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Comparing Upper Arm and Trunk Kinematics between Manufacturing Workers Performing Predominantly Cyclic and Non-cyclic Work Tasks

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Abstract

Musculoskeletal disorders (MSDs) are common among manufacturing workers. Exposure to non-neutral postures and high movement speeds associated with MSDs among manufacturing workers may depend on the extent of the variability in the work tasks performed (i.e., predominantly “cyclic” versus “non-cyclic” work). The objectives of this study were to (i) compare mean levels of full-shift exposure summary metrics based on both posture and movement speed between manufacturing workers performing predominantly cyclic (n=18) and non-cyclic (n=17) tasks, and (ii) explore patterns of between- and within-worker exposure variance and between-minute (within-shift) exposure level and variation within each group. Inertial sensors were used to measure exposures for up to 15 full shifts per participant. Results indicated (i) substantially higher upper arm and trunk movement speeds among workers performing predominantly cyclic tasks relative to workers performing non-cyclic tasks despite similar postures, and (ii) greater exposure variability both between and within workers in the non-cyclic group.

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Keywords

musculoskeletal disorders; exposure variability; inertial measurement unit; posture; low back; shoulder

1. Introduction

Manufacturing workers are at risk of developing musculoskeletal disorders (MSDs) from repeated exposure to physical risk factors in their work environment (Gerr et al., 2014; Häkkänen et al., 2001; Punnett et al., 2004; Vandergrift et al., 2012), including non-neutral working postures and high movement speeds of the upper arms and trunk (Balogh et al., 2019; Bernard and Putz-Anderson, 1997; Coenen et al., 2013; da Costa and Vieira, 2010; Hoogendoorn et al., 2000; NRC-IOM., 2001; Svendsen et al., 2004; van der Molen et al., 2017; van Rijn et al., 2010). The magnitude and variability of exposures over time to non-neutral postures and high movement speeds among manufacturing workers likely depends on the extent of work "routinization" (Gold et al., 2006; Wells et al., 2007). In both research and practice settings, the extent of work routinization is often used to categorize manufacturing workers into one of two groups: those that predominantly complete more repetitive, "cyclic" assembly work (often machine-paced), or those that predominantly complete less repetitive, "non-cyclic" work (e.g., maintenance tasks and stocking workstations). The cyclic/non-cyclic grouping approach is often applied (perhaps inappropriately) to the design of interventions to prevent MSDs, such as job rotation schemes intended to "balance" physical exposure magnitudes and/or increase exposure variability among workers (Jorgensen et al., 2005; Leider et al., 2015a; Mathiassen, 2006; Padula et al., 2017; Triggs and King, 2000).

Several studies have provided valuable information regarding the magnitudes and variability of directly measured upper arm and trunk kinematic exposure metrics among many occupational groups (Barbieri et al., 2015; Barbieri et al., 2019; Kazmierczak et al., 2005; Liv et al., 2011; Mathiassen et al., 2012; Svendsen et al., 2005; Wahlström et al., 2016; Wahlström et al., 2010), although few have been performed in the manufacturing environment. Kersten and Fethke (2019) recently assessed exposure magnitudes and components of exposure variance associated with upper arm postures and movement speeds among manufacturing workers completing cyclic, machine-paced assembly work. Results of their study indicated that while full-shift exposure summary measures exhibited substantial between-day variability, between-day variability was greatly reduced when repeated observations of the same task within a shift were included in the statistical model. A notable strength of their study was the collection of 14 full shifts of exposure data per participant, whereas similar studies among other occupational groups have typically been limited to a maximum of four shifts (Liv et al., 2011; Liv et al., 2012; Mathiassen et al., 2012; Wahlström et al., 2010). However, the sample size in Kersten and Fethke (2019) was small (n=6) and the study did not include participants completing primarily non-cyclic work tasks.

Characterizing both the magnitude and variability over time of directly measured physical exposures is a key component of contemporary exposure assessment in ergonomics (Mathiassen et al., 2015). In this study, we categorized manufacturing workers into cyclic and non-cyclic groups and, for each worker, measured full-shift upper arm and trunk kinematics for up to 15 consecutive weekday work shifts. Our objectives were to (i) compare mean levels of full-shift exposure summary metrics based on both posture and movement speed between the cyclic and non-cyclic groups, and (ii) explore patterns of between- and within-worker exposure variance and between-minute (within-shift) exposure level and variation within each group. We hypothesized that mean levels of full-shift exposure summary metrics would differ significantly between the groups, generally in the direction of favoring the non-cyclic group (e.g., greater time with neutral postures and lower movement speeds). We also expected to observe greater exposure variability among the non-cyclic group compared to the cyclic group.

2. Methods

2.1. Participants and Work Group Characteristics

The manufacturing facility involved in this study employed approximately 450 workers across three eight-hour work shifts. Prior to any data collection, members of the research team toured the manufacturing facility and reviewed its production processes with the facility safety director. The research team and safety director agreed that employees could be broadly categorized into one of two work groups: those predominantly completing ‘cyclic’ and ’noncyclic’ work tasks. Consistent with Paulsen et al. (2014), cyclic work tasks were defined as those completed following standard production procedures and characterized by cycle times of less than approximately three minutes.

All employees were made aware of the study via recruitment letters, flyers, and word of mouth. Interested employees volunteered to be considered as a candidate for potential inclusion in the study by informing the facility safety director. The research team then randomly selected from the pool of interested candidates that were separated into the two categories of work groups by the facility safety director to achieve an equal sample in each group. The research team followed the safety director’s recommendations on work group categorization of employees given his experience at the facility (15+ years) and intimate knowledge of the work tasks comprising the various production lines. Participant exclusion criteria included any self-reported: (i) history of physician-diagnosed muscle or bone diseases in the low back, neck/shoulder, or upper extremity; (ii) “chronic” (i.e., constantly recurring) low back, neck/shoulder, or upper extremity pain during the previous 14 days; or (iii) history of a physician-diagnosed neurodegenerative disorder that may affect movement (e.g. Parkinson’s Disease, multiple sclerosis, etc.).

Thirty-six participants (18 cyclic, 18 non-cyclic) enrolled in the study (Table 1). One participant in the non-cyclic study group withdrew from participation during the first day of data collection and no data collected from that participant were analyzed. Data were collected for 15 consecutive weekday shifts from each of the remaining 35 participants. One of the 35 participants switched job titles following the 10^{th} shift of participation. No data from the five shifts following the job title change from this participant were included in the

analyses. Thus, 520 work shifts were considered in the analyses. Each participant provided written informed consent. The Auburn University Institutional Review Board approved all study procedures.

2.2. Data Collection and Processing

Participants were fitted with four ActiGraph GT9X Link inertial measurement units (IMUs; ActiGraph, Pensacola, Florida, USA) secured to elastic hook-and-loop fastener straps using hypoallergenic cohesive bandages each work shift (Figure 1). An IMU was worn on i) the anterior trunk over the sternum approximately between the sternal notch and the xiphoid process (depending on the anatomy and comfort of each participant) over an item of each participant's clothes; ii) on each upper arm approximately one-half the distance between the lateral epicondyle and the acromion (either on the skin or over a participant's clothes depending on comfort); and 3) on the dominant wrist (on the skin). Each IMU measured linear acceleration (±16 g), angular velocity (±2000 deg/sec), and magnetic field strength (±4800 μT) at a sampling rate of 100 Hz using a tri-axial accelerometer, gyroscope, and magnetometer.

A calibration procedure was performed immediately following the placement of all sensors at the beginning of each work shift. The calibration procedure involved asking participants to briefly stand in a neutral posture and perform three bends to between approximately 30-60° of trunk flexion. After the three trunk bends, each participant then performed three lateral arms raises from a neutral posture to approximately 90° relative to gravity. A research team member noted the time that the calibration procedure began. These calibration periods were reviewed in MATLAB and used to identify the beginning of data collection. Upon completing the calibration procedure, participants proceeded with their normal work shift.

At the conclusion of each shift, the raw IMU data were downloaded to a computer using ActiLife software (version 6.13.3, ActiGraph, LLC, Pensacola, FL). The raw IMU data were then exported to comma-separated files for offline processing. Inclination measurements of the upper arms and trunk were calculated using a computationally efficient first-order complementary filter that combined accelerometer and gyroscope measurements (Chen et al., 2020; Chen et al., 2018). No magnetometer data were used. The trunk inclination measurements (flexion/extension and lateral bending) were calibrated to register an inclination of 0° (i.e., aligned with gravity) when in the neutral calibration posture to compensate for differences in subject anatomy. Upper arm inclination (i.e., elevation) measurements were also relative to gravity; however, they were not aligned to a neutral posture. After calculating the inclination measurements, the data were then downsampled to 20 Hz using the resample function in MATLAB to improve computational speed during post-processing. Movement speeds (i.e., the absolute value of velocities) of the upper arms and trunk were calculated using the derivative of the upper arm and trunk posture waveforms with respect to time.

During each shift, participants logged in a pre-printed diary the times when work tasks were performed. The research team used information from the diaries to classify the work tasks into one of six categories. Tasks categorized as assembly or operating machinery were predominantly performed by participants in the cyclic group. Tasks categorized as

maintenance or set-up were predominantly performed by participants in the non-cyclic group. “Other” tasks that did not meet the primary task categories identified for each group were routinely performed by participants in both groups. All participants (cyclic and non-cyclic) were also asked to report their work breaks.

