HHS Public Access

Author manuscript

Hum Factors. Author manuscript; available in PMC 2024 May 01.

Published in final edited form as:

Hum Factors. 2023 May ; 65(3): 419–434. doi:10.1177/00187208211022122.

Work-related risk factors for rotator cuff syndrome in a prospective study of manufacturing and healthcare workers

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Abstract

Objective—This prospective study assessed the risk of developing rotator cuff syndrome (RCS) with separate or specific combinations of biomechanical exposures measures, controlling for individual confounders.

Background—Compared to other musculoskeletal disorders, rates of work-related shoulder musculoskeletal disorders have been declining more slowly.

Method—We conducted up to two years of individual, annual assessments of covariates, exposures, and health outcomes for 393 U.S. manufacturing and healthcare workers without RCS at baseline. Task-level biomechanical exposures assessed exposure to forceful exertions (level, exertion rates, duty cycles), vibration, and upper arm postures (flexion, abduction). Hazard ratios (HR) were calculated with Cox proportional hazard models.

Results—We observed 39 incident RCS cases in 694 person-years (incidence rate = 5.62 per 100 person-years). Adjusting for confounders, we found increased risk of incident RCS associated

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Author Contributions

ARM wrote the manuscript and led the data analysis and peer review process. ARM, SJW, EFK made substantive editorial contributions to the manuscript. The overall study of work-related upper limb disorders was led by SB, who planned, initiated, and oversaw all data collection. EFK conducted statistical analysis for this manuscript. ARM led the data analysis for this manuscript. KC, JGR, and SJW made major contributions related to exposure data collection. SJW, LL, SB, KC, and ARM made major contributions to exposure data reduction. ALC and ARM made major contributions to case coding and health data extraction. SB (through 2013) and ARM (starting in 2013) oversaw data reduction. LL created the computer-assisted, video-based posture analysis program. SB initiated the Upper Limb Musculoskeletal Disorder Consortium. All authors were involved in drafting the manuscript, approved the final manuscript, and agree to be accountable for all aspects of the work.

We have no known conflicts to disclose.

with forceful hand exertions per minute for three upper arm posture tertiles: flexion ≥ 45° (≥ 28.2%-time, HR = 1.11, CI [1.01, 1.22]), abduction ≥ 30° (11.9–21.2%-time, HR = 1.18, CI [1.04, 1.34]), and abduction > 60° (≥ 4.8%-time, HR = 1.16, CI [1.04, 1.29]). We failed to observe statistically significant effects for other interactions or any separate measures of biomechanical exposure.

Conclusion—This study highlights the importance of assessing combinations of exposure to forceful repetition and upper arm elevation when developing interventions for preventing RCS.

Application—Based on these results, interventions that reduce exposure to forceful repetition (i.e., lower force levels and/or slower exertion rates) may reduce the risk of RCS, especially when upper arm elevation cannot be avoided.

Précis:

We examined associations between biomechanical exposures at work and incident rotator cuff syndrome (RCS). Increased risk of incident RCS was associated with interactions between forceful repetition and upper arm elevation variables. This study highlights the importance of reducing exposure to forceful repetition, especially when upper arm elevation cannot be avoided.

Keywords

shoulder pain; ergonomics; occupational diseases; musculoskeletal diseases; rotator cuff tendinopathy; rotator cuff syndrome; work-related factors; posture; repetition; incidence

INTRODUCTION

From 1999–2013, in the U.S. State of Washington alone, the total direct cost (medical and indemnity) of lost-time rotator cuff syndrome (RCS) workers' compensation claims was $1.5 billion, representing 8 million lost work days (Marcum & Adams, 2017). While musculoskeletal disorder (MSD) rates have been declining, rates of RCS and other work-related shoulder MSDs have been declining more slowly (Bureau of Labor Statistics, 2019; Marcum & Adams, 2017). Although the etiology of work-related RCS is multifactorial, our understanding of what causes RCS is still evolving (Seitz et al., 2011); it is clear that work-related biomechanical exposures are important risk factors (Bernard, 1997; Seidler et al., 2020; Seitz et al., 2011; van Der Molen et al., 2017).

One obstacle to reducing the burden of shoulder MSDs is our limited understanding of modifiable, biomechanical risk factors, including combinations of exposure to: upper arm elevation, high repetition, static shoulder postures, forceful exertion, hand-arm vibration. Based on several review articles (Bernard, 1997; Mayer et al., 2012; Seidler et al., 2020; van Der Molen et al., 2017), there is agreement that risk factors for shoulder MSDs include: 1) upper arm elevation and 2) a combination of exposure to repeated or sustained upper arm elevation and other biomechanical factors (e.g., repetition, force). The evidence is weaker that high repetition or static shoulder postures are independent risk factors (Bernard, 1997; Mayer et al., 2012). In contrast to other upper extremity MSDs, for shoulder MSDs there is weaker evidence that forceful exertion (Dalbøge et al., 2018; Mayer et al., 2012; Seidler et al., 2020; Thygesen et al., 2016) is an independent risk factor and little indication that vibration is an independent risk factor. Combinations of biomechanical exposures as risk factors for shoulder MSDs are not well characterized. The Danish job exposure matrix (JEM) “shoulder load” variable is the most commonly reported measure of combined exposure associated with shoulder MSD risk (Dalbøge et al., 2014, 2018; Svendsen et al., 2013). The Danish JEM shoulder load variable is categorical with three-levels (high, medium, and low) and refers to separate or combined exposures to three measures — forceful exertion rating, upper-arm elevation above 90° (hours/day), and repetitive work (hours/day). Recently, Gallagher and colleagues have proposed that forceful repetition could be an important biomechanical risk factor for any MSD based on their research applying fatigue failure theory to understand cumulative soft tissue damage involved in MSDs (Gallagher & Schall Jr, 2017; Gallagher et al., 2018). Among fourteen articles included in a 2020 systematic review (Seidler et al., 2020), two cross-sectional studies (Frost et al., 2002; Silverstein et al., 2008) and zero longitudinal studies analyzed specific combinations of biomechanical exposures.

