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A Prospective Study of Musculoskeletal Outcomes Among Manufacturing Workers: I. Effects of Physical Risk Factors

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Objective: To better characterize associations between physical risk factors and upper-extremity musculoskeletal symptoms and disorders, a prospective epidemiologic study of 386 manufacturing workers was performed.

Background: Methodological limitations of previous studies have resulted in inconsistent associations.

Method: An individual, task-based exposure assessment strategy was used to assess upper-extremity exertion intensity, repetition, and time-in-posture categories. Participants recorded time spent performing daily work tasks on a preprinted log, which was then used to calculate time-weighted-average exposures across each week of follow-up. In addition, a weekly Strain Index (SI) risk category was assigned to each participant. Incident musculoskeletal symptoms and disorders were assessed weekly. Proportional hazards analyses were used to examine associations between exposure measures and incident hand/arm and neck/shoulder symptoms and disorders.

Results: Incident symptoms and disorders were common (incident hand/arm symptoms = 58/100 person-years (PY), incident hand/arm disorders = 19/100 PY, incident neck/shoulder symptoms = 54/100 PY, incident neck/shoulder disorders = 14/100 PY). Few associations between separate estimates of physical exposure and hand/arm and neck/shoulder outcomes were observed. However, associations were observed between dichotomized SI risk category and incident hand/arm symptoms (hazard ratio [HR] = 1.73, 95% confidence interval [CI] = [0.99, 3.04]) and disorders (HR = 1.93, 95% CI = [0.85, 4.40]).

Conclusion: Evidence of associations between physical risk factors and musculoskeletal outcome was strongest when exposure was estimated with the SI, in comparison to other metrics of exposure.

Application: The results of this study provide evidence that physical exposures in the workplace contribute to musculoskeletal disorder incidence. Musculoskeletal disorder prevention efforts should include mitigation of these occupational risk factors.

Keywords: manufacturing workers, musculoskeletal, risk factor, epidemiological study, occupational health

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INTRODUCTION

Work-related musculoskeletal disorders (MSDs) are an important occupational health problem among manufacturing workers. Recent data from the U.S. Bureau of Labor Statistics (BLS) show the incidence rate for MSDs requiring days away from work among all U.S. workers was 34/10,000 worker-years and accounted for 29% of all illness and injuries requiring days away from work (U.S. BLS, 2012). Reported physical risk factors for MSDs include forceful exertions, repetitive movements, and awkward postures (Bernard, 1997).

Despite the publication of many epidemiological studies exploring associations between occupational physical factors and MSDs, methodological limitations have led to inconsistent associations. Such limitations include use of self-report of exposure to forceful exertions, repetitive movements, and awkward postures (Devereux, Vlachonikolis, & Buckle, 2002; Kim, Geiger-Brown, Trinkoff, & Muntaner, 2010; Miranda, Viikari-Juntura, Martikainen, Takala, & Riihimaki, 2001; Shiri, Viikari-Juntura, Varonen, & Heliovaara, 2006; Solidaki et al., 2010); cross-sectional data collection (Devereux et al., 2002; Frost et al., 2002; Latko et al., 1999; Silverstein et al., 2008); nonspecific health outcome metrics (Devereux et al., 2002; Hsu, Chang, Wu, Chen, & Yang, 2011; Lapointe, Dionne, Brisson, & Montreuil, 2009; Werner, Franzblau, Gell, Ulin, & Armstrong, 2005); and insufficient control of confounding factors, especially those resulting from occupational psychosocial stress (Hsu et al., 2011).

Because of methodological concerns and inconsistent associations, authors have been questioning the role of occupational exposure to physical risk factors in the development of MSDs for decades. Over 20 years ago, Nortin Hadler suggested that occupational MSDs were "iatrogenic" rather than a consequence of occupational exposures (Hadler, 1990). More recently, the authors of a major review noted "scarce evidence regarding some of the frequently reported risk factors for work-related MSDs" (da Costa & Vieira, 2010). They concluded that studies with stronger methodology were needed.

In response to ongoing controversy about the role of work in the development of MSDs, the U.S. National Institute for Occupational Safety and Health funded a set of studies examining associations between physical risk factors and MSD risk. The current study was funded by this mechanism and addressed several methodological limitations of previous studies by using a prospective design, validated quantitative measures of exposure, thorough assessment of relevant covariates, and both self-reported and examination-based MSD outcomes. In a companion paper (Gerr et al., 2014), we provided results of analyses examining associations between occupational psychosocial stress and work organization factors and MSD risk.

METHOD

Study Participants

All employees of a household appliance manufacturing facility in Iowa who were at least 18 years of age and working full-time were eligible to participate. Eligible employees were recruited randomly from an employee roster. Enrollment began in April 2004 and data collection continued until March 2007. The study protocol was approved by the University of Iowa Institutional Review Board. Written consent was obtained from all participants.

Study Facility

The study facility employed approximately 2,000 workers on multiple household appliance assembly lines. The workers were represented by a labor union. Specific trade skills (e.g., electrician or machinist) were not necessary for employment on the assembly line. Skills required for the manufacturing process (e.g., brazing) were taught on the assembly line. Assembly line work stations were not designed for adjustability of height. The assembly lines were in operation during two nonrotating 8-hr shifts (day and evening).

Each assembly line was organized into distinct "areas" related to product assembly (e.g., "shelving," "door hang," and "crating"), and participants performed one or more "tasks" within each area. In this study, *task* indicates as a set of usual assembly procedures performed at a specific workstation (e.g., "install wiring" and "install condenser"). Tasks were classified as either cyclic or noncyclic. Noncyclic tasks were defined as (a) tasks for which there was no identifiable work cycle or (b) tasks for which the work cycle was longer than 3 min.

Data Collection Instruments

Data collected at enrollment. A questionnaire was administered at the time of entry into the study to obtain information about demographic characteristics, personal health, history of symptoms, illness or injury of the upper extremities, and current and past employment (see Table 1 for specific variables).

Participants who reported pain, numbness, tingling, or burning of the distal upper extremity or neck/shoulders (a) of 30 min or more total duration during the previous week, (b) of intensity 5 or higher on a 0-to-10 visual analog scale or resulting in use of analgesic medication, and (c) not resulting from acute trauma were classified as symptom positive. Distal upper extremity (i.e., hand/arm) and neck/shoulder symptoms were assessed separately.

A second questionnaire was administered to assess occupational psychosocial stress (Karasek, 1985; Karasek & Theorell, 1990) and positive and negative affectivity (Watson, Clark, & Tellegen, 1988). A detailed description of the methods used to assess stress and affectivity are provided in a companion manuscript (Gerr et al., 2014).

Data collected during follow-up. During each week of follow-up, study participants completed a preprinted log of the hours worked each day at each task and answered questions about changes in their work practices. *Weekly job change*, a time-varying dichotomous variable,

TABLE 1: Descriptive Statistics of Demographic and Personal Health Characteristics (N = 318)

Variable	M (SD)	n (%)
Personal characteristics		
Age	43.1 (10.0)	—
Female sex	—	165 (51.9)
Height males (cm)	178.7 (9.1)	—
Height females (cm)	165.2 (6.5)	—
Body mass index	27.5 (5.4)	—
Education beyond high school	—	95 (29.9)
Proportion right-handed	—	280 (88.1)
Non-White ethnicity	—	26 (8.2)
Annual household income ≥ $50,000	—	130 (40.9)
Health and comorbid conditions[a]		
Hormone medication (% of women)	—	35 (21.2)
Currently pregnant (% of women)	—	1 (0.6)
Currently smoke	—	104 (32.7)
Hand outcome comorbidity	—	45 (14.2)
Past history of hand/arm pain	—	64 (21.1)
History of cervical disk disease	—	10 (3.1)
Past history of neck/shoulder pain	—	26 (8.2)
Work and nonwork activities		
Hours per week primary assembly job	31.9 (10.0)	—
Hours per week at second job	1.1 (4.4)	—
Hours per week UE-intense activities	3.7 (6.4)	—
Hours per week nonwork aerobic activity	0.2 (0.4)	—
Years at study worksite	15.8 (11.1)	—
Second shift	—	84 (26.4)
Psychosocial factors and work organization		
Decision latitude ("control")[b]	56.2 (9.8)	—
Psychological job demand[b]	23.1 (3.3)	—
Coworker support[b]	17.7 (2.4)	—
Supervisor support[b]	14.3 (2.9)	—
Negative affectivity	16.5 (5.2)	—
Stress (from task log VAS)	3.3 (2.1)	—
Task or job change		48 (15.1)