2.3 Data Quality

Of the 520 measured work shifts, 515 left arm, 517 right arm, and 477 trunk files were included in the final analysis. Instrumentation failures and data collection issues (e.g., participants removing/not wearing a sensor) led to the loss of the files not included in the analysis. In particular, the fastener straps used to secure the IMUs to the trunk were susceptible to shifting along the sternum. This led to 14 of the 43 removed trunk files being considered outliers (conservatively defined as measurements that were more than 1.5 times the interquartile range below the first quantile or more than 1.5 times the interquartile range above the third quantile for the 50^{th} percentile of posture across each respective participant’s 15 days of measurement). The location of the trunk sensor on the anterior sternum also led to occasional transient artifacts (i.e., the sensor being contacted). Of the 477 trunk data files included in the analysis, 72 (15%) required replacement of transient artifacts with the mean posture of the entire recording duration. On average, 99.49% of the original data from these 72 full trunk posture data files was retained for processing and analysis.

2.4. Exposure Metrics

Several common posture, movement speed, and rest/recovery exposure metrics were calculated using full-shift inclination and movement speed measurements (Barbieri et al., 2015; Jackson et al., 2020; Kazmierczak et al., 2005; Kersten and Fethke, 2019; Wahlström et al., 2010). For the upper arms, exposure metrics included the mean amplitude and the 10^{th}, 50^{th}, and 90^{th} percentiles of the posture and movement speed time-series waveforms. The percentage of time in neutral (<20°) and “extreme” (≥60°) upper arm posture angles as well as the percentage of time moving in low (<5°/s) and high movement speeds (≥90°/s) were calculated. ‘Posture variation,’ or the exposure range, was expressed as the difference between the 90^{th} and 10^{th} percentiles of posture; a similar measure was calculated for movement speed (Ciccarelli et al., 2014; Mathiassen, 2006; Mathiassen et al., 2012; Wahlström et al., 2010). Rest/recovery exposure metrics included the percentage of time in a neutral posture for ≥ 3s, the percentage of time moving at a low speed for ≥ 3s, and the percentage of time in both a neutral posture and moving at a low speed. Identical variables were used to describe trunk motion in the flexion/extension and lateral bending planes except that a neutral posture was defined as the range from −20° (extension or left lateral bending) to 20° (flexion or right lateral bending).

We also examined within-shift ‘exposure variability’ by (i) parsing each full-shift recording into non-overlapping one-minute windows, (ii) calculating the mean amplitude and 90^{th} – 10^{th} percentile range of both posture and movement speed within each one-minute window, and then (iii) calculating the standard deviation (SD) of the one-minute means (i.e., SD_{means}) and the SD of the one-minute 90^{th} – 10^{th} percentile ranges (i.e., SD_{ranges}) across the duration of the recording for both posture and movement speed. Conceptually, for any one participant, SD_{means} quantifies the between-minute dispersion of the average posture

and average movement speed, while SD_{ranges} quantifies the between-minute dispersion of the within-minute posture variation and movement speed variation (Barbieri et al., 2015; Jackson et al., 2020).

Information from the diaries completed by participants during each shift was used to generate a second dataset containing time-weighted averages of each posture and movement speed exposure metric by predominant task category. Only one time-weighted value for each task category per participant per shift was calculated for each exposure metric; however, not every participant performed every task associated with his/her group status (i.e., cyclic or non-cyclic) during each shift. Table 2 provides information about the number of time-weighted average task-based exposure estimates calculated, along with means and SDs of the total task durations, during a shift for the primary task categories.

2.5. Statistical Analysis

The mean and SD of each posture, movement, and rest/recovery exposure metric across participants were calculated by work group (i.e., cyclic vs. non-cyclic). Potential violations of the normality assumption for mixed-effect analysis of variance (ANOVA) were reviewed by examining distributions of the studentized conditional residuals for each exposure metric. Although the normality assumption was violated for some exposure metrics, particularly where skewing may be anticipated (e.g., percentage of time in an extreme posture), no transformations were applied to maintain consistency with previous studies (e.g., Kersten & Fethke, 2019) and because ANOVA models are generally regarded as being robust to violations of normality in the absence of bias (Blanca et al., 2017).

For each full-shift exposure metric, a hierarchical mixed-effects linear model was used to test the fixed effect of work group (cyclic vs. non-cyclic) on mean values of the exposure summary metrics. The model had the following general form:

$$y_{ijk} = \mu + \alpha_i + \beta_{j(i)} + \varepsilon_{k(ij)} \quad (1)$$

where y_{ijk} is the full-shift exposure metric value associated with the k^{th} shift on the jth subject within the i^{th} group, μ is the overall mean exposure metric value across all shifts, α_i is the fixed effect of group i, $\beta_{j(i)}$ is the random effect of subject j within group i, and the residual term, $\varepsilon_{k(ij)}$ is the random effect of shift k within both group i and subject j. Both random effects were assumed normally distributed, and observations from different participants were assumed independent. Non-independence of observations from the same participant (i.e., observations from different shifts) was modeled using the first-order autoregressive (AR(1)) covariance structure. The AR(1) structure was selected based on examining model fit using the Akaike Information Criterion. The dataset was unbalanced due to unequal numbers of shifts among the participants in each group. Therefore, the restricted maximum likelihood (REML) approach was used to fit the models. An alpha value of 0.05 was used for assessing statistical significance of the fixed effect of group.

Variance components associated with the random effects of subject (nested within group) and shift (nested within both group and subject) were also calculated (Rappaport et al., 1999; Searle et al., 2009). Model outputs included estimates of the variance between

subjects (S^2_{BS}, i.e., the variance of $\beta_{j(i)}$) and the variance between shifts within subject (S^2_{WS}, i.e., the variance of $\varepsilon_{k(ij)}$, as well as the Wald 95% confidence intervals around the estimated variances. For each exposure metric and separately for the cyclic and non-cyclic groups, the ratio of S^2_{WS} to S^2_{BS} was calculated as a measure of exposure homogeneity ($\lambda = S^2_{WS}/S^2_{BS}$) (Burdorf, 1992; Houba et al., 1997).

Finally, SD_{means} and SD_{ranges} for both posture and movement speed were summarized using means and SDs across participants, by work group. Although no formal inferential statistical procedures were applied, the results were used to make a qualitative assessment regarding differences in the within-shift exposure variability between the cyclic and non-cyclic work groups. Likewise, the task-based measures were used to add context to and assist in the interpretation of the observed differences in the full-shift exposure metrics between the cyclic and non-cyclic groups (i.e., it was not our objective to compare task-level exposures statistically).

All statistical procedures were performed using SAS (version 9.4, SAS Institute Inc., Cary, NC). The PROC MEANS procedure was used to calculate all presented means and SDs. The PROC MIXED procedure was used test the fixed effect of group for statistical significance and to estimate variance components (along with associated confidence intervals).

3. Results

3.1. Effect of Group (Cyclic vs. Non-Cyclic) on Full-Shift Exposure Metrics

3.1.1. Upper Arms—Means and SDs for each upper arm posture, movement speed, and rest/recovery exposure metric across the full work shifts by work group are provided in Tables 3 (for the left arm) and 4 (for the right arm). The fixed effect of group (cyclic vs. non-cyclic) was not statistically significant for any posture-based exposure metric. For example, both groups spent approximately 31-33 % time with the arms in a neutral posture, 7-8 % time with their arms in an extreme posture, and 18-21 % time with the arms in a neutral posture for substantial periods (≥ 3s). In contrast, the fixed effect of group was statistically significant for every exposure metric based solely on movement speed. For example, workers in the cyclic group moved approximately 10°/s faster at peak speeds (i.e., the 90th percentile left arm [39.14° vs. 29.80°; $F_{1,33} = 12.36$; $p < 0.01$] and right arm [41.78° vs. 31.68°; $F_{1,33} = 17.81$; $p < 0.01$] movement speeds), spent 13-14% less time moving at low speeds (left arm: [42.98° vs. 56.40°; $F_{1,33} = 25.96$; $p < 0.01$]; right arm: [40.50° vs. 54.35°; $F_{1,33} = 30.86$; $p < 0.01$]), and spent approximately half the percentage of time at low speed for ≥ 3s as the non-cyclic participants (left arm: [14.95° vs. 32.42°; $F_{1,33} = 35.85$; $p < 0.01$]; right arm: [13.89° vs. 29.18°; $F_{1,33} = 30.16$; $p < 0.01$]).

Measured differences between the groups in upper arm exposure metrics based on movement speed appeared to be a consequence of exposures while operating machinery and performing assembly tasks (Tables 5 and 6). While posture metrics were similar across the tasks regardless of group status, operating machinery and assembly work (performed mostly by those in the cyclic group) generally involved approximately 10-17 % less time spent at low speeds than maintenance and set-up activities (performed mostly by those in the non-cyclic group). The “other” activities performed by the cyclic workers also involved

approximately 10-12 % less time spent at low speeds relative to the non-cyclic workers. However, "other" activities comprised a substantially smaller proportion the shift among those in the cyclic group than among those in the non-cyclic group (see Section 2.4). Movement speeds during breaks were also similar between the groups (e.g., 3-5% difference in proportion of time spent working at low speeds).