More high-quality, longitudinal epidemiology studies of clinically assessed shoulder MSDs designed to detect quantitative exposure-response relationships are still needed (Bernard, 1997; Mayer et al., 2012). This research project is one of ten high-quality, field-based MSD cohort studies funded by the U.S. National Institute for Occupational Safety and Health (NIOSH) (Garg & Marrass, 2014) to examine associations between biomechanical work exposures and work-related MSDs. To address methodological limitations of previous epidemiologic MSD studies, the study methods for these cohorts (Upper Limb Musculoskeletal Disorder Consortium) all included: 1) using a prospective study design; 2) using quantitative, task-based exposure measures that included computer-assisted posture analysis; 3) using case definitions based on self-reported symptoms and clinical examinations; and 4) controlling for confounding by personal characteristics, psychosocial exposures, and other work factors. The current study of RCS was conducted to quantify exposure-response relationships between risk of developing RCS when controlling for personal, work environment, and dissimilar biomechanical confounders (different primary domains). Specifically, our aim was to quantify dose-response associations between incident RCS using: 1) separate measures of biomechanical exposure to forceful exertion, repetition, vibration, and upper arm elevation; and 2) specific combinations of those biomechanical exposure variables. We expected that dose-response patterns for the risk of developing RCS would be stronger for combinations of exposures, especially when upper arm elevation was combined with higher exposure to other biomechanical exposure variables.

METHODS

In this study, we analyzed data from the NIOSH cohort study of work-related upper limb MSDs. The analyses presented in this paper are specific to incident RCS. Study cohort and data collection methods for the overall study have been described more fully in prior publications that focused on hand/wrist exposures and carpal tunnel syndrome (Burt et al., 2011; Burt et al., 2013; Wurzelbacher et al., 2010). We briefly summarized the study population and methods below and provide detailed descriptions of methods specific to studying RCS. This research complied with the American Psychological Association Code of Ethics and was approved by the NIOSH Institutional Review Board. Informed consent was obtained from each participant.

Study participants and procedures

Participants—For this prospective cohort study, shoulder symptom and clinical exam data were available for 485 participants from a cohort of manufacturing (Heavy Duty Truck Manufacturing, Motor Vehicle Gasoline Engine and Engine Parts Manufacturing) and healthcare (General Medical and Surgical Hospital) workers recruited from three research sites. All study participants were full-time workers and had at least three months work experience (Burt et al., 2011). We excluded participants with missing health outcome variables or who met the case definition criteria for RCS at baseline; participants with missing health outcome follow-up data were lost to follow-up.

Data collection—From 2002–2005, complete, individual on-site assessments were conducted at baseline and annually for up to two years to administer questionnaires, conduct biomechanical exposure assessments, videotape all job tasks, and perform clinical assessments (Burt et al., 2013). Our investigators used a questionnaire to collect information on personal characteristics, health history, work history, work environment (including psychosocial factors such as job strain) (Hurrell Jr & McLaney, 1988; Karasek et al., 1998; McNair et al., 1971; Radloff, 1977), physical activities outside of work, and musculoskeletal symptoms (neck, hand, wrist, elbow, shoulder) (Kuorinka et al., 1987). Trained analysts (e.g., ergonomists, industrial hygienists) conducted biomechanical exposure assessments that included force ratings and determining vibration exposure (yes/no) by job task (Borg, 1982). Each job task, as defined by Bao and colleagues (2009), was video recorded at 30 frames/s from two angles (17 minutes for single task jobs and 12 minutes per task for multi-task jobs). Usually, the cameras were positioned at right angles to each other to allow clear views of the subject's sagittal and transverse planes. Biomechanical exposures were also reassessed after baseline site visits every six months if an individual participant changed job titles, production lines, or departments (Burt et al., 2013).

Laboratory exposure analysis

Detailed time study: Repetition rates and duty cycles of total exertion and forceful exertions (grip force ≥ 40N or pinch force ≥ 10N) were extracted by conducting a detailed time study using the Multimedia Video Task Analysis™ system (Yen & Radwin, 1995), as described by Wurzelbacher et al. (2010).

Posture analyses: The computer-assisted, video-based method we used to conduct upper extremity posture analysis for this study was based on a video frame sampling protocol similar to the one developed by Bao et al. (2006). The methods for selecting random sets of non-overlapping, one-minute video segments are presented in more detail in the online Appendix (Burt et al., 2011; Burt et al., 2006). First, 75 randomly selected still frames were analyzed for each single task job (fifteen frames from five, non-overlapping, one-minute video segments), while 45 still frames were analyzed from each task for multiple task jobs (fifteen frames from three, non-overlapping, one-minute video segments per task for multiple task jobs) (Appendix, Supplemental Figure 1). While the number of frames used to characterize each task was shorter for a multiple task job, there were more total frames used to characterize their workday. This aligns with methods used by researchers in a similar prospective cohort study that used individual, task-level exposure assessment methods (Bao et al., 2007). The sampling strategy was appropriate for this study because 1) the tasks were clearly distinguishable, 2) major tasks tended to differ in exposure, 3) we could accurately estimate task proportions, 4) task transitions were irregular, and 5) task durations were available prior to sampling (Mathiassen et al., 2003). We analyzed upper arm posture angles for each still frame and each arm using two visual analog scales accompanied by two scales depicting the full range of joint articulation for upper arm-trunk angles in two planes of motion — sagittal (60° extension–180° flexion) and frontal (75° adduction–180° abduction). Two screenshots of the program's interface for rating upper arm flexion/extension and upper arm abduction are presented in Supplemental Figure 2 (Appendix). Among three analysts who analyzed 315 frames from five tasks, interrater reliability based on Shrout/Fleiss intraclass correlation coefficients (ICC) were good (> 0.70) for all upper arm rating scales (right flexion/extension ICC = 0.84, CI [0.86, 0.81]; left flexion/extension ICC = 0.82, CI [0.84, 0.79]; right abduction ICC = 0.72, CI [0.76, 0.67]; left abduction ICC = 0.74, CI [0.77, 0.70] (Burt et al., 2006). For each posture variable, we calculated percent time per task based on the proportion of still frames where the posture angle was within a given range (e.g. ≥ 45°). For example, we calculated percent time ≥ 45° flexion by dividing the number of frames where the upper arm was flexed ≥ 45° by total number of sampled frames. Time weighted averages (TWAs) were used to estimate percent time per shift spent in upper arm flexion or abduction, using several sets of overlapping cut-points based on the literature (Bao et al., 2007; Silverstein et al., 2008).

