reduction in activation and shoulder flexion was also significantly reduced. Again, the rotate carrier was an effective intervention tool for reducing the physical demands on the shoulder during assembly tasks. Biomechanically, shoulder flexion and abduction affects the muscle length and when a muscle is stretched beyond the resting length, the strength capability of the muscle decreases (Gordon et al., 1966). The reduction in shoulder flexion and abduction found in several regions would improve the strength capabilities of the worker. However, further ergonomics changes may be needed to reduce exposure and MSD risk to the shoulder.

Muscle activation levels can also be examined in the shoulder muscles. At 10% of MVC, there is little mechanical hindrance of blood flow and metabolism is aerobic, thus this level of exertion would be considered safe (Sjogaard et al., 1988). Table 3 the interior low height, center reach region results indicate the right lateral deltoid muscle was at 62% of maximum for the horizontal condition

**Table 7**
Means (standard deviation) for dependent measures during the engine room from front bumper.

| | Auto | Rotation | Angles | *P*-values |
|---|---|---|---|---|
| | Horizontal (0°) | Forty-five (45°) | Ninety (90°) | |
| Dependent measures | | | | |
| *Spine loads (N)* | | | | |
| Compression (L5/S1) | 1446.25 (454.27)$^A$ | 1181.77 (495.37)$^B$ | 959.65 (381.46)$^C$ | 0.0001* |
| Lateral shear (L2/L3) | 241.23 (78.60)$^A$ | 157.40 (84.35)$^B$ | 81.64 (33.08)$^C$ | 0.0001* |
| A/P shear (L2/L3) | 733.14 (300.92) | 698.70 (285.09) | 634.58 (240.60) | 0.1256 |
| *Spine posture (degrees)* | | | | |
| Maximum flexion | 26.09 (7.74)$^A$ | 15.12 (5.14)$^B$ | 8.66 (4.64)$^C$ | 0.0001* |
| Maximum lateral bend | 10.07 (4.67)$^A$ | 8.21 (4.19)$^A$ | 3.69 (1.71)$^B$ | 0.0010* |
| Maximum twist | 14.75 (5.5)$^A$ | 5.78 (3.68)$^B$ | 5.26 (2.74)$^B$ | 0.0001* |
| *Shoulder normlized EMG* | | | | |
| Right lateral deltoid | 0.25 (0.15)$^A$ | 0.11 (0.08)$^B$ | 0.06 (0.04)$^B$ | 0.0001* |
| Left lateral deltoid | 0.45 (0.26)$^A$ | 0.07 (0.04)$^B$ | 0.07 (0.03)$^B$ | 0.0001* |
| Right anterior deltoid | 0.22 (0.10)$^A$ | 0.13 (0.10)$^B$ | 0.09 (0.09)$^B$ | 0.0011* |
| Left anterior deltoid | 0.37 (0.14)$^A$ | 0.19 (0.06)$^B$ | 0.16 (0.06)$^B$ | 0.0001* |
| *Shoulder posture (degrees)* | | | | |
| Max right shoulder flexion | 82.88 (31.82)$^A$ | 49.32 (34.55)$^B$ | 30.31 (28.24)$^C$ | 0.0001* |
| Max left shoulder flexion | 105.08 (17.06)$^A$ | 66.51 (10.72)$^B$ | 55.84 (12.65)$^C$ | 0.0001* |
| Max right shoulder abduction | 14.82 (20.94) | 6.41 (9.51) | 3.83 (11.96) | 0.1397 |
| Max left shoulder abduction | 32.70 (20.78)$^A$ | 11.78 (21.78)$^B$ | 4.63 (20.34)$^B$ | 0.0001* |
| *Neck normalized EMG* | | | | |
| Right superior trapezius | 0.16 (0.10)$^A$ | 0.17 (0.12)$^A$ | 0.08 (0.06)$^B$ | 0.0065* |
| Left superior trapezius | 0.23 (0.12)$^A$ | 0.15 (0.09)$^B$ | 0.07 (0.05)$^C$ | 0.0001* |
| *Neck posture (degrees)* | | | | |
| Maximum flexion | −11.50 (14.03)$^A$ | 11.54 (13.41)$^B$ | 20.44 (14.61)$^C$ | 0.0001* |
| Maximum extension | −29.97 (11.39)$^A$ | 0.83 (11.99)$^B$ | 6.81 (10.28)$^B$ | 0.0001* |
| Maximum right side bend | 6.00 (9.93) | 0.53 (5.91) | 8.08 (10.29) | 0.0974 |
| *Wrist posture (degrees)* | | | | |
| Maximum right radial | 7.10 (10.73)$^A$ | 6.04 (13.41)$^B$ | 2.24 (8.52)$^B$ | 0.0019* |
| Maximum right ulnar | 7.40 (8.21)$^A$ | 17.33 (15.01)$^B$ | 12.99 (12.02)$^{AB}$ | 0.0213* |
| Maximum left radial | 15.44 (7.70) | 10.86 (5.81) | 14.92 (7.01) | 0.1548 |
| Maximum left ulnar | 14.01 (7.83)$^A$ | 16.06 (11.38)$^A$ | 3.90 (10.55)$^B$ | 0.0023* |
| Maximum right flexion | 20.57 (17.68) | 5.84 (22.49) | 9.58 (11.95) | 0.0569 |
| Maximum right extension | 51.70 (17.87)$^A$ | 24.77 (25.11)$^B$ | 21.22 (17.44)$^B$ | 0.0040* |
| Maximum left flexion | 5.39 (8.61)$^A$ | 17.85 (15.02)$^B$ | 5.84 (13.49)$^A$ | 0.0004* |
| Maximum left extension | 39.98 (8.35)$^A$ | 27.17 (8.49)$^B$ | 40.02 (10.28)$^A$ | 0.0002* |