3.1.2. Trunk—Means and SDs for each trunk posture, movement speed, and rest/recovery exposure metric across the full work shifts by work group are provided in Tables 7 (for flexion/extension) and 8 (for lateral bending). Similar to the upper arms, posture-based exposure summary metrics were generally similar between the two work groups. However, the effect of group was statistically significant in two cases: 1) for flexion/extension, posture variation (i.e., 90^{th} -10^{th} percentile) was greater among those in the non-cyclic group than among those in the cyclic group (35.56° vs. 28.86°; $F_{1,33} = 4.56$; $p = 0.04$); and 2) for lateral bending, the percentage of time with neutral posture for ≤ 3s was greater among those in the non-cyclic group than among those in the cyclic group (76.67% vs. 72.38%; $F_{1,33} = 4.57$; $p = 0.04$).

Several statistically significant differences were identified for movement speed metrics of the trunk. For example, non-cyclic workers spent a greater percentage of time working at low speeds (60.03% vs. 53.15%; $F_{1,33} = 7.16$; $p = 0.01$) and almost twice the percentage of time working at low speeds for three seconds or more (24.53% vs. 13.53%; $F_{1,33} = 12.98$; $p < 0.01$) relative to the cyclic workers for movements in the sagittal plane (i.e., flexion/extension).

Similar to the upper arms, differences in work activities (i.e., operating machinery and assembly activities completed primarily by the cyclic participants vs. maintenance and set-up activities completed primarily by the non-cyclic participants) contributed to the differences (Tables 9 and 10). Non-cyclic work tasks generally required a greater percentage of time moving at low speeds (56-59% vs. 47-53%) and almost twice the time spent working at low speeds for three seconds or more (19-22% vs. 10-11%) for movements in the sagittal plane (i.e., flexion/extension) than cyclic work tasks.

3.2. Variance Components and Exposure Homogeneity

For the upper arms (both left and right) and regardless of group status, the between-subjects variance component (S^2_{BS}) exceeded the within-subject (i.e., between-shifts) variance component (S^2_{WS}) for most posture, movement speed, and rest/recovery metrics (Tables 3 and 4). As the lone exception, among participants in the cyclic group, S^2_{WS} exceeded S^2_{BS} with respect to the percentage of time with low movement speed for ≥ 3s.

For the trunk, however, a more complex pattern of variance component estimates was observed than for the upper arms. Most notably, S^2_{WS} exceeded S^2_{BS} for the majority of posture-based metrics while S^2_{BS} exceeded S^2_{WS} for the majority of metrics based on movement speed (Tables 7 and 8), particularly for those in the non-cyclic group.

Patterns of differences between the cyclic and non-cyclic groups with respect to exposure homogeneity ($\lambda = S^2_{WS}/S^2_{BS}$) can also be observed in Figure 2. In general, median values

of λ across both posture-based metrics and metrics based on movement speed were greater for those in the cyclic group than for those in the non-cyclic group. The lone exception occurred for posture-based metrics of the left arm (i.e., median λ of the cyclic group < median λ of the non-cyclic group), which was the non-dominant arm among all participants except for one. Also, for both trunk flexion/extension and lateral bending, and for both the cyclic and non-cyclic groups, the median values of λ were >1.0 for posture-based metrics (implying homogeneous exposures) but ≤1.0 for metrics based on movement speed (implying heterogeneous exposures).

3.3. Within-Shift Exposure Variability

Table 11 provides means and SDs of SD_{means} and SD_{ranges}. Results suggest greater between-minute variability in both the average exposure levels and the within-minute exposure variation among those in the non-cyclic group compared to those in the cyclic group. The magnitude of the differences in mean SD_{means} and mean SD_{ranges} between the groups was generally greater for posture than for movement speed.

4. Discussion

The objectives of this study were to (i) compare mean levels of full-shift exposure summary metrics based on both posture and movement speed between manufacturing workers performing predominantly cyclic and non-cyclic tasks, and (ii) explore patterns of between- and within-worker exposure variance and between-minute (within-shift) exposure level and variation within each group. Results suggested that, for both the upper arms and the trunk, full-shift posture-based exposure metrics were similar between the cyclic and non-cyclic groups. However, full-shift exposure metrics based on movement speed were less favorable for those in the cyclic group than for those in the non-cyclic group.

Observational studies suggest that increased routinization or repetitiveness of work increases MSD risk (Nordander et al., 2009). However, few field-based studies using direct measures are available that document differences in upper arm and trunk kinematic exposure magnitudes or exposure variability between workers engaged in repetitive work and those engaged in more varied work. Hansson et al. (2010) examined several measures of upper extremity kinematic exposures among groups of workers categorized by the type of work performed. Work categories included “repetitive industrial” and “varied industrial” work (among others), which broadly correspond to the cyclic and non-cyclic categorization used in the current study. Category-level averages for upper arm posture metrics (e.g., 99^{th} percentile elevation) appeared similar between the “varied industrial” and “repetitive industrial” categories, while category-level averages for movement speed metrics (e.g., 50^{th} percentile) appeared lower for the “varied industrial” category than for the “repetitive industrial” category. Although the results of Hansson et al. (2010) seem consistent with the findings of the current study, the small number of groups (n=3) in the “varied industrial” category and absence of statistical tests of differences in mean exposure levels between categories limit our ability to make direct comparisons.

In general, the patterns of variance components from analyses of full-shift exposure metrics and of between-minute (within-shift) variability in average exposure levels and within-

minute exposure variation were consistent with our expectations, i.e., results suggest greater exposure variability both between and within workers in the non-cyclic group. Whether our results imply reduced MSD risk among those in the non-cyclic group on the basis of exposure variability is not known. Furthermore, the value of increasing exposure variability with respect to MSD risk remains an unsettled question. Theoretically, and perhaps intuitively, designing jobs to allow for greater variation in exposures within and across tasks should promote more varied loading patterns to internal biomechanical structures in ways that minimize MSD risk (Mathiassen, 2006; Straker and Mathiassen, 2009). In some circumstances, however, greater exposure variation may act to increase MSD risk. Using the trunk as an example, we observed for both cyclic and non-cyclic groups relatively neutral working postures and low movement speeds with respect to suggested thresholds (Ferguson and Marras, 2013; Marras et al., 2007; Marras et al., 2010). In addition, we observed greater between-minute (within-shift) variability in average exposures and exposure variation (for both trunk posture and movement speed) among those in the non-cyclic group, which might imply lesser MSD risk compared to those in the cyclic group. On the other hand, variability in lifting kinematics may contribute to scenarios in which spinal loads exceed recommended tolerance limits despite a “typical” lift being safely below those limits (Granata et al., 1999; Mirka and Baker, 1996). Ultimately, additional research involving manufacturing workers stratified according to the variability of their work is needed to understand how exposure variability in this context might affect their health and well-being.

The results of this study may also have implications for those interested in job rotation as an intervention to prevent MSDs. Job rotation schemes are typically based on the concept of more equitably distributing exposure and/or increasing exposure variation (Jorgensen et al., 2005; Mehdizadeh et al., 2020; Triggs and King, 2000). In particular, “posture, movement frequency, the level of exposure, and the level of task complexity” are aspects of biomechanical loading often used to design job rotation schemes (Padula et al., 2017, pg. 395). One potential reason for using such parameters is that they may be more easily assessed with simple tools that require limited training (Dempsey et al., 2005; Lowe et al., 2018; Wells, 2009) relative to more comprehensive analyses (Leider et al., 2015b). Results of this study suggest that rotating manufacturing workers between cyclic and non-cyclic work tasks based solely on postural exposures would likely not have the desired effect, as posture-based exposure metrics were generally similar both between the work groups and across the work task categories. Instead, our results indicate that movement speed-based exposure metrics may be more promising to consider when developing and implementing job rotation schemes. This is consistent with a recent synthesis of epidemiological analyses, in which exposure metrics based on movement speed were more consistently associated with musculoskeletal symptoms than exposure metrics based on posture (Balogh et al., 2019).

The current study had several strengths and limitations. First, this study of variance components included one of the largest field samples of workers as well as number of data collection days for each participant conducted to date involving objective, directly measured full-shift upper arm and trunk kinematic data for any occupational group. The majority of previous studies examining variance components have typically been limited to a maximum of four work days (Liv et al., 2011; Liv et al., 2012; Mathiassen et al., 2012; Wahlström et al., 2010) or a small number of participants (Kersten and Fethke, 2019). The large number

of participants and measurement days theoretically provide more stable characterizations of manufacturing work than what has been available from previous investigations. Additionally, while participants needed to volunteer to be considered as a candidate for potential inclusion in the study, we randomly selected participants from the pool of interested candidates that represented nearly every department of the manufacturing facility. Thus, the results of the study may be reasonably generalized to the majority of workers at the study facility and to similar external industrial populations.

The random selection of participants in this study paired with the existence of gender-dominated roles in the manufacturing plant (e.g., men more commonly held non-cyclic jobs; a high prevalence of older females worked cyclic jobs) may have also inadvertently contributed to the uneven distribution of sex, age, height, and body mass index characteristics between the work groups (Table 1). Although the differences in age, height, and body mass index between the work groups were not found to be statistically significantly different (in analysis not presented), the differences in work group composition may partially explain statistically significant differences in upper arm and trunk kinematic exposure magnitude and exposure variability findings. Our results indicate, however, that differences in movement speed were likely not a function of differences in posture (e.g., shorter workers covering a larger range of motion). Rather, the demands of the work activities themselves (i.e., higher speeds needed to operate machinery and assemble parts completed primarily by the cyclic participants vs. slower speeds needed to complete maintenance and set-up activities completed primarily by the non-cyclic participants) appear to better explain the differences.