Job-level exposures: We used three methods to calculate job-level exposures (Burt et al., 2011; Burt et al., 2013; Wurzelbacher et al., 2010): 1) TWAs of mean values using percent time spent in each task, 2) peak values among all tasks, and 3) a weighted sum of percent time using percent time spent in each task. For several participants with changes in exposure six months between annual visits (years 0.5 or 1.5), the means or maximums of the two previous values were used to calculate lagged exposure values at the next annual visit (e.g., we used the mean of exposure values from year 0 and year 0.5 for mean exposure up to year 1). Study team members who collected and analyzed exposure data were blinded to information collected for the health assessment or determination of outcome status and vice versa.

Outcome

To diagnose work-related RCS (also called rotator cuff tendinosis, tendinopathy, or disease; subacromial pain syndrome), physical therapists conducted clinical examinations of both arms and hands on all participants at baseline with annual follow-up for up to two years. Our case definition for dominant arm RCS case included a combination of 1) shoulder pain during a clinical examination induced by at least one provocative test (Sluiter et al., 2001)]; and 2) meeting both self-reported shoulder symptom criteria: a) in the past twelve months, they experienced any shoulder symptoms, and b) any shoulder pain in the past seven days (Supplemental Figure 3). Prevalent cases — met all case criteria at baseline — were excluded (censored) from the analyses for this study. Participants who met only criteria #1 or #2 were included in the study.

Statistical analysis

Univariate and multivariable Cox proportional hazard models were used to analyze the incidence of RCS. The models were stratified within the Cox model by year of follow up (years 1 and 2). Baseline values (year 0) were used for the demographic and psychosocial variables.

Missing exposure variable values were replaced with the first non-missing value from a previous visit. The final exposure variables used in the analysis represent a lag of one year. The final exposure variables were analyzed as continuous and categorical variables (tertiles/thirds). To improve model stability, tertile cut-points were determined using baseline values among cases.

Shoulder pain in the last seven days at baseline was the only demographic, psychosocial, or biomechanical characteristic excluded as a potential confounder because it is on the causal pathway between exposure and RCS. Based on subject matter knowledge, we included all other demographic/psychosocial factors in this study based on their potential to be a confounder between biomechanical exposures and RCS. Likewise, we considered biomechanical exposures with different primary domains could be confounded by other biomechanical exposures. The selection of confounders for the multivariate models began by selecting potential demographic, psychosocial, and exposure variables associated with time to event in univariate models with $p < 0.20$. A form of backward elimination was used to determine the confounders for each model (Harris-Adamson et al., 2015). All potential confounders were entered in a model and were retained if their removal resulted in a change of 10% or more in the regression coefficient of the exposure variable of interest. Potential confounders were tested in order from largest to smallest univariate p-value. To avoid overfitting the models for a given exposure variable, exposure variables in the same primary domain (force, repetition, duty cycle, vibration, and posture) were not considered as a confounder. We reduced multivariable model instability attributed to highly skewed distribution of forceful repetition values by using a categorical form of forceful repetition rate (median split). Otherwise, only continuous exposure variables were used in the selection of confounders.

Interactions between the categorical posture variables and continuous, non-posture exposure variables were tested in multivariable models to determine if the effect of a non-posture exposure variable varied by categories of a posture variable. The main effects of one categorical and one continuous variable as well as their interaction were included in a model. We used the final multivariable models for the non-posture exposure variables to analyze interactions.

We used SAS® (Release 9.4, SAS Institute, Inc., Cary, North Carolina) to conduct all calculations. The assumptions of the Cox proportional hazard model were tested in univariate models.

RESULTS

Cohort description

We excluded 34 participants from the longitudinal analyses who met the case definition criteria for RCS at baseline, resulting in 451 eligible cohort participants. We lost 58 participants due to lack of health outcome follow-up data, leaving 393 workers in the cohort (Table 1, Supplemental Figure 4). We observed 39 incident cases of RCS in 694 person-years (incidence rate = 5.62 per 100 person-years, 95% CI 4.12, 7.69). Baseline demographic, medical history, and psychosocial characteristics are presented by case status in Table 1 and descriptive results for baseline biomechanical exposures are presented in Table 2. Compared to non-cases, incident cases were older (difference in means = 5.3 years, CI [1.8, 8.8]), were more likely to have a BMI ≥ 30 kg/m2 (X^2 = 5.1, p = .02), had a higher BMI (difference in means = 2.3kg/m2, CI [0.2, 4.4]), and fewer had completed high school (X^2 = 6.0, p = .01). Mean years worked at employer for the cohort was 9.9 (SD = 8.1) and was not meaningfully different for cases compared to non-cases. Compared to non-cases, the 77 participants who had shoulder pain at baseline, but were not classified as a prevalent case, were more likely to become an incident case eventually (p < .001). No significant baseline comparisons were observed for any psychosocial factor measured. Exposures at baseline were not significantly different when stratified by baseline symptom status (data not shown).