Note. UE = upper extremity; VAS = visual analog scale.
[a]Comorbidity includes rheumatoid arthritis and other collagen vascular disease, tobacco use, diabetes, alcoholism, thyroid disease, and renal failure.
[b]Obtained from the Job Content Questionnaire.

was coded as positive for participants who reported on the weekly task log a change in "your usual tasks or workstations" or "the tools used at your workstation" that, in the opinion of the study ergonomist, resulted in a meaningful change in exposure to physical risk factors. In addition, the experience of new musculoskeletal symptoms was captured on the log using the symptom questions and criteria described earlier. The logs also included a visual analog scale to collect information on current job stress and questions about participants' hobbies and other

TABLE 2: Prevalence and Incidence of Hand/Arm Symptoms, Hand/Arm Disorders, Neck/Shoulder Symptoms, and Neck/Shoulder Disorders

Condition	n^a	Prevalence (%)	n^b	Incidence[c]
Hand/arm symptoms	77	19.0	100	58.0
All hand/arm disorders	45	11.8	43	19.0
Medial epicondylitis	2	0.5	4	1.8
Lateral epicondylitis	4	1.0	14	6.2
Flexor carpi radialis tendonitis	3	0.8	5	2.2
Flexor carpi ulnaris tendonitis	0	0	3	1.3
Digital flexor tendonitis	0	0	3	1.3
Dorsal Compartment 1 tendonitis[d]	4	1.0	7	3.1
Dorsal Compartment 2 tendonitis	1	0.2	2	0.9
Dorsal Compartment 3 tendonitis	1	0.2	3	1.3
Dorsal Compartment 4 tendonitis	1	0.2	3	1.3
Dorsal Compartment 5 tendonitis	2	0.5	0	0
Dorsal Compartment 6 tendonitis	5	1.3	0	0
Trigger finger	2	0.5	0	0
Carpal tunnel syndrome	26	6.8	20	8.8
Guyon canal syndrome	0	0	0	0
Neck/shoulder symptoms	65	16.8	93	53.8
All neck/shoulder disorders	29	7.6	33	14.1
Somatic neck pain syndrome	22	5.7	25	10.7
Rotator cuff tendonitis	11	2.9	7	9.4
Bicipital tendonitis	6	1.6	7	9.4

[a]Number of prevalent events.
[b]Number of incident events.
[c]Incidence reported as events per 100 person-years.
[d]DeQuervain's tendonitis.

employment, if any. The logs were collected and reviewed weekly by study staff.

Clinical Assessment

An experienced occupational medicine physician performed a standard clinical assessment of newly enrolled participants who met criteria for musculoskeletal symptoms. Participants reporting symptoms during follow-up were also asked to participate in a clinical assessment. The physician was blinded to participants' work and physical exposure status. Specific MSDs assessed are listed in Table 2. Disorder case definitions and associated examination maneuvers were based on published literature (Gerr et al., 2002; Harrington, Carter, Birrell, & Gompertz, 1998; Sluiter, Rest, & Frings-Dresen, 2001; Waris et al., 1979).

Assessment of Exposure to Physical Factors

For each participant, a 10-min sample of the intensity of forceful exertions, repetition, and postures assumed by the upper extremity and neck was obtained during performance of each of his or her assigned task(s). For study participants with multiple tasks, each task was sampled separately so that representative measures of exposures typical for that participant were obtained. The time spent performing each task during each work day (reported on the logs) was combined with the exposure measures to construct time-weighted-average (TWA) exposure estimates for each week of follow-up. Repeat exposure measures were obtained when participants met criteria for a "weekly job change" (see earlier definition).

Forceful exertions. The intensities of distal upper extremity and neck/shoulder forceful exertions were estimated with surface electromyography (EMG). Muscles of interest included the flexor digitorum superficialis (flexor) and the extensor digitorum communis (extensor) for the distal upper extremity and the upper trapezius for the neck/shoulder. The fundamental variable of forceful exertions was, for each task and for each muscle separately, the mean normalized root mean square (RMS) EMG amplitude (expressed as percentage relative voluntary exertion, %RVE). Weekly TWAs of %RVE values were estimated by weighting the mean %RVE for each task by the proportion of the total work week engaged in each task.

Preamplified surface EMG electrodes (EQ, Inc., Chalfont, PA) were secured using standard placement guidelines (Zipp, 1982) and skin preparation procedures. The electrodes were attached to a custom four-channel data logger providing real-time RMS processing (100-ms time constant). Additional technical details can be found elsewhere (Fethke, Anton, Cavanaugh, Gerr, & Cook, 2007). The RMS-processed EMG signals were sampled at 100 Hz.

Only the dominant upper extremity was instrumented. All task EMG was normalized to submaximal, isometric reference exertions (%RVE) and corrected for resting EMG amplitude. Each reference exertion was 15 s in duration, and a minimum of three repetitions were performed. With the instrumented arm abducted in the scapular plane, the elbow extended, and the forearm pronated, participants grasped a handgrip dynamometer (GripTrack Commander, J-Tech Medical Industries, Heber City, UT). A 20 N weight was then placed over the dorsum of the hand, and simultaneously, participants were instructed to maintain a handgrip force of 89 N.

The mean RMS amplitude of the middle 10 s of each reference exertion was calculated for each muscle separately. Additional repetitions were performed if, for any muscle, the coefficient of variation of the mean RMS amplitudes from the first three repetitions exceeded 10% (Mathiassen, Winkel, & Hägg, 1995). For each muscle, the reference value used for normalization was the average of the mean RMS amplitudes from the three (or more) reference exertions. For each participant, EMG signals were then recorded during typical performance of each of his or her tasks. All postrecording EMG processing and analyses were performed with a custom program (Fethke, Anton, Fuller, & Cook, 2004).

Repetition. Repetitive hand movements were assessed with the Hand Activity Level (HAL) method (Latko et al., 1997). Video recordings were obtained with two digital video cameras, one focused on the dominant-side sagittal plane and the other on the frontal plane. The video recordings from each task were synchronized and combined into a single split-screen video file.

Two trained investigators blinded to participant health status rated repetition on the HAL scale for each participant and each task by viewing three representative work cycles. Rating consensus was obtained as described by Latko et al. (1997). Weekly TWAs of the HAL ratings were estimated by weighting the HAL rating for each task by the proportion of the total work week the participant spent engaged in each task.

Posture. Multimedia Video Task Analysis™ (MVTA; Ergonomics Analysis and Design Research Consortium, Madison, WI) was used to assess postures of the neck, shoulder, and wrist (Bao, Spielholz, Howard, & Silverstein, 2006; Meyer & Radwin, 2007; Yen & Radwin, 2000). The method has good inter- and intrarater reliability for the neck and upper extremity (Dartt et al., 2009).