Given the broad scope of the data collection and the need of the research team to limit interference with production at the manufacturing facility, the research team elected to use quick to secure and adjust fastener bands rather than potentially more burdensome approaches (e.g., sensors taped directly to the skin). The fastener straps were also considered a practical means of securing the sensors that an occupational health and safety practitioner at a typical manufacturing facility may employ on a regular basis. This decision, however, like contributed to shift-to-shift inconsistencies in sensor placement as well as sensor movements throughout each shift that likely increased between-shift variance estimates (Dahlqvist et al., 2018). The trunk sensor, in particular, was susceptible to shifting down the sternum towards the xiphoid process. This shifting likely contributed to an overestimation of the amount of trunk extension and an underestimation of the amount of trunk flexion as the sensor may have become tilted as it rested near the abdomen which was often distended among our sample of workers with an average body mass index >30 kg/m^2.

The shifting may have also contributed to an increase in transient artifacts that we replaced with the mean posture of the entire recording duration. The decision to replace transient artifacts rather than exclude those periods allowed for simpler time synchronization between our kinematic measures and the daily work diaries collected from participants. However, it may have affected our measures of exposure variability. Along these lines, it is important to note that we did not apply a zero-angle reference measurement to compensate for any offset with the gravity vector for the upper arms and the reliability of the zero-angle reference method applied for the trunk is unknown. We also did not mark the skin to identify where

research team members secured IMU units, a step that would have allowed measurement of the magnitude of sensor movement throughout a shift. Movement speeds were also calculated as a derivative of inclination, which will result in a noisier signal than using direct measurements of velocity.

Finally, the criteria used to categorize participants into cyclic and non-cyclic work groups were similar to those reported in previous research (Paulsen et al., 2014) and were considered reasonable by the site safety director. However, broadly categorizing participants into cyclic or non-cyclic groups as a surrogate for the "routinization" or "repetitiveness" of their work likely oversimplifies the construct of repetition as a physical risk factor for MSDs. We did not analyze the collected data in such a way as to confirm that each participant was categorized appropriately with respect to cyclic/non-cyclic criteria, and we did not observe the participants during data collection. Given these data collection limitations, a pragmatic interpretation of the results is needed.

5. Conclusions

Manufacturing workers performing either predominantly cyclic or non-cyclic work tasks exhibited differences in upper arm and trunk movement speeds and variability in exposures during work despite having similar mean postural exposures. The findings suggest that future studies place a greater emphasis on assessing the temporal pattern of exposure variability of manufacturing work. Categorization of workers to primarily cyclic and non-cyclic work groups may be an important factor to consider in future research to understand how exposure differences, both in terms of magnitude and variation, between the groups affects their health and well-being.

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Figure 1.
A manufacturing worker wearing the four IMUs.

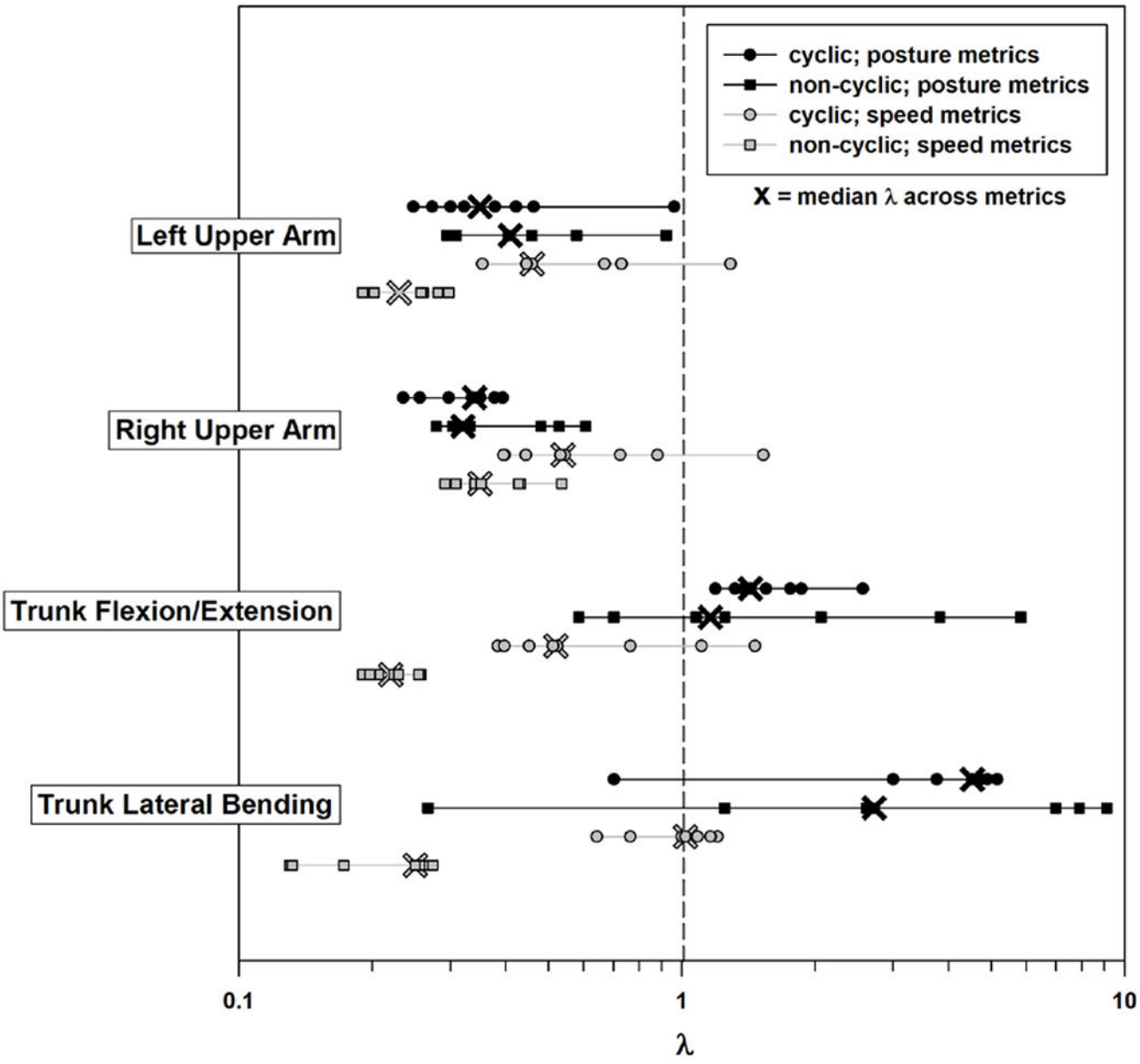

Figure 2.
Exposure homogeneity ($\lambda = S^2_{WS}/S^2_{BS}$) by sensor location for the cyclic and non-cyclic work groups.

Table 1.

Participant age, height, body mass index, and shift duration by work group and sex.

		Cyclic			Non-cyclic	
	n	**Mean**	**SD**	**n**	**Mean**	**SD**
Male	6			12*		
Age (years)		29.0	6.9		40.0	12.1
Height (cm)		183.7	6.9		179.5	5.0
Body mass index (kg/m^2)		32.1	10.7		30.2	4.6
Shift Duration (hours)		8.3	0.5		8.1	0.7
Female	12			5		
Age (years)		44.3	13.1		47.6	12.4
Height (cm)		164.9	6.1		163.6	6.9
Body mass index (kg/m^2)		31.1	6.1		33.3	7.8
Shift Duration (hours)		8.5	1.1		9.0	1.0

*All participants in this study were right hand dominant except for one male in the non-cyclic group.

Table 2.

Primary task categories by work group. The number (n) of time-weighted average exposure estimates included in the task-based dataset and the means ± SDs of the total task durations by sensor location.

Cyclic	
Assembly: tasks associated with machine-paced production (e.g. constructing part from sub-components; packaging parts).	Trunk (n=175; 7.2 ± 1.7 hours per day) Arms (n=188; 7.2 ± 1.7 hours per day)
Operating machinery: tasks associated with running a machine (e.g. loading parts into machining cell; operating crane lift).	Trunk (n=63; 5.7 ± 2.0 hours per day) Arms (Left n=72; Right n=71; 5.9 ± 1.9 hours per day)
Other: productive, work-related task (e.g., working on computer; walking between work cells; meetings).	Trunk (n=76; 1.5 ± 1.5 hours per day) Arms (n=81; 1.5 ± 1.5 hours per day)
Break: non-productive pause of the above work categories (e.g. meal break).	Trunk (n=239; 0.8 ± 0.3 hours per day) Arms (n=261; 0.8 ± 0.3 hours per day)
Non-cyclic	
Maintenance: tasks associated with cleaning or clearing work equipment and/or space (e.g., washing a machine; fixing equipment that had broken down).	Trunk (n=126; 3.0 ± 2.3 hours per day) Arms (Left n=133; Right n=134; 3.0 ± 2.3 hours per day)
Set-up: tasks associated with preparing a workstation for work activities (e.g., moving pallets; coordinating production line change; restocking).	Trunk (n=141; 4.5 ± 3.2 hours per day) Arms (Left n=148; Right n=149; 4.5 ± 3.1 hours per day)
Other: productive, work-related task (e.g., working on computer; walking between work cells; meetings).	Trunk (n=171; 4.2 ± 2.3 hours per day) Arms (Left n=185; Right n=186; 4.2 ± 2.3 hours per day)
Break: non-productive pause of the above work categories (e.g. meal break).	Trunk (n=188; 1.0 ± 0.7 hours per day) Arms (n=202; 1.1 ± 0.7 hours per day)

Table 3.