NOTE: *p*-values in differences among angles, * indicates statistical significance at alpha = 0.05. Letter (A,B,C) indicate statically significant different exposure among the angle.

and was reduced to 49% at the 45° condition, which is a significant decrease however, 49% is well above the 10% threshold value indicating a substantial risk of injury to the shoulder may still exist. Thus, the rotate carrier reduced shoulder exposure however, further interventions may be necessary to reduce the risk of shoulder MSDs. The effectiveness of the rotate carrier on reducing the risk of shoulder MSDs was dependent on the region of the vehicle.

MSDs of the neck were also assessed with posture and muscle activity measures. Neck inclination angles greater than 30° of flexion increased neck muscle fatigue (Chaffin, 1973). The means in Tables 1–7 may be compared to the 30° threshold. Examination of the tables shows that several of the regions have extreme neck extension rather than neck flexion in the standard horizontal assembly condition. In general the rotate body conditions reduced neck extension without causing extreme neck flexion exceeding the 30° threshold. Thus, the rotate carrier intervention appears to reduce the risk of MSD to the neck due to awkward posture.

MSDs of the wrist were examined with wrist posture measures. The National Institute of Occupational Safety and Health (1997) published a critical review of epidemiological literature indicating that greater than 45° flexion/extension of the wrist would create high risk of wrist disorders. These thresholds can be compared to the flexion/extension values in Tables 1–7. There are several wrist flexion/extension measures that have significant changes indicating that the rotate carrier influenced wrist posture. However, few of the

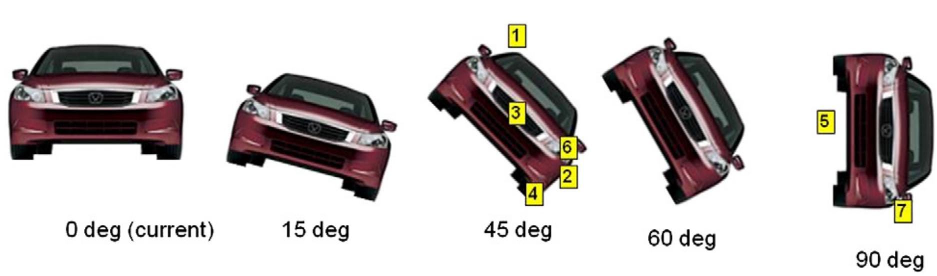


**Fig. 5.** All vehicle rotation angles evaluated. The rotation angle with the region number indicates the rotation angle that minimizes MSD exposure for that region.

flexion/extension measures cross the 45 threshold due to the rotation of the vehicle.