Neck posture was categorized as neutral (20° extension to 45° flexion), non-neutral flexion (>45° flexion), or non-neutral extension (>20° extension) (Juul-Kristensen, Fallentin, & Ekdahl, 1997; Keyserling, 1986). Three shoulder posture categories were used: 0° to 59° elevation (i.e., flexion or abduction), 60° to 90° elevation, and >90° elevation (Juul-Kristensen et al., 1997; Keyserling, 1986). Since the precision of estimates of observed wrist posture is modest (Juul-Kristensen, Hansson, Fallentin, Andersen, & Ekdahl, 2001; Ketola, Toivonen, & Viikari-Juntura, 2001; McAtamney & Corlett, 1993; Moore & Garg, 1995), three categories of wrist posture were used: neutral (30° flexion to 30° extension), non-neutral wrist flexion (> 30° flexion), and non-neutral wrist extension (> 30° extension) (Spielholz, Silverstein, Morgan, Checkoway, & Kaufman, 2001).

The work cycles identified for HAL analyses were also used for the MVTA analyses. For each cycle, postures of the neck, shoulder, and wrist were categorized on a frame-by-frame basis. The percentage of time in each posture category was calculated as the frequency count of observations within each category divided by the total number of video frames across the three work cycles. Weekly TWAs were estimated by weighting the percentage of time in each posture category for each task by the proportion of the total work week the participant spent engaged in each task.

Exposure assessment for noncyclic tasks. The exposure assessment sampling duration was increased to 20 min for noncyclic tasks. For forceful exertions, the mean EMG amplitude was computed over the 20-min sampling duration. For repetition, a fixed-interval sampling strategy was used to estimate the HAL ratings. Specifically, the 20-min video recording was parsed into 10 sequential 2-min periods, and a HAL rating was made during observation of the first 30 s of each 2-min period. The final HAL rating for the task was computed as the average of the 10 HAL ratings. For posture analyses, the first 30 s of each of the 10 sequential 2-min periods were analyzed frame-by-frame. The percentage of time in each posture category was then calculated as the frequency count of observations within each category divided by the total number of video frames across the ten 30-s analysis periods.

Strain Index. In contrast to the separate measures of forceful exertion, repetition, and posture described previously, the Strain Index (SI; Moore & Garg, 1995) combines ratings of six exposure parameters (i.e., overall intensity of exertion, hand-wrist posture, exertions per minute, percentage duration of exertion, speed of work, and duration per day) into a single continuous score, with higher scores indicating greater distal upper-extremity MSD risk. SI scores were calculated separately from all other exposure assessment procedures. Once calculated, the scores were dichotomized, with values of <5 assigned to the referent category and values of ≥5 assigned to the exposed category (Moore & Garg, 1995).

Because of limited resources, a grouped exposure assessment strategy was used for the purpose of assigning SI scores (rather than the individual exposure assessment strategy described earlier). First, tasks were consolidated into "task similarity groups" on the basis of assembly area, assembly procedures performed, and judgment of study ergonomists. Next, the intensity of exertion, hand-wrist posture, exertions per minute, percentage duration of exertion, and speed of work were rated for a single randomly selected task within each group and the ratings assigned to all tasks within that group. Detailed descriptions of the procedures used to establish and verify task similarity groups are available elsewhere (Meyers, Gerr, & Fethke, 2014). The final SI parameter, the duration per day each task was performed, was obtained from the logs completed by participants during each week of follow-up. With all SI parameter ratings available for each task, the Cumulative Strain Index approach (Garg, 2006) was used to calculate daily SI scores for each participant. The SI score category associated with the highest daily SI score during each week of follow-up was used as the time-varying SI exposure variable.

Data Analysis and Statistical Methods

All neck and shoulder disorders were pooled into a single neck/shoulder disorders outcome, and all distal upper-extremity disorders were pooled into a single hand/arm disorders outcome. The analyses were performed separately for each of four primary musculoskeletal outcomes: (a) hand/arm symptoms, (b) hand/arm disorders, (c) neck/shoulder symptoms, and (d) neck/shoulder disorders. For each outcome, participants meeting the study case definition at the time of entry were not eligible for inclusion in the analyses of risk factors for that outcome. For example, a participant reporting wrist pain at entry that met study symptom criteria (i.e., a prevalent symptom case) but who had no wrist disorder on examination was not included in the analysis of incident hand/arm symptoms; however, the participant was included in the analysis of incident hand/arm disorders.

Imputation of exposure. Occasionally, repeat exposure measures were not feasible to obtain for participants who reported task changes. For example, a participant may have moved to a different assembly area for a single day and then back to his or her original assignment on the following day. Imputation of missing exposure data was performed using multiple information sources, starting with participants' prior exposure estimates while engaged in similar tasks and, if not available, then with measures of others performing the same tasks, exposure information collected in that assembly area, or finally, the average of the entire study facility. All imputations were performed independently of health outcomes.

Unadjusted rates and relative risks. Prevalence and incidence rates were calculated separately for each of the four primary musculoskeletal outcomes and for the specific disorders meeting study case definitions. Unadjusted relative risks (i.e., hazard ratios [HRs]) of the associations between physical risk factors and time from enrollment to the first occurrence of each of the four outcomes were estimated separately using Cox regression models (Cox & Oakes, 1984; Kalbfleisch & Prentice, 2002). Consistent with standard analytical practice, participants who left the study without manifesting the outcome were censored at the time they were lost to follow-up. Separate models were constructed for each of the four primary musculoskeletal outcomes. When appropriate, time-varying independent variables were used to model changes in a participant's risk due to changes in his or her exposure during the study (Cox & Oakes, 1984).

Multivariable analysis. Adjusted relative risks were also estimated using survival analysis methodology. Because of the large number of variables, an initial screening to eliminate variables unlikely to be confounders was performed. First, the association between all potential confounders (i.e., personal characteristics, health and comorbid conditions, occupational characteristics, occupational psychosocial stress, and work organizational factors) and time to the first occurrence of each of the four outcomes was estimated separately. Those variables associated with each outcome with probability of <0.2 were retained as potential confounders and included in the initial, fully saturated multivariable model for that outcome. Thus, for each of the four outcomes, the initial multivariable models included the a priori selected physical risk factor variables of interest and all potentially confounding variables remaining after initial screening.

The a priori selected physical risk factor variables were chosen for inclusion in the multivariable models on the basis of biomechanical and physiological reasoning. Specifically, a priori selected physical exposure variables for the hand/arm outcomes were percentage time wrist flexion, percentage time wrist extension, extensor EMG amplitude, flexor EMG amplitude, and HAL. Multivariable models of the hand/arm outcomes included all of these variables, simultaneously. Analyses of associations between SI category (an additional a priori physical risk metric) and the hand/arm outcomes were modeled separately from the other physical risk factors. A priori selected physical exposure variables for the neck/shoulder outcomes were percentage time shoulder elevation category (≥60° to 90°, >90°), percentage time neck flexion, percentage time neck extension, HAL, and trapezius EMG amplitude. Multivariable models of the neck/shoulder outcomes included all of these variables, simultaneously.

Once models with the a priori physical risk factor variables and the potentially confounding variables remaining after initial screening were constructed, the potentially confounding variables were removed sequentially, and the change in the HR for the association of each of the psychosocial and work-organizational measures with each musculoskeletal outcome was examined separately. While performing this modified backward elimination procedure, we removed the least statistically significant potential confounder first, with the next least statistically significant potential confounder removed next, and so on. If the HR for any of the a priori psychosocial or work organizational measures changed by more than 15% when a covariate was removed, then that covariate was retained in the model. All covariates were subject to removal. The final model for each of the four outcomes included the a priori selected physical risk factors and only those covariates that confounded their relationships with the outcome.

Additional analyses. With the exception of the SI, two full sets of data analyses were performed. In the first set of analyses, all continuous variables were categorized into quartiles, with the lowest quartile analyzed as the referent category. In the second set of analyses, all continuous measures were analyzed in their continuous form. The analyses of categorical variables allowed us to assess possible nonlinear associations, and the analysis of continuous variables allowed us to minimize the number of parameters in the models and use the full information content of the data. For the SI, only categorical analyses were performed.