Full-shift left arm elevation exposure metrics across all data collection days and results of variance components analyses.

Exposure Metric	Fixed effect of group					Random effects of between-subjects and between-shifts within subject									
	Cyclic		Non-cyclic			Cyclic					Non-cyclic				
	Mean	SD	Mean	SD	*p*	S^2_{BS}	(95% CI)	S^2_{WS}	(95% CI)	λ	S^2_{BS}	(95% CI)	S^2_{WS}	(95% CI)	λ
Posture															
Mean (°)	30.43	7.14	31.29	6.32	0.67	37.90	(20.94- 88.45)	14.35	(11.91- 17.64)	0.38	32.14	(17.65- 75.93)	9.47	(7.96- 11.45)	0.29
10th Percentile (°)	13.91	5.48	13.88	4.59	1.00	23.88	(13.25- 55.27)	7.19	(5.98- 8.82)	0.30	16.79	(9.22- 39.69)	5.21	(4.38- 6.30)	0.31
50th Percentile (°)	26.20	7.62	27.02	6.74	0.70	45.06	(24.95- 104.72)	14.54	(12.04- 17.92)	0.32	36.32	(19.95- 85.82)	11.00	(9.25- 13.29)	0.30
90th Percentile (°)	53.18	10.64	54.20	9.16	0.73	79.10	(43.64- 185.27)	36.61	(30.57- 44.66)	0.46	54.86	(29.86- 132.13)	31.74	(26.69- 38.37)	0.58
90th-10th Percentile (°)	39.27	8.91	40.32	7.21	0.67	57.27	(31.76- 132.67)	24.22	(20.39- 29.25)	0.42	27.80	(14.95- 68.71)	25.64	(21.56- 31.01)	0.92
Neutral (<20°) (%time)	32.85	18.75	31.32	15.60	0.76	290.79	(162.12- 666.65)	71.87	(60.30- 87.13)	0.25	180.14	(98.67- 428.14)	73.10	(61.51- 88.33)	0.41
Extreme (≥60°) (%time)	7.41	5.68	7.90	5.53	0.75	16.70	(8.94- 41.64)	16.05	(13.27- 19.83)	0.96	22.50	(12.31- 53.65)	9.12	(7.66- 11.04)	0.41
Movement speed															
Mean (°/s)	14.92	3.64	10.83	3.26	**<0.01**	9.58	(5.19- 23.29)	4.28	(3.39- 5.58)	0.45	9.28	(5.10- 21.86)	1.89	(1.58- 2.30)	0.20
10th Percentile (°/s)	0.49	0.28	0.22	0.12	**<0.01**	0.05	(0.03- 0.12)	0.03	(0.03- 0.04)	0.72	0.01	(0.01- 0.03)	0.00	(0.00- 0.00)	0.37
50th Percentile (°/s)	7.16	2.62	3.88	2.18	**<0.01**	4.84	(2.63- 11.68)	2.21	(1.77- 2.83)	0.46	3.96	(2.18- 9.35)	1.01	(0.85- 1.23)	0.26
90th Percentile (°/s)	39.14	9.14	29.80	8.33	**<0.01**	60.57	(32.86- 146.86)	27.30	(21.70- 35.38)	0.45	61.18	(33.67- 144.03)	11.63	(9.72- 14.18)	0.19
90th-10th Percentile (°/s)	38.64	8.93	29.59	8.23	**<0.01**	57.83	(31.37- 140.30)	26.23	(20.86- 33.99)	0.45	59.73	(32.87- 140.63)	11.37	(9.50- 13.86)	0.19
Low speed (<5°/s) (%time)	42.98	7.43	56.40	9.99	**<0.01**	32.77	(17.46- 82.54)	23.92	(19.21- 30.62)	0.73	82.65	(45.36- 195.61)	21.57	(18.05- 26.23)	0.26
High speed (≥90°/s) (%time)	1.64	0.93	0.95	0.63	**<0.01**	0.70	(0.38- 1.65)	0.25	(0.20- 0.32)	0.36	0.35	(0.19- 0.82)	0.07	(0.06- 0.08)	0.20
Rest/Recovery															
Neutral for ≥ 3s (%time)	20.42	16.57	21.48	13.64	0.81	221.72	(123.40- 510.03)	60.56	(50.70- 73.61)	0.27	132.46	(72.48- 315.49)	60.80	(51.16- 73.45)	0.46
Low speed for ≥ 3s (%time)	14.95	6.19	32.42	12.27	**<0.01**	17.14	(8.81- 46.83)	22.12	(17.86- 28.12)	1.29	122.75	(67.28- 291.31)	34.58	(28.90- 42.13)	0.28
Neutral and low speed (%time)	15.03	8.95	16.83	9.04	0.48	55.72	(30.57- 132.05)	26.21	(21.57- 32.53)	0.47	58.82	(32.22- 139.77)	26.16	(22.01- 31.61)	0.44

Table 4.

Full-shift right arm elevation exposure metrics across all data collection days and results of variance components analyses.

Exposure Metric	Fixed effect of group					Random effects of between-subjects and between-shifts within subject									
	Cyclic		Non-cyclic			Cyclic					Non-cyclic				
	Mean	SD	Mean	SD	*p*	S^2_{BS}	(95% CI)	S^2_{WS}	(95% CI)	λ	S^2_{BS}	(95% CI)	S^2_{WS}	(95% CI)	λ
Posture															
Mean (°)	30.40	6.53	30.96	5.55	0.75	35.37	(19.74- 80.87)	9.07	(7.65- 10.93)	0.26	24.08	(13.24- 56.85)	7.98	(6.72- 9.64)	0.33
10th Percentile (°)	13.70	5.18	13.62	4.80	0.97	21.55	(11.99- 49.59)	6.39	(5.38- 7.71)	0.30	18.45	(10.02- 44.63)	5.58	(5.28- 5.90)	0.30
50th Percentile (°)	26.38	7.01	26.78	6.30	0.83	41.48	(23.16- 94.78)	9.73	(8.20- 11.74)	0.23	31.75	(17.47- 74.74)	9.62	(8.09- 11.62)	0.30
90th Percentile (°)	52.83	10.09	53.50	9.03	0.80	78.73	(43.74- 181.82)	26.39	(22.13- 32.00)	0.34	57.34	(31.36- 136.70)	27.57	(23.22- 33.28)	0.48
90th-10th Percentile (°)	39.13	9.04	39.88	8.15	0.76	62.03	(34.31- 144.49)	21.75	(18.00- 26.82)	0.35	45.03	(24.52- 108.38)	23.79	(20.00- 28.77)	0.53
Neutral (<20°) (%time)	32.44	16.08	31.46	15.52	0.84	199.96	(97.61- 616.00)	69.04	(65.41- 72.98)	0.35	193.02	(106.32- 453.45)	58.34	(55.40- 61.53)	0.30
Extreme (≥60°) (%time)	7.36	5.50	6.94	4.16	0.78	22.76	(12.70- 52.11)	8.58	(7.22- 10.35)	0.38	11.16	(6.06- 26.94)	6.75	(5.68- 8.16)	0.60
Movement speed															
Mean (°/s)	16.04	3.94	11.51	2.94	**<0.01**	11.51	(6.29- 27.48)	5.13	(4.17- 6.46)	0.45	6.65	(3.64- 15.85)	2.34	(1.96- 2.85)	0.35
10th Percentile (°/s)	0.55	0.34	0.25	0.14	**<0.01**	0.07	(0.04- 0.18)	0.05	(0.04- 0.07)	0.76	0.02	(0.01- 0.04)	0.01	(0.00- 0.01)	0.36
50th Percentile (°/s)	8.02	3.04	4.28	2.22	**<0.01**	7.15	(3.92- 16.93)	2.82	(2.29- 3.55)	0.39	3.93	(2.15- 9.31)	1.20	(1.01- 1.46)	0.31
90th Percentile (°/s)	41.78	9.46	31.68	7.15	**<0.01**	62.10	(33.72- 150.30)	33.08	(26.86- 41.76)	0.53	37.21	(20.28- 89.38)	15.93	(13.33- 19.39)	0.43
90th-10th Percentile (°/s)	41.24	9.21	31.43	7.04	**<0.01**	58.29	(31.62- 141.41)	31.74	(25.75- 40.10)	0.54	35.94	(19.58- 86.37)	15.60	(13.05- 18.98)	0.43
Low speed (<5°/s) (%time)	40.50	7.24	54.35	9.71	**<0.01**	29.39	(15.47- 75.94)	25.94	(20.80- 33.27)	0.88	75.18	(41.22- 178.34)	23.24	(19.51- 28.17)	0.31
High speed (≥90°/s) (%time)	1.87	1.17	1.01	0.50	**<0.01**	1.05	(0.58- 2.47)	0.42	(0.35- 0.52)	0.40	0.17	(0.09- 0.42)	0.09	(0.07- 0.11)	0.52
Rest/Recovery															
Neutral for ≥ 3s (%time)	18.16	13.43	20.57	13.36	0.57	133.38	(73.43- 313.74)	52.53	(43.21- 65.24)	0.39	146.03	(80.22- 344.96)	40.67	(34.20- 49.17)	0.28
Low speed for ≥ 3s (%time)	13.89	5.92	29.18	11.94	**<0.01**	14.18	(7.14- 40.55)	21.68	(17.45- 27.67)	1.53	114.96	(62.97- 273.18)	33.50	(27.98- 40.84)	0.29
Neutral and low speed (%time)	13.72	6.93	15.74	8.44	0.39	31.06	(16.93- 74.61)	18.64	(15.38- 23.06)	0.60	54.64	(29.90- 130.11)	19.63	(16.48- 23.80)	0.36

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Table 5.