Potential confounders

The twelve potential confounders (p < .20) are presented in Table 3 in ascending order by p-value. Age in years (HR = 1.05, CI [1.02, 1.08], p < .01), body mass index (BMI, HR = 1.05, CI [1.00, 1.10], p = .04), and TWA forceful repetition rate (HR =1.06, CI [1.00, 1.13], p = .04) were all significantly associated with increased incidence of RCS. To improve model stability, we controlled for forceful repetition rate using a two category model with a cut-point at the median, 2.8 repetitions per minute (HR =1.70, CI [0.87, 3.31], p = .12). Having at least a high school education was associated with a significant decrease in incident RCS (HR = 0.27, CI [0.10, 0.75], p < .001). Participants who had shoulder pain at baseline, but did not meet the RCS case definition, had an increased risk of developing RCS (HR = 3.91, CI [2.01, 7.63], p < .001). Univariable results for are presented in Supplemental Table 1 for demographic and psychosocial covariates where p ≥ .20, and Supplemental Table 2 for biomechanical univariable.

RCS risk associated with biomechanical exposures

Survival analysis results for adjusted models of the association between biomechanical exposures are presented in Table 4. Five variables were confounders in > 69% of models — Site (1, 2, or 3), forceful repetition rate category, supervisor support, age (years), and BMI (kg/m^2). For most results by tertile, associations were attenuated toward the null in the highest tertile. We failed to observe any meaningful associations of increased risk of RCS among the single biomechanical exposures by tertile (Table 4) and linear (trend) effects (Supplemental Table 2). It appears that there may have been a difference in risk by tertile for forceful repetition rate (p = .06), where the second tertile was less hazardous than the first or third tertiles. Any risk associated with forceful repetition rate was unlikely to be linear

(linear effect: HR = 1.06, CI [0.98, 1.14]). For linear effects, adjusted results did not vary substantially compared to unadjusted hazard ratios (Supplemental Table 2).

Figure 1 presents hazard ratios for interactions between tertiles of upper arm flexion and abduction posture exposures (% time) and analyst rated force (charts A-D), total repetition rate (charts E-H), and forceful repetition rate (charts I-L). When working with the upper arm abducted ≥ 30° for 12%-time to 21%-time, each unit increase in total repetition rate and forceful repetition rate was associated with a statistically significant increased risk of incident RCS (total repetition: HR = 1.11 , CI [1.04, 1.34]; forceful repetition: HR = 1.18 , CI [1.04, 1.34]) . Forceful repetition was also associated with increased risk of RCS when working with the upper arm abducted ≥ 60° for ≥ 5%-time (HR = 1.16 , CI [1.04, 1.29]) or flexed ≥ 45° for ≥ 29%-time (HR = 1.11 , CI [1.01, 1.22]). Overall, significant interactions between posture variables and biomechanical variables from other domains were rare; we found no significant increased risk of RCS for interactions between upper arm posture tertiles and force ratings, duty cycle, or vibration exposure measures. Numeric interaction results for all variables are available in Supplemental Tables 3-6.

DISCUSSION

The prevalence and incidence of clinically assessed RCS in our study of 393 manufacturing and healthcare workers were consistent with other work-related shoulder MSDs studies (Bodin et al., 2012; Hegmann et al., 2014; Herin et al., 2012; Miranda et al., 2008; Silverstein et al., 2008). In this cohort, we found significant increased risk of incident RCS for interactions between forceful repetition and three of four upper arm elevation variables. Imprecise, monotonic increases were observed for both repetition variables for upper arm postures ≥ 45° flexion and ≥ 60° abduction but were attenuated in the High tertile for abduction ≥ 30°.

Forceful, repetitive work combined with upper arm elevation

Positive associations with incident RCS for forceful repetition rate alone approached statistically significance ($p < .10$), but when combined with Medium or High upper arm elevation exposure groups the risk increased and was statistically significant. In general, as upper arm elevation angles increased, participants could spend less time in those postures (lower tertile cut-points) without increasing their risk of developing RCS for each unit increase in forceful repetition rate. Working with upper abduction ≥ 60° for as little as 5%-time was associated with increased risk when combined with forceful, repetitive work. Although these results were consistent with two cross-sectional studies (Frost et al., 2002; Silverstein et al., 2008), most similar studies included in recent systematic reviews have not included a specific measure of forceful repetition (Dalbøge et al., 2014; Mayer et al., 2012; van Der Molen et al., 2017). The Danish JEM lacks a forceful repetition component; their shoulder load variable includes forceful exertion rating, upper-arm elevation above 90° (hours/day), and repetitive work (hours/day). Despite the differences between our forceful repetition variable and the Danish JEM shoulder load variable (includes upper arm elevation > 90°), our results for exposure to forceful repetition and interactions with our posture variables seem consistent with the Danish results for combinations of exposures (Dalbøge et al., 2014, 2018; Svendsen et al., 2013). Our results also may support recent work conducted by Gallagher and colleagues who hypothesize that cumulative damage to musculoskeletal soft tissues can be explained by applying fatigue failure theory to understand cumulative soft tissue damage involved in MSDs (Gallagher & Schall Jr, 2017; Gallagher et al., 2018). If true, forceful repetition could be an important biomechanical risk factor for any MSD, including RCS. More research is needed in this area; however, our results may support their hypothesis (Gallagher & Schall Jr, 2017; Gallagher et al., 2018).