Two sets of analyses were conducted to explore differences in association between exposure and musculoskeletal outcome by gender. First, separate gender-stratified analyses were performed, and the parameter estimates of the physical exposure variables were compared between the male and female strata. Second, formal Gender × Exposure interaction terms were introduced into all models to formally test for effect modification.

In addition, because of the possibility that the highest exposure to each physical risk factor experienced during each week of follow-up was more strongly associated with musculoskeletal outcomes than were weekly *average* exposures, associations between weekly peak physical risk factor exposures and musculoskeletal outcomes were also modeled.

All analyses were performed using the SAS v 9.2 (SAS Institute, Cary, NC).

RESULTS

Study Participants

Initial contact was made with 749 eligible workers, of whom 386 agreed to participate (51.5%). Participants contributed a total of 12,119 person-weeks of observation to the study. Refusals were slightly younger (39.8 years, *SD* = 11.4, vs. 42.3 years, *SD* = 10.6), were more frequently male (61.0% vs. 48.9%), and had worked fewer years at the facility (11.0 years, *SD* = 10.0, vs. 14.7 years, *SD* = 11.4). However, the participants' demographics were similar to the demographics of the production workers as a whole at the facility (data not shown). Flow charts that depict study participants for hand/arm symptoms, hand/arm disorders, neck/shoulder symptoms, and neck/shoulder disorders are provided in Figures 1 and 2.

Demographics and personal health. Demographic, personal health, occupational, psychosocial, and work-organizational characteristics of the study participants are provided in Table 1 for the 318 study participants who contributed person time to the analysis of incident neck/shoulder disorders. The mean age of the participants was 43 years, and just over half were female. The average body mass index was 27.5 kg/m^2. Slightly fewer than one third of the participants had education beyond high school, and about one third were smokers. Slightly more than one quarter worked on second shift (3 p.m. to 11 p.m.). Participants had worked at the study facility an average of 16 years at the time of enrollment.

Comparison between nondropouts and dropouts. Of the 318 participants who were eligible for inclusion in the follow-up for neck/shoulder disorders, 269 remained disorder free. Of the 269, 97 voluntarily left the study (i.e., dropped out), 77 became ineligible during follow-up (e.g., moved or quit work), and 111 remained in the study until completion. The 97 dropouts each contributed a mean of 25 person-weeks of follow-up time to the analysis. Dropouts were typically younger and worked at the facility for a shorter duration than nondropouts (Table 3).

Prevalence and Incidence of Musculoskeletal Symptoms and Disorders

Hand/arm. On entry into the study, the prevalence of hand/arm symptoms was 19% and of hand/arm disorders was 11.8% (Table 2). The most prevalent hand/arm disorder was carpal tunnel syndrome (CTS; prevalence = 6.8%).

During follow-up, the incidence of hand/arm symptoms was 58/100 PY and of hand/arm disorders was 19/100 PY (Table 2). Among hand/arm disorders, the highest incidence rate was observed for CTS (8.8/100 PY). Common tendon disorders included lateral epicondylitis (6.2/100 PY) and DeQuervain's tendonitis (tendonitis of the first dorsal compartment, 3.1/100 PY).

Neck/shoulder. The prevalence of neck/shoulder symptoms was 16.8% and of neck/shoulder disorders was 7.6% (Table 2). The most prevalent neck/shoulder disorder was

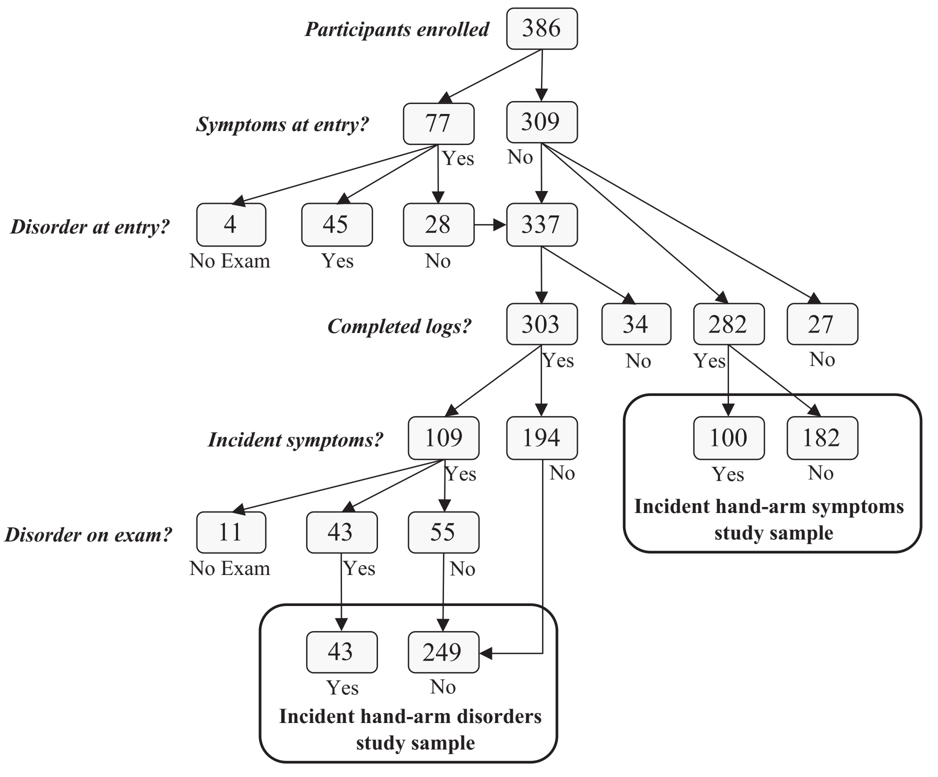

Figure 1. Hand/arm study sample flow chart.

somatic neck pain syndrome (also called tension neck syndrome, prevalence = 5.7%).

The incidence of neck/shoulder symptoms was 54/100 PY and of neck/shoulder disorders was 14/100 PY (Table 2). Among neck/shoulder disorders, the highest incidence rate was observed for somatic neck pain syndrome (10.7/100 PY). Incident rotator cuff tendonitis and bicipital tendonitis were also common.

Physical Exposure Characteristics

Exposure measurements were made for 1,098 tasks during the course of the study. Of these, 984 (90%) were cyclic, with an average cycle time of 61.2 s (*SD* = 24.5 s). Descriptive statistics for the exposure summary measures are provided in Table 4. Mean EMG amplitudes (in %RVE) of the dominant flexor, extensor, and trapezius muscles were 90.0% (*SD* = 74.5), 47.2% (*SD* = 27.3), and 46.1% (*SD* = 44.2). The mean HAL was 4.7 (*SD* = 1.3). Mean percentage times in non-neutral postures were relatively low, ranging from 2.4% (*SD* = 4.0) for shoulder elevation >90° to 14.6% (*SD* = 15.2) for neck flexion. Approximately two thirds of participants had SI scores greater than 7 during the 1st week of observation.

Unadjusted and Multivariable Associations With Musculoskeletal Outcomes

Hand/arm. Statistically significant unadjusted associations were observed between hand/arm symptoms and female sex (HR = 1.84, $p = .003$), comorbid conditions (HR = 1.77, $p = .02$), past history of hand/arm pain (HR = 3.04, $p < .001$), hours per week at hand-intensive second job (HR = 1.05, $p = .003$), and hours per week in upper-extremity-intensive nonwork activities (HR = 1.04, $p = .009$) (data not shown). With the exception of hours per week in upper-extremity-intensive nonwork activities (HR = 0.99, $p = .82$), associations between hand/arm disorders and the demographic factors were similar in magnitude to those between hand/arm symptoms and the demographic factors.