Left arm elevation exposure metrics across primary work task categories across all data collection days.

Exposure Metric	Work Tasks															
	Assembly		Operate Machinery		Maintenance		Set-up		Other				Break			
	Cyclic		Cyclic		Non-cyclic		Non-cyclic		Cyclic		Non-cyclic		Cyclic		Non-cyclic	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Posture																
Mean (°)	29.51	6.08	32.78	8.85	31.01	6.73	31.74	6.19	29.44	7.14	31.43	7.12	33.02	7.80	33.50	11.53
10th Percentile (°)	13.01	4.79	17.39	5.92	14.60	4.62	14.99	4.72	14.07	5.23	15.15	5.09	16.57	6.36	17.43	9.97
50th Percentile (°)	25.32	6.74	28.90	8.83	26.61	6.80	27.88	6.59	25.43	7.70	27.49	7.42	30.89	8.63	31.99	12.79
90th Percentile (°)	52.82	9.73	53.49	12.95	53.72	12.59	54.17	10.85	50.61	12.19	53.22	11.98	51.99	12.60	51.05	14.80
90th-10th Percentile (°)	39.80	9.00	36.10	8.88	39.12	11.19	39.18	9.23	36.55	11.30	38.07	10.57	35.42	11.54	33.62	10.81
Neutral (<20°) (%time)	35.41	16.89	25.89	20.47	31.68	15.99	28.56	16.31	34.30	21.46	30.30	16.91	25.76	17.64	30.16	23.39
Extreme (≥60°) (%time)	7.05	5.10	8.54	7.33	8.26	6.97	7.91	5.22	6.93	5.99	7.73	6.41	7.37	8.44	8.44	11.78
Movement Speed																
Mean (°/s)	15.26	2.71	16.61	5.56	10.90	3.28	12.26	3.62	12.40	3.15	10.26	3.47	9.35	4.08	7.58	3.51
10th Percentile (°/s)	0.64	0.23	0.83	0.53	0.32	0.28	0.33	0.18	0.56	0.35	0.28	0.19	0.20	0.22	0.17	0.20
50th Percentile (°/s)	7.36	1.82	9.26	4.09	4.32	2.57	5.22	2.41	5.93	2.50	4.00	2.38	2.73	2.53	2.07	2.18
90th Percentile (°/s)	39.84	7.04	41.97	13.54	29.20	7.64	32.68	9.56	31.52	7.74	27.40	8.78	26.75	11.09	21.36	9.34
90th-10th Percentile (°/s)	39.20	6.89	41.15	13.09	28.89	7.47	32.35	9.44	30.96	7.51	27.12	8.63	26.55	10.94	21.20	9.20
Low Speed (<5°/s) (%time)	41.51	6.22	37.99	10.23	55.21	11.95	50.95	10.04	47.27	10.80	57.70	12.86	64.09	12.63	69.21	11.86
High Speed (≥90°/s) (%time)	1.73	0.79	1.77	1.35	0.89	0.53	1.13	0.77	1.10	0.79	0.83	0.49	0.86	0.73	0.59	0.56
Rest/Recovery																
Neutral for ≥ 3s (%time)	21.78	15.44	13.73	14.45	20.92	14.35	18.32	13.50	22.33	20.47	20.72	14.90	18.34	16.72	23.24	21.65
Low Speed for ≥ 3s (%time)	11.43	5.74	12.89	7.77	30.65	15.38	25.22	11.66	18.27	13.64	33.88	16.59	43.25	16.50	50.29	15.81
Neutral and Low Speed (%time)	15.57	7.59	11.64	9.40	17.11	10.58	14.48	8.68	16.45	11.38	16.60	9.79	15.19	13.33	19.60	18.86

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Table 6.

Right arm elevation exposure metrics across primary work task categories across all data collection days.

Exposure Metric	Work Tasks															
	Assembly		Operate Machinery		Maintenance		Set-up		Other				Break			
	Cyclic		Cyclic		Non-cyclic		Non-cyclic		Cyclic		Non-cyclic		Cyclic		Non-cyclic	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Posture																
Mean (°)	29.93	6.46	30.81	7.09	30.64	5.64	30.38	5.35	29.55	6.68	31.37	6.52	33.88	6.81	34.32	9.64
10th Percentile (°)	13.48	5.54	15.06	4.09	14.23	4.76	13.87	4.93	13.41	4.98	15.15	5.60	17.51	7.15	18.15	8.16
50th Percentile (°)	25.70	6.84	27.14	7.15	26.19	6.03	26.68	6.13	25.47	7.32	27.62	7.27	32.90	8.21	33.73	10.90
90th Percentile (°)	52.81	10.42	51.91	12.42	53.67	11.91	51.99	8.73	51.53	12.02	52.53	10.89	50.54	9.60	49.93	11.99
90th-10th Percentile (°)	39.33	10.09	36.85	10.24	39.44	11.93	38.12	8.69	38.12	12.18	37.38	10.64	33.03	10.47	31.78	9.46
Neutral (<20°) (%time)	34.21	16.33	29.96	15.65	32.00	14.84	31.52	16.81	35.30	19.01	29.94	16.80	21.50	16.34	23.55	19.31
Extreme (≥60°) (%time)	7.50	5.67	7.36	5.96	7.54	5.36	6.26	4.10	7.46	6.52	6.84	4.94	6.18	6.36	6.58	8.88
Movement Speed																
Mean (°/s)	16.32	2.60	18.19	6.55	12.13	3.31	12.64	3.04	14.00	4.05	10.89	3.53	9.99	4.99	8.38	3.28
10th Percentile (°/s)	0.73	0.30	0.94	0.65	0.37	0.29	0.38	0.21	0.64	0.39	0.32	0.23	0.22	0.26	0.19	0.20
50th Percentile (°/s)	8.27	1.93	10.49	4.99	4.95	2.77	5.52	2.21	7.02	3.19	4.31	2.49	3.16	3.15	2.46	2.12
90th Percentile (°/s)	42.24	6.52	45.37	15.50	32.82	7.77	33.60	7.70	35.87	10.26	29.16	8.89	28.50	13.53	23.73	8.81
90th-10th Percentile (°/s)	41.52	6.33	44.43	14.94	32.44	7.60	33.22	7.57	35.23	10.03	28.84	8.73	28.27	13.36	23.53	8.69
Low Speed (<5°/s) (%time)	38.78	5.96	35.57	10.14	52.50	12.13	49.38	9.44	43.99	11.60	56.06	12.70	63.02	14.31	66.16	11.91
High Speed (≥90°/s) (%time)	1.89	0.91	2.31	1.98	1.07	0.54	1.08	0.54	1.35	0.96	0.92	0.54	1.02	0.96	0.62	0.43
Rest/Recovery																
Neutral for ≥ 3s (%time)	19.24	13.09	13.61	10.77	19.65	12.60	20.08	14.65	21.43	18.54	19.41	13.81	13.93	13.82	16.42	16.93
Low Speed for ≥ 3s (%time)	10.43	5.81	11.73	6.81	27.41	15.34	22.43	11.01	16.93	13.74	30.75	16.18	42.25	17.58	44.79	15.72
Neutral and Low Speed (%time)	14.48	6.76	11.78	6.83	16.02	8.71	15.03	8.93	15.50	10.21	15.19	9.03	10.71	10.44	13.60	14.09

Table 7.

Full-shift trunk flexion/extension exposure metrics across all data collection days and results of variance components analyses.