### 4.1. Application of results

In application at the plant floor it would not be possible to make an infinite number of adjustments to the angle of the assembly line also the whole body must be considered as one. Fig. 5 illustrates the assembly condition with the least amount of musculoskeletal demand for each region. The results of the two interior regions that were not reported middle height and middle reach as well as middle height edge reach had similar results to regions 2 and 3. It should be noted that this does not necessarily mean than all risk has been minimized with the use of the rotate carrier.

### 4.2. Interior processes

As illustrated in Fig. 5, the interior processes in general had the greatest reduction in MSD exposure at a vehicle rotation angle of 45°. In a plant setting the vehicle could be rotated 45° clockwise or counter-clockwise and remain at that angle for an extended length of the conveyor line and not need continuous adjustment.

#### 4.2.1. Underbody

The underbody edge region illustrated clear reduction in MSD exposure at 45° compared to 0°, however there was little difference between the two rotated conditions. Therefore, as indicated in Fig. 5 the underbody edge (region 4) could be grouped with the interior processes at 45°. The underbody center region had a clear reduction in MSD exposure at 90° compared to standard and 45°. Thus, in application workers would benefit from rotating the vehicle to 90°.

#### 4.2.2. Engine room

The engine room firewall results showed no difference between 45° and 60° but both showed significant reduction compared to the standard horizontal condition. Therefore, in practice region 6 could be added to the interior region of the vehicle with assembly tasks being completed at 45°, as indicated in Fig. 5.

The engine room front bumper region showed reduction in MSD risk at 45° compared to the standard and further reduction at 90° compared to 45°. In Fig. 5, region 7 was grouped with the underbody center region at 90°.

#### 4.2.3. Overall application

In application for all of the regions there would be two rotation angle 45° where 5 out of the seven regions would be assembled and 90° where the remaining 2 regions of the vehicle would be assembled. The one caveat is that the vehicle would need to be rotated both clockwise and counter-clockwise for the both angle (ie total of 4 locations).

In the interior regions of the vehicle the rotate body eliminates the worker getting in and out of the vehicle that may be required in the standard condition. Getting in and out of the vehicle may result in not only MSD but also other injuries (cuts, trauma). Furthermore, eliminating the in and out of the vehicle may also increased productivity. Thus, the rotate carrier would not only reduce the risk of MSDs, it would improve general safety and possibly enhance productivity.

### 4.3. Limitations

The first limitation is that only one assembly task was examined in each region of the vehicle. The task was selected to be a representative sample from that region of the vehicle however there might be some difference in task within that region of the vehicle. It would be too expensive to test every task in every region of the vehicle in order to determine the effectiveness of the rotate carrier intervention. Therefore, it is hypothesized that the task evaluated in the study may be representative of most tasks in that region of the vehicle.

The second limitation was that only six of the twelve subjects were experienced automotive assembly workers. In order to minimize the influence of the inexperienced subjects the inexperienced group received three training session compared to one for the experienced group.

The third limitation was that only one vehicle was used in the study. It may be hypothesized that the results may change as a function of the vehicle. This may be especially true for vehicles that are much larger or smaller than the vehicle tested. A four door sedan was used in the test thus the largest difference may be in two door compact vehicle and larger SUVs or Vans. Further testing would be necessary to quantify the influence of the vehicle on the results. Finally, the instrumentation may have influence the work style of the subjects. However, this would have influenced all the rotation angles equally so the effect was thought to be minimal.

## 5. Conclusions

Overall rotation of the vehicle reduced MSD exposure. Seven of the nine regions had the most reduction is MSD exposure and subsequent MSD risk reduction at 45° of rotation. Two of the seven regions had the most reduction in MSD exposure and subsequent MSD risk at 90° of vehicle rotation.

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