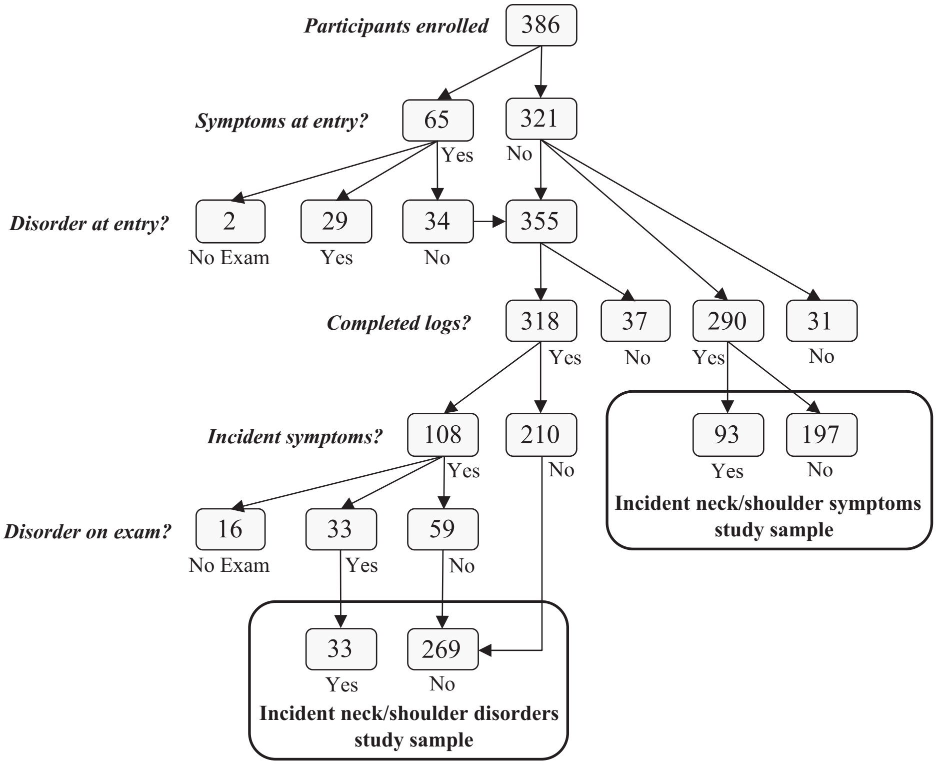

Figure 2. Neck/shoulder study sample flow chart.

Unadjusted associations between the separate physical exposure variables and hand/arm symptoms and hand/arm disorders were mostly small (Table 5). A nonsignificant unadjusted association was observed between each unit increase in HAL score and incident hand/arm disorders (HR = 1.20, 95% confidence interval [CI] = [0.95, 1.52]). Nonsignificant increases in risk of modest magnitude were observed for the SI for both hand/arm symptoms (HR = 1.69, 95% CI = [0.97, 2.93]) and disorders (HR = 1.58, 95% CI = [0.70, 3.57]).

In the adjusted models (Table 5), the association between HAL score and incident hand/arm disorders remained elevated but was not statistically significant (HR = 1.18, 95% CI = [0.89, 1.55]). SI category was nearly significantly associated with hand/arm symptoms (HR = 1.73, 95% CI = [0.99, 3.04]) and strongly, but nonsignificantly, associated with hand/arm disorders (HR = 1.93, 95% CI = [0.85, 4.40]).

Neck/shoulder. Statistically significant associations were observed between neck/shoulder symptoms and female sex (HR = 2.32, $p < .001$) and past history of neck/shoulder pain (HR = 2.07, $p = .02$) (data not shown). Nearly statistically significant associations were observed between neck/shoulder symptoms and education beyond high school (HR = 1.48, $p = .07$) and history of disc disease (HR = 2.61, $p = .06$) (data not shown). When compared to unadjusted associations with neck/shoulder symptoms, unadjusted associations between neck/shoulder disorders and female sex (HR = 5.46, $p < .001$) and past history of neck/shoulder pain (HR = 3.76, $p = .002$) were larger. Similar to neck/shoulder symptoms, a history of disc disease was strongly, but not statistically significantly, associated with neck/shoulder disorders (HR = 3.21, $p = .11$).

Most of the unadjusted associations between the separate physical exposure variables and neck/shoulder symptoms and neck/shoulder disorders were small and nonsignificant (Table 6). However, the adjusted associations between percentage time of shoulder elevation >90° and both neck/shoulder symptoms and disorders

TABLE 3: Comparison of Those Who Remained in the Study Until Outcome or Study End (Nondropout) Versus Those Who Left Before Outcome or Study End (Dropout)

	Nondropout (n = 111)		Dropout (n = 97)		
Variable	*M* (*SD*)	*n* (Proportion)	*M* (*SD*)	*n* (Proportion)	Probability
Age (years)	46.2 (8.5)		42.0 (10.2)		.002
Duration of work at facility (years)	21.2 (9.3)		14.5 (11.0)		<.001
Time in study (weeks)	70.4 (53.0)		24.9 (28.4)		<.001
BMI (kg/m^2)	27.9 (5.1)		27.1 (5.3)		.27
Gender (female)		54 (48.7)		46 (47.6)	.86
Education (>HS Graduate)		24 (21.6)		32 (33.0)	.07
Decision latitude scale score	57.0 (9.7)		55.9 (9.6)		.37
Psychological job demand scale score	23.2 (3.4)		23.1 (2.9)		.84
Negative affectivity scale score	16.5 (5.0)		16.2 (5.3)		.65
Positive affectivity scale score	32.5 (6.7)		30.7 (7.5)		.07
Hand/arm symptoms at entry		11 (9.9)		14 (14.4)	.32
Neck/shoulder symptoms at entry		8 (7.2)		6 (6.2)	.77

Note. Nondropouts were defined as symptom-free participants who remained in the study for the full duration of follow-up. See text for details.

were statistically significant. No other statistically significant associations were observed between separate physical exposure variables and these outcomes (Table 6). The adjusted association between HAL score and incident neck/shoulder disorders was elevated but not statistically significant (HR = 1.15, 95% CI = [0.96, 1.38]).

Additional analyses. All analyses (both hand/arm and neck/shoulder) were repeated with all physical exposure variables in categorical form. No meaningful associations were observed in either unadjusted or adjusted analyses. In addition, all analyses were repeated with peak weekly physical exposure rather than TWA. Again, no meaningful associations were observed in either unadjusted or adjusted analyses. Separate analyses stratified by gender resulted in no meaningful differences in observed associations between physical risk factors and musculoskeletal symptoms or disorders. In addition, no Gender × Exposure interaction term achieved statistical significance.

DISCUSSION

We conducted a prospective epidemiological study of incident upper-extremity musculoskeletal symptoms and disorders among machine-paced assembly line workers in a large manufacturing facility. Exposures to physical risk factors and relevant covariates were ascertained with objective quantitative measures prior to incident symptoms. Musculoskeletal outcomes were ascertained by questionnaire and physical assessment.

Musculoskeletal Symptom and MSD Incidence Rates

Musculoskeletal symptoms were reported frequently by study participants. The incidence rate for hand/arm symptoms was 58/100 PY, and the incidence rate for neck/shoulder symptoms was 54/100 PY. As expected, rates for disorders were considerably lower than rates for symptoms and varied by specific disorder. Specifically, the incidence rate for hand/arm

TABLE 4: Descriptive Statistics of Physical Exposure Variables (*N* = 318)

Exposure Characteristic	*M*	*SD*
Hand Activity Level	4.7	1.3
Percentage time wrist flexion (*N* = 303)	2.8	2.9
Percentage time wrist extension (*N* = 303)	9.1	7.1
Percentage time shoulder elevation 60° to 90°	10.8	8.0
Percentage time shoulder elevation >90°	2.4	4.0
Percentage time neck flexion	14.6	15.2
Percentage time neck extension	4.9	7.0
Forearm extensor muscle (%RVE) (*N* = 303)	47.2	27.3
Forearm flexor muscle (%RVE) (*N* = 303)	90.0	74.5
Trapezius muscle (%RVE)	46.1	44.2
Strain Index category	*n*	%
≤3	60	20
>3 to <5	13	4
5 to <7	21	7
≥7	203	68

disorders was 19/100 PY, and the incidence rate for neck/shoulder disorders was 14/100 PY. During follow-up, the most common hand/arm disorders were CTS, lateral epicondylitis, and DeQuervain's tendonitis. The incidence of specific neck/shoulder disorders ranged from 9 to 11 per 100 PY.