Exposure Metric	Fixed effect of group					Random effects of between-subjects and between-shifts within subject									
	Cyclic		Non-cyclic			Cyclic					Non-cyclic				
	Mean	SD	Mean	SD	*p*	S^2_{BS}	(95% CI)	S^2_{WS}	(95% CI)	λ	S^2_{BS}	(95% CI)	S^2_{WS}	(95% CI)	λ
Posture															
Mean (°)	−6.15	12.07	−5.01	11.63	0.68	66.33	(35.04- 170.29)	87.49	(72.83- 107.10)	1.32	66.65	(35.42- 168.89)	71.69	(59.80- 87.54)	1.08
10th Percentile (°)	−19.87	14.38	−22.68	13.95	0.44	99.86	(53.20- 251.65)	118.86	(98.98- 145.42)	1.19	88.76	(46.54- 231.54)	110.93	(92.09- 136.24)	1.25
50th Percentile (°)	−7.31	11.67	−6.00	11.03	0.61	59.46	(31.13- 155.64)	85.20	(70.84- 104.46)	1.43	60.40	(32.15- 152.55)	65.12	(54.39- 79.39)	1.08
90th Percentile (°)	8.99	12.62	12.88	16.14	0.29	59.16	(30.56- 159.55)	104.00	(86.29- 127.82)	1.76	155.74	(84.18- 380.56)	109.50	(91.47- 133.47)	0.70
90th-10th Percentile (°)	28.86	9.60	35.56	14.11	**0.04**	26.70	(12.98- 83.09)	68.53	(55.93- 85.95)	2.57	129.92	(70.66- 313.42)	76.09	(63.65- 92.61)	0.59
Neutral (>−20° to <20°) (%time)	74.89	22.93	73.71	18.06	0.87	192.25	(97.72- 537.91)	358.29	(296.25- 442.22)	1.86	108.07	(56.05- 288.85)	222.97	(186.52- 271.31)	2.06
Extreme (≥60°) (%time)	0.60	0.77	1.07	2.90	0.21	0.24	(0.13- 0.61)	0.37	(0.31- 0.45)	1.54	1.23	(0.55- 4.78)	7.17	(5.99- 8.75)	5.82
Movement speed															
Mean (°/s)	8.23	2.26	7.05	1.80	**0.04**	4.10	(2.25- 9.72)	1.63	(1.32- 2.05)	0.40	2.71	(1.49- 6.38)	0.62	(0.52- 0.76)	0.23
10th Percentile (°/s)	0.55	0.20	0.42	0.20	**0.02**	0.02	(0.01- 0.06)	0.02	(0.02- 0.02)	0.77	0.03	(0.02- 0.08)	0.01	(0.01- 0.01)	0.21
50th Percentile (°/s)	4.70	1.58	3.53	1.50	**0.01**	2.02	(1.11- 4.77)	0.77	(0.63- 0.96)	0.38	1.95	(1.07- 4.59)	0.38	(0.31- 0.46)	0.19
90th Percentile (°/s)	19.84	5.20	17.95	3.94	0.11	19.63	(10.67- 47.41)	10.05	(8.07- 12.86)	0.51	12.75	(7.01- 30.12)	3.26	(2.72- 3.97)	0.26
90th-10th Percentile (°/s)	19.29	5.06	17.52	3.81	0.13	18.46	(10.02- 44.67)	9.64	(7.73- 12.37)	0.52	11.88	(6.53- 28.07)	3.07	(2.56- 3.75)	0.26
Low speed (<5°/s) (%time)	53.15	8.41	60.03	9.75	**0.01**	53.34	(29.08- 128.04)	24.10	(19.47- 30.60)	0.45	79.63	(43.78- 187.80)	17.81	(14.85- 21.77)	0.22
High speed (≥90°/s) (%time)	0.19	0.26	0.11	0.12	0.09	0.04	(0.02- 0.10)	0.04	(0.03- 0.05)	1.04	0.01	(0.01- 0.03)	0.00	(0.00- 0.00)	0.18
Rest/Recovery															

Exposure Metric	Fixed effect of group					Random effects of between-subjects and between-shifts within subject									
	Cyclic		Non-cyclic			Cyclic					Non-cyclic				
	Mean	SD	Mean	SD	*p*	S^2_{BS}	(95% CI)	S^2_{WS}	(95% CI)	λ	S^2_{BS}	(95% CI)	S^2_{WS}	(95% CI)	λ
Neutral for ≥ 3s (%time)	55.25	20.49	57.26	16.55	0.52	186.43	(97.79- 485.96)	256.58	(212.96- 315.19)	1.38	57.18	(28.04- 174.30)	218.87	(183.08- 266.33)	3.83
Low speed for ≥ 3s (%time)	13.53	5.68	24.53	13.43	**<0.01**	13.45	(6.80- 38.04)	19.75	(15.86- 25.28)	1.47	154.53	(85.02- 363.95)	30.50	(25.38- 37.36)	0.20
Neutral and low speed (%time)	38.70	14.70	41.00	12.55	0.36	126.02	(67.77- 311.29)	105.57	(87.32- 130.24)	0.84	35.76	(17.42- 110.69)	123.67	(103.27- 150.80)	3.46

[a]Positive values denote trunk flexion; Negative values denote trunk extension.

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Table 8.

Full-shift trunk lateral bending exposure metrics across all data collection days and results of variance components analyses.

Exposure Metric	Fixed effect of group					Random effects of between-subjects and between-shifts within subject									
	Cyclic		Non-cyclic			Cyclic					Non-cyclic				
	Mean	SD	Mean	SD	*p*	S^2_{BS}	(95% CI)	S^2_{WS}	(95% CI)	λ	S^2_{BS}	(95% CI)	S^2_{WS}	(95% CI)	λ
Posture															
Mean (°)	−1.26	4.64	−1.01	4.79	0.73	3.71	(1.71- 13.21)	18.21	(15.21- 22.19)	4.91	2.29	(0.95- 11.02)	20.77	(17.37- 25.27)	9.06
10th Percentile (°)	−8.41	4.93	−8.30	4.98	0.86	6.09	(3.02- 18.05)	18.35	(15.29- 22.44)	3.01	3.13	(1.38- 12.53)	21.92	(18.34- 26.68)	7.01
50th Percentile (°)	−1.38	4.73	−1.12	4.91	0.72	4.11	(1.94- 13.91)	18.64	(15.58- 22.69)	4.53	2.72	(1.17- 11.83)	21.57	(18.04- 26.25)	7.92
90th Percentile (°)	5.95	5.14	6.37	5.37	0.70	5.69	(2.75- 17.99)	21.35	(17.84- 26.02)	3.75	7.85	(4.00- 21.91)	21.37	(17.88- 26.00)	2.72
90th-10th Percentile (°)	14.37	3.68	14.67	4.00	0.87	8.11	(4.44- 19.32)	5.72	(4.77- 6.99)	0.71	12.98	(7.14- 30.59)	3.46	(2.90- 4.21)	0.27
Neutral (>−20° to <20°) (%time)	97.66	4.18	97.42	3.27	0.81	2.90	(1.34- 10.19)	14.89	(12.46- 18.12)	5.14	4.88	(2.62- 12.05)	6.10	(5.09- 7.45)	1.25
Extreme (≥60°) (%time)	0.00	0.01	0.00	0.03	0.27	0.00	(0.00- 0.00)	0.00	(0.00- 0.00)	-	0.00	(0.00- 3.50E+72)	0.00	(0.00- 0.00)	-
Movement speed															
Mean (°/s)	6.11	1.38	5.56	1.81	0.16	1.04	(0.54- 2.80)	1.05	(0.81- 1.43)	1.01	2.93	(1.61- 6.87)	0.50	(0.42- 0.61)	0.17
10th Percentile (°/s)	0.30	0.12	0.18	0.09	**<0.01**	0.01	(0.00- 0.02)	0.01	(0.01- 0.01)	0.92	0.01	(0.00- 0.01)	0.00	(0.00- 0.00)	0.30
50th Percentile (°/s)	3.43	1.02	2.34	1.19	**<0.01**	0.64	(0.34- 1.62)	0.50	(0.40- 0.63)	0.77	1.14	(0.63- 2.70)	0.31	(0.26- 0.38)	0.28
90th Percentile (°/s)	15.58	3.41	15.65	4.91	0.80	6.01	(3.00- 17.50)	6.95	(4.97- 10.43)	1.16	22.16	(12.23- 51.90)	2.92	(2.43- 3.57)	0.13
90th-10th Percentile (°/s)	15.27	3.34	15.47	4.86	0.88	5.64	(2.80- 16.66)	6.76	(4.80- 10.25)	1.20	21.69	(11.96- 50.78)	2.84	(2.36- 3.47)	0.13
Low speed (<5°/s) (%time)	60.68	7.15	66.93	8.98	**<0.01**	33.77	(18.15- 83.60)	21.68	(17.41- 27.74)	0.64	66.35	(36.45- 156.72)	16.97	(14.16- 20.69)	0.26
High speed (≥90°/s) (%time)	0.01	0.09	0.01	0.02	0.48	0.00	(0.00- 0.00)	0.01	(0.01- 0.01)	-	0.00	(0.00- 0.00)	0.00	(0.00- 0.00)	-
Rest/Recovery															
Neutral for ≥ 3s (%time)	72.38	12.41	76.67	11.32	**0.04**	26.95	(12.62- 92.23)	127.49	(106.40- 155.57)	4.73	36.11	(18.16- 103.51)	94.40	(78.85- 115.07)	2.61
Low speed for ≥ 3s (%time)	23.29	8.39	40.37	12.78	**<0.01**	36.03	(18.58- 97.58)	39.11	(31.19- 50.51)	1.09	132.52	(72.71- 313.86)	35.36	(29.44- 43.28)	0.27

Exposure Metric	Fixed effect of group					Random effects of between-subjects and between-shifts within subject									
	Cyclic		Non-cyclic			Cyclic					Non-cyclic				
	Mean	SD	Mean	SD	*p*	S^2_{BS}	(95% CI)	S^2_{WS}	(95% CI)	λ	S^2_{BS}	(95% CI)	S^2_{WS}	(95% CI)	λ
Neutral and low speed (%time)	59.52	7.69	65.48	9.75	**0.02**	35.86	(19.03- 91.15)	29.41	(23.60- 37.66)	0.82	77.12	(42.36- 182.20)	20.98	(17.54- 25.56)	0.27

[a]Positive values denote right lateral bending; Negative values denote left lateral bending.