Exposure to upper arm elevation

In contrast to this study, other studies have demonstrated that working with extreme upper arm postures (e.g., ≥ 60°) is a risk factor for shoulder MSDs — especially ≥ 90° (Bernard, 1997; Dalbøge et al., 2014; Mayer et al., 2012; Seidler et al., 2020; Svendsen et al., 2013). We propose that the lack of positive findings for extreme upper arm postures in this study may be attributed to three factors: (1) Healthy worker survival bias may be a limitation of our study that could account for the unexpected upper arm elevation results; we will discuss this topic in the Limitations section. (2) Compared to most large, Scandinavian registry studies (Dalbøge et al., 2014, 2018, 2019; Svendsen et al., 2013), where exposures are accumulated across a minimum of five years up to a person's working lifetime, our follow-up time was limited to two years (Dalbøge et al., 2014, 2018; Svendsen et al., 2013). At low exposure magnitudes, it may take many years of cumulative exposure to increase risk. This is consistent with a recent meta-analysis that calculated risk of developing specific shoulder diseases by calculating cumulative exposures for a number of studies and then conducting a meta-analysis that found an increase in risk after 1000 cumulative hours of work above shoulder level (Seidler et al., 2020). In contrast, recent analyses by Dalbøge et al (2018, 2019) found that compared to people who worked above shoulder level for no more 2.25 min/day, the risk of developing one of several rotator cuff related shoulder diagnoses was elevated when a person's cumulative exposure was at least 2.25 min/day for 1 year working above shoulder level (Dalbøge et al., 2019). (3) Due to sparse numbers of cases per tertile, our analysis was sensitive to relatively minor differences in category cut-points. For example, in early analyses we found a significant association between spending ≥ 4.3%-time in ≥ 90° flexion; however, after the cut-point was changed to 3.5%-time to improve model stability, the association was no longer significant.

Limitations

A lack of statistical power, our simple method of characterizing shoulder posture, and potential bias due to healthy worker survivor bias (Picciotto et al., 2013) are the three main limitations of this study. (1) As mentioned above, sometimes relatively small changes in the tertile cut-points had a substantial effect on our results due sparse numbers of cases per group. Despite a relatively large sample size, the number of RCS cases was relatively small. It is possible that some of our results were not statistically significant and unstable due to inadequate power. For example, our power to detect a HR of 2.0 between the middle tertile exposure group compared to low group, with an alpha level of .05 was 33% for flexion ≥ 45° flexion. For each unit change in forceful repetition rate at an alpha level of .05, our power was 81% to detect a HR of 1.12; for middle tertile exposure group compared to the low group our power was 81% to detect a HR 3.0, but only 43% to detect HR 2.0 for the same group comparison. Despite this limitation, we found statistically significant, meaningful results for interactions between forceful repetition and three of four posture variables. (2) Our upper arm flexion and abduction measures may have overly simplified shoulder loading. Even using the most sophisticated methods available today (e.g., three-dimensional kinematics using imaging, motion capture, digital human models, multibody kinematics optimization), the three bones, four joints, and seventeen muscles help make the shoulder anatomically complex, highly mobile, and challenging to model the joint and muscle loads (Blache et al., 2019; Chopp-Hurley & Dickerson, 2015; Dickerson et al., 2020). Superior humeral head translation (e.g., shoulder shrug), or other scapulothoracic motions were not measured in this study. By assessing two-dimensional upper arm posture angles, we were unable to measure the effects of other shoulder positions on the kinematic loads at the shoulder. Scapulothoracic motions affect rotator cuff muscle demands and, depending on the upper arm elevation angles, can increase or decrease subacromial space (Chopp-Hurley & Dickerson, 2015). Humeral elevation seems to be along the causal pathway to rotator cuff damage (Dickerson et al., 2020). (3) Healthy worker survival bias occurs when healthy workers are lost disproportionately from highly exposed groups due to employment termination (Applebaum et al., 2011; Picciotto et al., 2013; Stayner et al., 2003). For many of our analyses, we observed attenuation or decline of risk for the highest exposure group. This pattern has been observed in other studies of MSDs and is often attributed to healthy worker survival bias (Applebaum et al., 2011; Picciotto et al., 2013; Stayner et al., 2003). Among the 58 participants lost to follow-up, 17 left the study because they left employment, but only one person listed shoulder pain as a reason for leaving employment. Among the 41 other participants who left the study, seven reported shoulder pain at baseline. Also, at baseline, the mean and median time at current job for this cohort were 6.9 and 4.0 years. Although tenure at current employer, current job, and in current occupation were not different between cases and non-cases, all values were relatively high. It is possible that these relatively long tenure employees are less vulnerable to developing work-related MSDs that might lead someone to change jobs. When years of tenure met our criteria, we did control for it as a confounder. In Table 4, the footnotes for confounder code g can be used to find the four models that retained the variable.

Conclusions

This study highlights the importance of assessing forceful repetition and upper arm elevation as risk factors when developing JEMs and interventions for preventing RCS. Based on these results, interventions that reduce exposure to forceful repetition (i.e., lower force levels and/or slower exertion rates) may reduce the risk of RCS, especially when upper arm elevation cannot be avoided. Likewise, when forceful and repetitive work cannot be eliminated, limiting time spent with upper arms elevated ≥ 30° abduction and ≥ 45° flexion may reduce risk of RCS.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

This research was supported by intramural funds, awarded as part of a competitive process within the U.S. Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. We would like to acknowledge contributions to many current and former NIOSH staff or contractors whose contributions to this study at various stages over the last twenty years have been invaluable (in alphabetical order): Steve Allee, James Deddens, Bill Ehling, Lawrence J. Fine, TJ Lentz, Jean Geiman, Kim Jenkins, Denise Giglio, Chip Lehman, Donna Pfirman, Diane Papes, Avima Ruder, Diane Wormus, and Yan Yin. The authors would also like to acknowledge the contributions of Stephen Bao for consultation on exposure assessment and for reviewing the manuscript; Carisa Harris Adamson, Candice Johnson, and Kaitlin Kelly-Reif for consultation on epidemiology methods and interpretation; Brian Lowe and Andreas M. Neophytou for reviewing the manuscript. We also thank the employees, management and union representatives at participating worksites.