Rates of musculoskeletal symptoms and MSDs reported among working populations vary considerably. For example, Punnett, Gold, Katz, Gore, and Wegman (2004) reported a 1-year cumulative upper-extremity symptom incidence of 14% among automobile manufacturing workers, about half of the rate we observed. Three-year incidences among persons employed across numerous occupational "sectors" in France were 12.2% for CTS, 12.2% for lateral epicondylitis, and 5.7% for wrist tendonitis (Leclerc et al., 2001). Smith, Silverstein, Fan, Bao, and Johnson (2009) reported an incidence rate of new-onset shoulder symptoms of 23.5 per 100 person-months (equivalent to 28.2 per 100 PY). Gell, Werner, Franzblau, Ulin, and Armstrong (2005) reported an annual incidence rate of CTS among industrial and clerical workers of 1.2 per 100 PY. Harris, Eisen, Goldberg, Krause, and Rempel (2011) reported an incidence rate of 5.4 per 100 PY for wrist tendinosis. In the current study, incidence rates were somewhat higher than those reported in many previous studies. Such differences in rates may be the result of varying methodology across studies or may represent true differences in actual rates.

Associations Between Musculoskeletal Outcomes and Physical Risk Factors

A statistically significant 7% increase in adjusted risk of neck/shoulder symptoms for each 1% of time with shoulder elevation >90° was observed. Nonstatistically significant adjusted increases of 18% and 15% per unit of HAL were observed for hand/arm disorders and neck/shoulder symptoms. Few other associations were observed between separate physical exposure variables and musculoskeletal outcomes.

Contrary to the modest associations between separate physical exposure variables and hand/arm outcomes, consistent positive adjusted associations were observed between the dichotomized SI category and both hand/arm symptoms and hand/arm disorders. Furthermore, when all four SI categories were included in multivariable models, a monotonic increase in HR was

TABLE 5: Crude and Adjusted Associations Between Physical Risk Factors and Hand/Arm (H-A) Outcomes

	Unadjusted				Adjusted			
	H-A Symptoms		H-A Disorders		H-A Symptoms		H-A Disorders	
Physical Risk Factor	HR	95% CI	HR	95% CI	HR	95% CI	HR	95% CI
Percentage time wrist flexion	0.97	[0.90, 1.04]	1.00	[0.91, 1.10]	0.96	[0.88, 1.04]	1.02	[0.91, 1.13]
Percentage time wrist extension	1.02	[0.99, 1.04]	0.99	[0.95, 1.03]	1.01	[0.98, 1.04]	0.97	[0.92, 1.02]
Extensor EMG amplitude (%RVE)	1.00	[1.00, 1.01]	1.00	[0.99, 1.01]	1.01	[1.00, 1.01]	1.00	[0.99, 1.02]
Flexor EMG amplitude (%RVE)	1.00	[1.00, 1.00]	1.00	[0.99, 1.00]	1.00	[1.00, 1.01]	1.00	[1.00, 1.01]
Hand Activity Level	1.10	[0.94, 1.28]	1.20	[0.95, 1.52]	1.01	[0.84, 1.21]	1.18	[0.89, 1.55]
SI category[a]	1.69	[0.97, 2.93]	1.58	[0.70, 3.57]	1.73	[0.99, 3.04]	1.93	[0.85, 4.40]

Note. HR = hazard ratio; CI = confidence interval; EMG = electromyography; SI = Strain Index. Adjusted associations between physical risk factors and hand/arm symptoms adjusted for all physical risk factors listed in table (except SI) as well as sex, height, history of hand symptoms, job strain, weekly stress level, weekly job change, second job hours per week, hand intensive activity hours per week, and supervisor support. Adjusted associations between physical risk factors and hand/arm disorders adjusted for all physical risk factors listed in table (except SI) as well as sex, weekly job stress, body mass index, comorbid conditions, and history of hand symptoms. Adjusted associations between SI risk category and hand/arm symptoms adjusted for height, history of hand symptoms, job strain, weekly stress level, weekly job change, second job hours per week, hand intensive activity hours per week. No adjustment was for any other physical risk factor. Adjusted associations between SI risk category and hand/arm disorders adjusted for weekly stress level. No adjustment was for any other physical risk factor.
[a]Dichotomized SI category.

observed across the three nonreferent categories despite very small cell sizes (data not shown), suggesting that the risk increases reported were not statistically spurious.

Differences in the associations between the separate physical exposure variables and hand/arm musculoskeletal outcomes and the associations between the SI and hand/arm musculoskeletal outcomes were not anticipated. Given the objective nature of our exposure assessment methods (EMG, in particular), we expected to observe stronger associations between the separate physical exposure variables and the musculoskeletal outcomes. Furthermore, given that some of the components of the SI are based on observer judgment and the fact that SI risk categories were developed among meatpacking workers, we did not expect associations as strong as those that were observed in this cohort. The SI may be a better metric of exposure than the separate measures of physical exposure because of its implicit assumption of multiplicative interactions among its six exposure variables. Furthermore, by pooling six exposure metrics into a single scale, the SI may also produce more stable estimates of biomechanically relevant exposure than does each of the separate exposure variables. Additional research with a large cohort in which multiple measures of physical exposure are made may allow greater insight into this observation.

Review of Previous Studies

Although suggestive of causal associations, considerable inconsistency is observed, possibly due to differences in exposure assessment methodology, ascertainment of health outcomes, and study populations. A brief review of recent prospective studies of associations between

TABLE 6: Crude and Adjusted Associations Between Physical Risk Factors and Neck/Shoulder (N/S) Outcomes

	Unadjusted				Adjusted			
	N/S Symptom		N/S Disorder		N/S Symptom		N/S Disorder	
Physical Risk Factor	HR	95% CI	HR	95% CI	HR	95% CI	HR	95% CI
Percentage time shoulder elevation 60° to 90°	1.00	[0.98, 1.03]	1.00	[0.96, 1.04]	1.00	[0.97, 1.03]	1.00	[0.95, 1.05]
Percentage time shoulder elevation >90°	1.03	[0.97, 1.07]	1.07	[1.02, 1.14]	1.04	[0.99, 1.09]	1.07	[1.00, 1.15]
Percentage time neck flexion	0.99	[0.98, 1.00]	0.98	[0.95, 1.01]	0.98	[0.97, 1.00]	0.97	[0.94, 1.00]
Percentage time neck extension	1.01	[0.98, 1.04]	0.98	[0.93, 1.04]	0.98	[0.95, 1.01]	0.94	[0.88, 1.00]
Hand Activity Level	1.06	[0.90, 1.23]	1.10	[0.85, 1.43]	1.15	[0.96, 1.38]	1.02	[0.75, 1.39]
Trapezius EMG amplitude (%RVE)	1.00	[0.99, 1.01]	1.00	[0.99, 1.01]	0.99	[0.98, 1.00]	1.00	[0.98, 1.02]

Note. HR = hazard ratio; CI = confidence interval; EMG = electromyography. Adjusted associations between physical risk factors and neck/shoulder symptoms controlled for all physical risk factors listed in table as well as sex, height, education, history of neck pain, job strain, weekly job change, and weekly job stress. Adjusted associations between physical risk factors and neck/shoulder disorders controlled for all physical risk factors listed in table as well as sex, shift, job strain, hours worked per week, history of neck pain, and weekly job stress.

musculoskeletal outcomes and occupational factors is provided next.