Table 9.

Trunk flexion/extension exposure metrics across primary work task categories across all data collection days.

Exposure Metric	Work Tasks															
	Assembly		Operate Machinery		Maintenance		Set-up		Other				Break			
	Cyclic		Cyclic		Non-cyclic		Non-cyclic		Cyclic		Non-cyclic		Cyclic		Non-cyclic	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Posture																
Mean (°)	−5.76	12.06	−5.63	11.73	−2.97	12.49	−4.21	10.92	−5.01	11.47	−4.05	13.76	−15.04	19.49	−9.93	16.11
10th Percentile (°)	−17.80	13.58	−15.86	11.15	−16.77	11.70	−18.00	10.77	−16.26	11.86	−19.77	14.04	−31.55	20.38	−26.84	15.36
50th Percentile (°)	−7.64	11.77	−7.08	11.98	−4.84	12.24	−5.92	11.16	−7.34	10.86	−5.14	13.50	−17.22	21.57	−10.73	17.57
90th Percentile (°)	7.64	12.66	5.52	13.08	12.84	17.15	10.85	14.48	8.94	16.01	12.47	18.08	3.29	20.21	6.28	18.47
90th-10th Percentile (°)	25.44	8.63	21.38	6.99	29.61	13.10	28.85	11.71	25.20	12.10	32.23	13.80	34.84	15.24	33.12	12.87
Neutral (>−20° to <20°) (%time)	76.24	23.75	76.81	26.50	76.64	20.58	77.09	18.87	78.43	25.48	72.32	21.67	52.89	28.25	60.87	24.84
Extreme (≥60°) (%time)	0.58	0.64	0.46	0.72	1.14	3.43	1.13	3.76	0.68	1.40	1.16	3.31	0.60	1.96	0.36	1.17
Movement Speed																
Mean (°/s)	8.13	2.09	9.27	2.71	7.13	1.82	7.81	1.95	8.04	2.32	6.77	2.09	5.99	2.74	5.57	1.97
10th Percentile (°/s)	0.65	0.25	0.75	0.30	0.51	0.27	0.54	0.26	0.63	0.29	0.47	0.26	0.27	0.16	0.33	0.19
50th Percentile (°/s)	4.77	1.46	5.81	2.05	3.85	1.64	4.22	1.66	4.66	1.83	3.61	1.74	2.34	1.54	2.55	1.40
90th Percentile (°/s)	19.33	5.06	21.69	5.47	17.73	3.92	19.35	4.24	18.82	4.98	16.71	4.71	16.23	7.46	14.33	4.89
90th-10th Percentile (°/s)	18.68	4.89	20.94	5.21	17.22	3.72	18.82	4.10	18.20	4.74	16.24	4.50	15.96	7.36	14.00	4.75
Low Speed (<5°/s) (%time)	52.96	8.30	47.18	9.58	58.50	10.99	55.67	10.20	54.07	10.68	61.16	12.51	69.80	11.83	69.36	11.52
High Speed (≥90°/s) (%time)	0.17	0.24	0.23	0.32	0.09	0.08	0.15	0.16	0.26	0.37	0.10	0.10	0.17	0.25	0.08	0.07
Rest/Recovery																
Neutral for ≥ 3s (%time)	57.31	21.42	53.63	22.76	59.30	18.96	59.19	18.04	58.80	21.88	56.72	18.91	41.82	25.35	49.05	22.50
Low Speed for ≥ 3s (%time)	10.52	6.11	9.90	5.92	22.05	15.05	19.19	13.73	14.19	11.51	25.75	17.09	43.30	17.73	37.83	19.40
Neutral and Low Speed (%time)	40.29	15.34	35.10	15.28	41.83	13.87	41.01	13.60	40.80	16.89	40.32	14.44	31.84	21.84	37.80	19.17

[a]Positive values denote trunk flexion; Negative values denote trunk extension.

Table 10.

Trunk lateral bending exposure metrics across primary work task categories across all data collection days.

Exposure Metric	Work Tasks															
	Assembly		Operate Machinery		Maintenance		Set-up		Other				Break			
	Cyclic		Cyclic		Non-cyclic		Non-cyclic		Cyclic		Non-cyclic		Cyclic		Non-cyclic	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Posture																
Mean (°)	−1.61	4.41	−0.36	5.29	−1.27	4.85	−0.88	5.20	−1.63	4.64	−0.90	4.78	−1.04	4.99	−1.46	5.21
10th Percentile (°)	−8.77	4.90	−6.58	4.98	−7.82	5.26	−8.26	5.29	−7.28	4.51	−7.49	4.96	−6.41	5.27	−6.89	5.42
50th Percentile (°)	−1.74	4.49	−0.60	5.45	−1.48	4.94	−1.07	5.27	−1.86	4.77	−0.94	4.85	−1.06	5.09	−1.51	5.29
90th Percentile (°)	5.61	4.73	6.07	5.86	5.52	5.14	6.68	6.14	4.28	5.37	5.68	5.52	4.28	5.61	3.83	5.66
90th-10th Percentile (°)	14.39	3.66	12.65	2.87	13.34	3.59	14.94	4.31	11.57	3.42	13.17	4.26	10.69	4.17	10.72	3.81
Neutral (>−20° to <20°) (%time)	97.51	3.71	97.74	5.51	97.64	3.39	97.01	4.10	98.65	2.10	97.68	3.61	98.29	4.78	98.67	2.49
Extreme (≥60°) (%time)	0.00	0.01	0.00	0.01	0.00	0.01	0.03	0.29	0.00	0.01	0.00	0.02	0.00	0.02	0.00	0.00
Movement Speed																
Mean (°/s)	6.02	1.26	7.24	1.56	5.41	1.69	6.45	1.90	5.79	1.67	5.03	1.81	3.86	1.77	3.90	1.91
10th Percentile (°/s)	0.38	0.12	0.46	0.21	0.24	0.15	0.26	0.12	0.36	0.17	0.21	0.13	0.13	0.09	0.14	0.13
50th Percentile (°/s)	3.54	0.90	4.40	1.36	2.57	1.36	3.09	1.28	3.31	1.26	2.38	1.35	1.38	1.10	1.38	1.37
90th Percentile (°/s)	14.93	3.10	18.14	3.52	14.69	3.98	17.55	5.31	14.71	4.10	13.56	4.55	11.14	4.89	11.19	5.10
90th-10th Percentile (°/s)	14.55	3.02	17.68	3.36	14.45	3.87	17.29	5.26	14.36	4.00	13.35	4.45	11.01	4.82	11.06	5.02
Low Speed (<5°/s) (%time)	60.65	6.78	54.15	8.26	66.33	10.14	62.05	8.88	62.29	9.99	68.73	11.24	76.81	10.35	77.55	10.64
High Speed (≥90°/s) (%time)	0.02	0.11	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.04	0.00	0.01	0.01	0.06	0.00	0.01
Rest/Recovery																
Neutral for ≥ 3s (%time)	72.28	11.98	67.74	16.36	77.23	13.08	73.02	12.89	72.70	14.26	78.22	12.37	83.84	10.99	83.93	10.73
Low Speed for ≥ 3s (%time)	19.75	8.52	19.35	10.25	38.94	15.15	32.60	12.30	26.38	15.39	42.33	17.05	55.57	17.39	58.55	15.79
Neutral and Low Speed (%time)	59.41	7.26	53.14	9.25	64.95	10.56	60.39	9.78	61.58	10.33	67.18	11.69	75.67	11.74	76.68	10.95

[a]Positive values denote right lateral bending; Negative values denote left lateral bending.

Table 11.

Means and SDs of SD_{means} and SD_{ranges} across all data collection days for the cyclic and noncyclic work groups by sensor location.

Exposure Metric	Cyclic		Noncyclic	
SD_{mean} for posture (°)	**Mean**	**SD**	**Mean**	**SD**
Left Arm	8.72	2.75	12.20	3.20
Right Arm	8.37	2.41	11.58	3.14
Trunk Flexion/Extension	10.96	3.44	13.06	4.99
Trunk Lateral Bending	3.13	1.20	3.93	1.16
SD_{range} for posture (°)				
Left Arm	14.50	4.16	17.05	3.64
Right Arm	14.60	4.44	16.96	3.24
Trunk Flexion/Extension	12.63	3.93	13.67	3.60
Trunk Lateral Bending	5.55	1.71	6.66	1.86
SD_{mean} for speed (°/s)				
Left Arm	6.32	1.22	6.87	1.21
Right Arm	6.71	1.34	7.28	1.42
Trunk Flexion/Extension	3.41	0.91	3.74	0.80
Trunk Lateral Bending	2.48	0.55	3.46	0.99
SD_{range} for speed (°/s)				
Left Arm	14.95	3.19	15.78	2.77
Right Arm	15.64	2.95	16.47	2.98
Trunk Flexion/Extension	7.42	1.96	8.16	1.79
Trunk Lateral Bending	5.26	1.13	7.38	2.00