Disclaimer

Note: The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

Biography

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Key points:

- This study found increased risk of incident RCS for interactions between forceful hand exertions per minute and all ranges of upper arm postures.
- This study highlights the importance of assessing combinations of exposure to forceful repetition and upper arm elevation variables when conducting ergonomic assessments and designing interventions to prevent RCS.
- Lowering forceful exertion levels, slowing exertion rates, or a combination of both job modifications may reduce the risk of RCS, especially when upper arm elevation is also a concern.

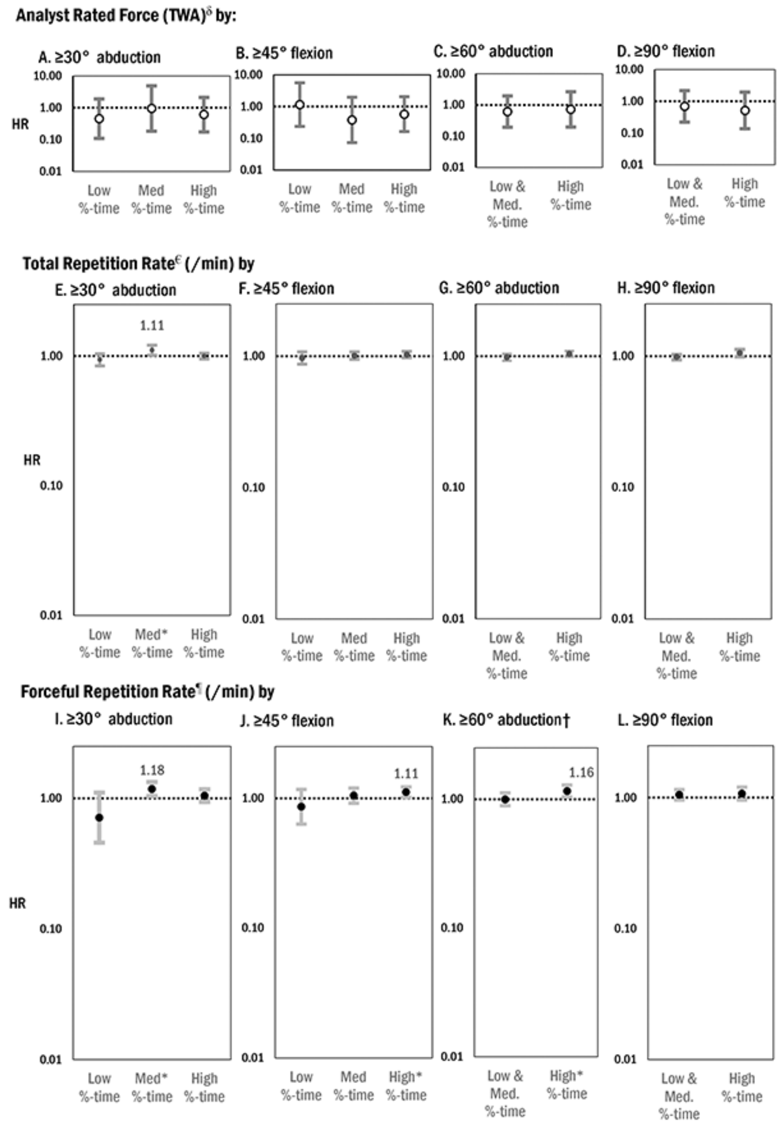

Figure 1.

Biomechanical exposure and risk of rotator cuff tendinosis: Cox proportional hazard ratios (dots) and 95% confidence intervals (grey vertical lines) for interactions between tertiles of all posture exposures (% Time) and (A-D) TWA forceful exertion ratings by analysts (Borg scale) (open dots); (E-H) total repetition (solid grey dots); and, (I-L) forceful repetition (black dots). All charts are presented on a log scale with a dashed lined to mark HR=1.0 along the y-axis.

$^{\delta}$Analyst Rated Force models main effect was HR = 0.60, CI [0.23,1.59], adjusted for: age (years), forceful element repetition rate (TWA) - median split, site (N=3), and supervisor support; None of the force differences by tertile were statistically significant, the P-value range was .25-1.00; $^{€}$Total repetition main effect was HR = 1.00, CI [0.97, 1.04], adjusted for age (years), education – at least high school, BMI, site (N=3), supervisor support, years worked at employer, job strain ratio (pd/dl), mental demands, and female; ¶Forceful repetition main effect was HR = 1.06, CI [0.98, 1.14], adjusted for BMI (kg/m2),site (N=3), supervisor support, job strain ratio; *p-value < .05; †p-value = .08 for differences between forceful repetition categories.

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Table 1.