In Denmark, Andersen et al. (2003) observed incident neck/shoulder outcomes among 3,123 workers for up to 4 years. Task-based exposure estimation relied on video analysis of posture and movements and observer-rated force requirements. Contrary to the results of the current study, clinically confirmed neck/shoulder outcomes were associated with repetition, force, neck flexion, and lack of recovery time. Among members of the same cohort, Thomsen et al. (2007) reported that incident wrist pain was associated with metrics of repetition and force and that incident possible wrist tendonitis was associated with force only. No associations between wrist posture and incident wrist pain or incident possible wrist tendonitis were observed.

Descatha, Leclerc, Chastang, Roquelaure, and the Study Group on Repetitive Work (2003) conducted a prospective epidemiological study of occupational risk factors for medial epicondylitis among 1,757 workers from five industries in France. Contrary to the current study, forceful exertions and repetition were assessed with a self-reported questionnaire rather than by direct measurement. Incident medial epicondylitis was significantly associated with forceful work, lack of work satisfaction, and number of years on the job.

Garg et al. (2012) followed 536 workers and reported on associations between exposure with both the SI and the threshold limit value (TLV) for HAL and incident cases of nerve conduction velocity–confirmed CTS. The average CTS incidence rate was 2.6 cases per 100 PY, considerably lower than observed in the current study. Consistent with our observations for the SI, however, a significant association was observed between the SI and incident CTS.

Harris et al. (2011) observed incident cases of wrist tendinosis among 413 workers followed prospectively for 28 months. Somewhat consistent with the current study, force and repetition estimates were based on field measurement and video analysis. As was observed in the current study, the most common tendinosis was deQuervain's disease. Wrist tendinosis was significantly associated with one of several estimates of percentage time in "heavy pinch" and was associated with the TLV for HAL when total repetition rate was used to calculate the exposure metric.

Gell et al. (2005) reported results of a longitudinal study of CTS among 501 workers evaluated after an average follow-up period of 5.4 years. CTS case status was confirmed with electrophysiological testing, and all jobs were rated for physical exposure. The annualized incidence of CTS was 1.2 cases per 100 PY, considerably lower than that observed in the current study. Somewhat consistent with the current study, a nonsignificant increase in risk for CTS (odds ratio = 1.6, $p = .15$) was observed for HAL > 3.

Leclerc et al. (2001) reported associations between self-reported occupational exposures and physical examination–confirmed upper-limb disorders in a prospective study of 598 workers engaged in repetitive work. Among men, incident CTS was associated with self-reported “tighten with force” and “hold in position.” Among women, no physical occupational factors were associated with incident CTS. Among all participants, only “turn and screw” was significantly associated with epicondylitis. Among men and women combined, “repetitive hitting,” but no other exposure metric, was nearly significantly associated with wrist tendonitis.

Leclerc et al. (2004) also performed a prospective study of risk factors for shoulder pain among 594 workers engaged in repetitive work. Results for men and women were analyzed separately. Among men, repetitive use of a tool was significantly associated with increased risk of shoulder pain. Among women, no statistically significant associations were observed, but use of the arm above the shoulder had a nonsignificant elevation in risk, a finding partially consistent with the current study.

Punnett et al. (2004) followed 458 automobile manufacturing workers free of baseline upper-extremity musculoskeletal symptoms and disorders for approximately 1 year. In contrast to the current study, exposure was assessed using a Borg CR-10 scale for each of eight interviewer-administered psychophysical questionnaire items. Similar to the current study, physical examinations were used to ascertain musculoskeletal health status. At 1-year follow-up, 14% of participants met study criteria for upper-extremity symptoms, and 12% met criteria for an upper-extremity disorder. A monotonic association was observed between an index of upper-extremity physical exposure and upper-extremity disorder cumulative incidence.

Roquelaure, Mariel, Dano, Fanello, and Penneau-Fontbonne (2001) followed 199 footwear factory workers for 1 year and assessed exposure by direct observation and questionnaire. CTS was assessed by symptoms and physical examination. The annual incidence of CTS was 12%. Although a marginally significant association was observed between CTS and “rapid trigger movements,” no association was observed with repetition, wrist flexion, wrist extension, or an increased “ergonomics score.”

Violante et al. (2007) ascertained the incidence of CTS among 2,092 workers followed for 1 year in addition to estimating their HAL. Similar to the current study, the annual incidence rate of CTS was 7.3%. Participants in the “Above TLV” category had an odds ratio of 3.0 ($p < .05$) when compared to the lowest tertile.

Limitations and Strengths of the Current Study

A number of methodological limitations likely resulted in observed associations smaller than true risks. First, the study sample was highly tenured in the study facility (the mean duration of employment among study participants was 16 years). Employees who were most susceptible to musculoskeletal symptoms and MSDs either might have left employment and were not available to participate in the study or might have opted for jobs with lower levels of exposure, leaving only those less susceptible to these effects remaining in high-exposure jobs. Such “selective survival” is a well-known null bias in observational epidemiological studies (Kleinbaum, Morgenstern, & Kupper, 1981).

In addition, some of the measures of exposure might not have captured the biomechanically important exposures among these participants. Because of resource constraints, video and EMG samples were collected for no longer than 20 min per task. Longer sampling durations may have resulted in more precise estimation of exposure and less attenuation of observed associations. A previous analysis, however, suggested the selected sampling duration was sufficient to achieve acceptable precision of the task-level EMG exposure estimates (Fethke et al., 2007). Furthermore, alternative EMG summary measures, such as amplitude percentiles (Jonsson, 1982), percentage time with muscular rest (Veiersted, Westgaard, & Andersen, 1990), or combined measures of amplitude and temporal variation (Anton, Cook, Rosecrance, & Merlino, 2003; Mathiassen & Winkel, 1991) may have captured different features of the EMG signals as compared with the mean RMS amplitude. In addition, as noted in the Method section, weekly TWAs were calculated for each study participant on the basis of objective exposure to physical risk factors associated with each task and a log of daily task durations compiled by the study participant. If participants did not accurately record time spent in each task, then misclassification of weekly TWAs would result. Such misclassification would likely be independent of health status and consequently result in attenuation of observed associations.

A substantial proportion of study participants failed to complete the full duration of follow-up (i.e., were dropouts from the study). Analyses showed that the dropouts were younger, were better educated, and had spent less time working in the facility. However, they did not enter the study with meaningfully different prevalences of hand/arm or neck/shoulder symptoms. Overall, although we have no evidence of bias, it is possible that the exposure-effect association among the dropouts differed from that of those who remained in the study.

Because participants were followed for a maximum of 147 weeks, we were unable to examine associations between exposure and outcome over longer durations. Hence, an important limitation of this (and many other similar prospective cohort studies) is the limited ability to examine effects of exposures experienced by participants before enrollment.

CONCLUSIONS

Musculoskeletal symptoms and MSDs were relatively common among the participants of this prospective study of musculoskeletal outcomes among manufacturing workers. With the exception of the association between percentage time of shoulder elevation >90° and neck/shoulder disorders, few separate measures of forceful exertion, repetition, and posture were associated with hand/arm and neck/shoulder outcomes. The SI, however, was associated with hand/arm symptoms and disorders. These results are consistent with those reported by other investigators using the SI in studies of MSDs among workers. Differences in observed associations between physical hazards and musculoskeletal outcomes when the physical hazards are estimated with the SI versus separate quantitative measures were not expected and suggest that exposure assessment tools that pool multiple separate hazards into a single scale may be more useful than separate measures alone.

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KEY POINTS

- Prevalent and incident musculoskeletal symptoms and disorders were common among manufacturing workers. The most common incident hand/arm disorders were carpal tunnel syndrome and lateral epicondylitis. The incidence of the three neck/shoulder disorders—somatic neck pain syndrome, rotator cuff tendinitis, and bicipital tendonitis—were similar.
- The Hand Activity Level and the Strain Index were the physical risk factors most strongly associated with hand/arm symptoms and disorders.
- The percentage time with shoulders elevated >90° was the physical risk factor most strongly associated with neck/shoulder symptoms and disorders.