Demographic characteristics

Characteristic	Total (N=393)*		Incident cases (N=39)		Non-cases (N=354)*		Incident case vs. Non-case
	N	%	N	%	N	%	p-value
Female	172	44	21	54	151	43	0.18
BMI ≥ 30 kg/m2	165	42	23	59	142	40	0.02
Current smoking	91	23	7	18	84	24	0.46
Tdyroid disease	30	8	3	8	27	8	0.99
Diabetes	16	4	3	8	13	4	0.23
Shoulder pain in the last seven days	77	20	17	44	60	17	< .001
Site (N =3)							0.06
Site 1. General Medical and Surgical Hospital	125	32	9	23	116	33	
Site 2. Heavy Duty Truck Manufacturing	182	46	25	64	157	44	
Site 3. Motor Vehicle Gasoline Engine and Engine Parts Manufacturing	86	22	5	13	81	23	
Age group							0.06
< 30 years old	63	16	3	8	60	17	
30 to < 40 years old	102	26	6	15	96	27	
40 to < 50 years old	130	33	17	44	113	32	
≥ 50 years old	86	22	13	33	73	21	
unknown	12	3	0	0	12	3	
Etdnicity							0.49
Asian	4	1	1	3	3	1	
African American	97	25	13	33	84	24	
Caucasian	270	69	23	59	247	70	
Hispanic	15	4	1	3	14	4	
Other	6	2	1	3	5	1	
Education							
At least a high school graduate	374		34	9	340	96	0.01
Job strain scales (high vs. low)							
High psychological job demand category	147	39	16	44	131	39	0.48
High decision latitude category	159	43	14	39	145	43	0.64
Job strain categories							0.80
Low strain (Q1, reference group)	97	26	7	19	90	27	0.35
Passive job (Q2)	132	35	13	36	119	35	
Active job (Q3)	62	17	7	19	55	16	
Job strain (Q4)	83	22	9	25	74	22	0.67
	Mean	SD	Mean	SD	Mean	SD	
Age (years)	41.6	10.6	46.4	10.2	41.6	10.6	< .01
BMI (kg/m^2)	29.6	6.3	31.6	7.1	29.6	6.3	0.06
Years worked at employer	9.9	8.1	11.9	8.1	9.9	8.1	0.09

Characteristic	Total (N=393)*		Incident cases (N=39)		Non-cases (N=354)*		Incident case vs. Non-case
	N	%	N	%	N	%	p-value
Years worked at current job	6.9	7.2	7.1	7.1	6.9	7.2	0.82
Years worked in current occupation	11.8	7.9	12.3	8.2	11.8	7.9	0.68
Psychological demands	31.6	5.4	32.6	5.8	31.5	5.3	0.22
Skill discretion	31.3	5.7	30.3	5.0	31.4	5.7	0.29
Decision autdority	31.6	6.6	31.0	7.2	31.7	6.6	0.54
Decision latitude	62.9	10.7	61.3	10.8	63.1	10.7	0.35
Job strain ratio (pd/dl)	0.5	0.1	0.6	0.2	0.5	0.1	0.11
Resource control	2.6	0.5	2.5	0.5	2.6	0.5	0.24
Task control	3.0	0.8	3.0	0.9	3.0	0.8	0.51
Task control (expanded version)	2.9	0.8	3.0	0.9	2.9	0.8	0.62
Mental demands	2.9	0.5	3.0	0.4	2.9	0.5	0.19
Supervisor support	2.3	0.8	2.5	0.7	2.2	0.8	0.09
Coworker support	2.2	0.7	2.2	0.7	2.5	0.5	0.79
Workgroup pressure	2.5	0.5	2.5	0.4	2.5	0.5	0.95
Depression (POMS)	2.9	2.1	3.2	2.0	2.8	2.1	0.41
Depression (CES-D scale score (sum))	9.2	6.1	9.8	6.6	9.2	6.0	0.56
Depression (CES-D scale mean)	0.6	0.4	0.7	0.4	0.6	0.4	0.56

BMI = body mass index; q=quartile; POMS = Profile of Mood States; CES-D = Center for Epidemiologic Studies Depression Scale

*When there was missing data for in the denominator the proportion calculations reflect the proportion among all non-missing data.

Table 2.

Dominant side biomechanical exposure values at baseline, by case status (N=393).

	Incident Cases (N=39)					Non-cases (N=354)					Incident case vs. Non-case
Exposure Variables	**N**	**Mean**	**Std Dev**	**Min**	**Max**	**N**	**Mean**	**Std Dev**	**Min**	**Max**	**(P-value†)**
Non-posture exposure variables											
Peak forceful exertion - analyst rated	39	1.26	0.42	1.00	2.55	352	1.2	0.5	1.0	5.0	0.73
TWA forceful exertion - analyst rated	39	1.24	0.53	0.33	2.75	347	1.2	0.6	0.1	5.0	0.48
Peak forceful exertion - worker rated	39	1.30	0.53	1.00	3.11	352	1.2	0.6	1.0	7.0	0.34
TWA forceful exertion - worker rated	39	1.28	0.62	0.38	3.55	348	1.2	0.7	0.1	6.0	0.49
TWA total repetition rate (/min)	39	15.88	8.41	0.80	35.43	348	14.2	9.7	0.7	62.6	0.30
TWA forceful repetition ratet‡ (/min)	39	4.83	6.00	0.00	30.60	348	3.1	4.2	0.0	22.2	0.09†
Total duty cycle (%Time)	39	71.2	19.3	9.7	95.8	348	69.7	19.8	9.4	100.0	0.65
Forceful duty cycle‡(%Time)	39	16.6	17.3	0.0	69.7	348	14.2	17.9	0.0	100.0	0.42
Vibration (yes/no)	39	0.28	0.41	0.00	1.00	352	0.3	0.4	0.0	1.0	0.95
Upper arm posture variables (%Time)											
Flexion ≥45°	39	23.4	14.5	0.0	66.7	338	26.9	18.9	0.0	100.0	0.26
Flexion ≥ 90°	39	4.0	5.5	0.0	21.0	338	4.8	6.7	0.0	40.7	0.48
Abduction ≥ 30°	39	16.3	11.4	0.0	46.3	338	20.0	14.4	0.0	86.1	0.13
Abduction ≥60°	39	4.7	6.8	0.0	25.7	338	6.6	7.6	0.0	44.4	0.14

‡Combination of multiple exposure variables

†When variances were unequal, we used Cochran statistic P-values and added notation (†) in last column; otherwise we used the pooled P-value.

Table 3.

Hazard ratios and p-values for univariable survival analyses with p-values < .20, in ascending order by p-value

Variable type	Characteristic or exposure variable description	Hazard Ratio	95% CI	p-value	code[†]
Demog/Psychosocial	Age (years)	1.05	1.02–1.08	< .01	a
Demog/Psychosocial	Educ - at least a high school graduate	0.27	0.10–0.75	0.01	b
Demog/Psychosocial	BMI (kg/m2)	1.05	1.00–1.10	0.04	c
Biomechanical Exp. - F,R	Forceful element repetition rate (TWA)	1.06	1.00–1.13	0.04	d
Biomechanical Exp. - F,R	Forceful element repetition rate (TWA)				d
	≤2.8 (referrent category)	1.00		-	
	≥2.8	1.70	0.87–3.31	0.12	
Demog/Psychosocial	Site (1,2, or 3)[$]			0.05	e
	Site 1. Hospital (referrent category)	1.00		-	
	Site 2. Manufacturing	2.03	0.93–4.44	0.08	
	Site 3. Manufacturing	0.73	0.24–2.24	0.59	
Demog/Psychosocial	Supervisor support	1.52	0.97–2.38	0.07	f
Demog/Psychosocial	Years worked at employer	1.04	1.00–1.08	0.07	g
Demog/Psychosocial	Job strain ratio (pd/dl)	7.42	0.72–76.20	0.09	h
Demog/Psychosocial	Mental demands	1.69	0.84–3.40	0.14	i
Demog/Psychosocial	Female	1.58	0.83–3.03	0.17	j
Demog/Psychosocial	Diabetes	2.43	0.69–8.61	0.17	k
Demog/Psychosocial	JCQ scales - High vs. low psychological job demands	1.04	0.98–1.11	0.18	l

CI=confidence interval, F=forceful exertion, R=repetition, D=duty cycle

[†] Confounder codes for multivariable results in Tables 4 and 5

[$] Site 1. General Medical and Surgical Hospital, Site 2. Heavy Duty Truck Manufacturing, Site 3. Motor Vehicle Gasoline Engine and Engine Parts Manufacturing.

Table 4.

Adjusted Hazard Ratios (HR) with 95% Confidence Intervals (CI) for associations between tertiles[¶] (among cases) of biomechanical exposures and incident rotator cuff syndrome (N=393).

Exposure variables	Cases (N)	Tertiles among cases	HR	95% CI	p-value	Confounders[†] (codes a-k)
Non-posture exposure variable domains						
Peak forceful exertion - analyst rated	37	n/a	0.97	0.46–2.04	0.93	abcdefj
TWA forceful exertion - analyst rated	11	< 0.89	1.00		0.29	adef
	13	≥ 0.89–< 1.3	0.93	0.33–2.60	0.89	
	13	≥ 1.3	0.37	0.09–1.59	0.18	
Peak forceful exertion - worker rated	37	n/a	0.91	0.43–1.95	0.81	cdefghij
TWA forceful exertion - worker rated	12	< 0.94	1.00		0.77	abcdej
	11	≥ 0.94–< 1.30	1.45	0.53–3.98	0.47	
	14	≥ 1.30	1.37	0.39–4.81	0.62	
TWA total repetition rate (/min)	13	< 9.7	1.00		0.88	abcefghij
	11	≥ 9.7–< 18.1	0.88	0.34–2.31	0.80	
	13	≥ 18.1	0.79	0.31–1.98	0.61	
TWA forceful repetition rate (/min)[δ]	12	< 0.40	1.00		0.06	cefh
	12	≥ 0.40–< 5.52	0.41	0.15–1.15	0.09	
	13	≥ 5.52	1.24	0.42–3.61	0.70	
Total duty cycle (%Time)	11	< 66.0	1.00		0.55	abcdefghijk
	14	≥ 66.0–< 84.0	1.43	0.54–3.80	0.48	
	12	≥ 84.0	0.82	0.28–2.43	0.72	
Forceful duty cycle‡ (%Time)[δ]	12	< 2.4	1.00		0.98	adef
	13	≥ 2.4–< 21.8	0.82	0.07–9.20	0.88	
	12	≥ 21.8	0.77	0.06–10.20	0.84	
Vibration (yes/no)[$]	37	n/a	0.76	0.26–2.22	0.61	acdefij
Upper arm posture variables (% Time)						
Abduction ≥ 30°	11	< 11.9	1.00		0.85	abcdfi
	10	≥ 11.9–< 21.3	0.73	0.23–2.33	0.59	
	14	≥ 21.3	0.80	0.31–2.10	0.65	
Flexion ≥ 45°	11	< 16.7	1.00		0.17	abdef
	12	≥ 16.7–28.2	1.48	0.55–3.98	0.44	
	12	≥ 28.2	0.54	0.18–1.60	0.27	
Abduction[$] ≥ 60°	22	< 4.8	1.00		0.09	be
	13	≥ 4.8	0.53	0.26–1.11	0.09	
Flexion[$] ≥ 90°	22	< 3.5	1.00		0.41	bcdeg
	13	≥ 3.5	0.72	0.33–1.58	0.41	

Note. Codes a–k in the last column refer to footnotes that list confounders included in each separate multivariable model (demographics, psychosocial, or biomechanical exposures from other domains). TWA = time weighted average.

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[†]a= Age (years); b= Education - at least a high school graduate; c= BMI (kg/m2); d= Forceful Element Repetition Rate (TWA) - median split; e= Site (N=3); f= Supervisor support; g= Years worked at employer; h= Job strain ratio; i= Mental demands; j= Female; k= diabetes

[$]for variables with two levels, the referent category includes the first and second tertile due to clustering of zero values

[*]p-value < .05.

[δ]Combination of multiple exposure domains.

[¶]First tertile is referent group;