REFERENCES

Andersen, J. H., Kaergaard, A., Mikkelsen, S., Jensen, U. F., Frost, P., Bonde, J. P., . . . Thomsen, J. (2003). Risk factors in the onset of neck/shoulder pain in a prospective study of workers in industrial and service companies. *Occupational and Environmental Medicine*, *60*, 649–654.

Anton, D., Cook, T. M., Rosecrance, J. C., & Merlino, L. A. (2003). Method for quantitatively assessing physical risk factors during variable noncyclic work. *Scandinavian Journal of Work, Environment, & Health*, *29*, 354–361.

Bao, S., Spielholz, P., Howard, N., & Silverstein, B. (2006). Quantifying repetitive hand activity for epidemiological research on musculoskeletal disorders: Part I. Individual exposure assessment. *Ergonomics*, *49*, 361–380.

Bernard, B. P. (1997). *Musculoskeletal disorders and workplace factors: A critical review of epidemiologic evidence for work-related disorders of the neck, upper extremity, and low back*

(DHHS [NIOSH] Publication No. 97-141). Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

Cox, D. R., & Oakes, D. (1984). *Analysis of survival data*. London, UK: Chapman and Hall.

da Costa, B. R., & Vieira, E. R. (2010). Risk factors for work-related musculoskeletal disorders: A systematic review of recent longitudinal studies. *American Journal of Industrial Medicine*, *53*, 285–323.

Dartt, A., Rosecrance, J., Gerr, F., Chen, P., Anton, D., & Merlino, L. (2009). Reliability of assessing upper limb postures among workers performing manufacturing tasks. *Applied Ergonomics*, *40*, 371–378.

Descatha, A., Leclerc, A., Chastang, J. F., Roquelaure, Y., & the Study Group on Repetitive Work. (2003). Medial epicondylitis in occupational settings: Prevalence, incidence and associated risk factors. *Journal of Occupational and Environmental Medicine*, *45*, 993–1001.

Devereux, J. J., Vlachonikolis, I. G., & Buckle, P. W. (2002). Epidemiological study to investigate potential interaction between physical and psychosocial factors at work that may increase the risk of symptoms of musculoskeletal disorder of the neck and upper limb. *Occupational and Environmental Medicine*, *59*, 269–277.

Fethke, N. B., Anton, D., Cavanaugh, J. E., Gerr, F., & Cook, T. M. (2007). Bootstrap exploration of the duration of surface electromyography sampling in relation to the precision of exposure estimation. *Scandinavian Journal of Work, Environment & Health*, *33*, 358–367.

Fethke, N. B., Anton, D., Fuller, H., & Cook, T. (2004). A versatile program for the analysis of electromyographic data. In *Proceedings of the Human Factors and Ergonomics Society 48th Annual Meeting* (pp. 2099–2103). Santa Monica, CA: Human Factors and Ergonomics Society.

Frost, P., Bonde, J. P., Mikkelsen, S., Andersen, J. H., Fallentin, N., Kaergaard, A., & Thomsen, J. F. (2002). Risk of shoulder tendinitis in relation to shoulder loads in monotonous repetitive work. *American Journal of Industrial Medicine*, *41*, 11–18.

Garg, A. (2006, July). *Multiple-task jobs and job rotations: Some considerations for job exposure assessment*. Paper presented at the 16th World Congress on Ergonomics (IEA 2006), Maastricht, Netherlands.

Garg, A., Kapellusch, J., Hegmann, K., Wertsch, J., Merryweather, A., Deckow-Schaefer, G., . . . Wistah Hand Study Research Team. (2012). The Strain Index (SI) and threshold limit value (TLV) for Hand Activity Level (HAL): Risk of carpal tunnel syndrome (CTS) in a prospective cohort. *Ergonomics*, *55*, 396–414.

Gell, N., Werner, R. A., Franzblau, A., Ulin, S. S., & Armstrong, T. J. (2005). A longitudinal study of industrial and clerical workers: Incidence of carpal tunnel syndrome and assessment of risk factors. *Journal of Occupational Rehabilitation*, *15*, 47–55.

Gerr, F., Fethke, N., Anton, D., Merlino, L., Rosecrance, J., Marcus, M., & Jones, M. P. (2014). A prospective study of musculoskeletal outcomes among manufacturing workers: II. Effects of psychosocial stress and work organization factors. *Human Factors, 56*, 178–190.

Gerr, F., Marcus, M., Ensor, C., Kleinbaum, D., Cohen, S., Edwards, A., & . . . Monteilh, C. (2002). A prospective study of computer users: I. Study design and incidence of musculoskeletal symptoms and disorders. *American Journal of Industrial Medicine*, *41*, 221–235.

Hadler, N. M. (1990). Cumulative trauma disorders. An iatrogenic concept. *Journal of Occupational Medicine*, *32*, 38–41.

Harrington, J. M., Carter, J. T., Birrell, L., & Gompertz, D. (1998). Surveillance case definitions for work related upper limb pain syndromes. *Occupational and Environmental Medicine*, *55*, 264–271.

Harris, C., Eisen, E. A., Goldberg, R., Krause, N., & Rempel, D. (2011). 1st place, PREMUS best paper competition: Workplace and individual factors in wrist tendinosis among blue-collar workers. The San Francisco study. *Scandinavian Journal of Work, Environment & Health*, *37*, 85–98.

Hsu, D. J., Chang, J. H., Wu, J. D., Chen, C. Y., & Yang, Y. H. (2011). Prevalence of musculoskeletal disorders and job exposure in Taiwan oyster shuckers. *American Journal of Industrial Medicin*e, *54*, 885–893.

Jonsson, B. (1982). Measurement and evaluation of local muscular strain in the shoulder during constrained work. *Journal of Human Ergology*, *11*, 73–88.

Juul-Kristensen, B., Fallentin, N., & Ekdahl, C. (1997). Criteria for classification of posture in repetitive work by observation methods: A review. *International Journal of Industrial Ergonomics*, *19*, 397–411.

Juul-Kristensen, B., Hansson, G. A., Fallentin, N., Andersen, J. H., & Ekdahl, C. (2001). Assessment of work postures and movements using a video-based observation method and direct technical measurements. *Applied Ergonomics*, *32*, 517–524.

Kalbfleisch, J. D., & Prentice, R. L. (2002). *The statistical analysis of failure time data* (2nd ed.). New York, NY: Wiley.

Karasek, R. A. (1985). *Job content questionnaire and users guide*. Los Angeles: University of Southern California, Department of Industrial and Systems Engineering.

Karasek, R. A., & Theorell, T. (1990). *Healthy work: Stress, productivity and the restructuring of working life*. New York, NY: Basic Books.

Ketola, R., Toivonen, R., & Viikari-Juntura, E. (2001). Interobserver repeatability and validity of an observation method to assess physical loads imposed on the upper extremities. *Ergonomics*, *44*, 119–131.

Keyserling, W. M. (1986). Postural analysis of the trunk and shoulders in simulated real time. *Ergonomics*, *29*, 569–583.

Kim, I. H., Geiger-Brown, J., Trinkoff, A., & Muntaner, C. (2010). Physically demanding workloads and the risks of musculoskeletal disorders in homecare workers in the USA. *Health & Social Care in the Community*, *18*, 445–455.

Kleinbaum, D. G., Morgenstern, H., & Kupper, L. L. (1981). Selection bias in epidemiologic studies. *American Journal of Epidemiology*, *113*, 452–463.

Lapointe, J., Dionne, C. E., Brisson, C., & Montreuil, S. (2009). Interaction between postural risk factors and job strain on self-reported musculoskeletal symptoms among users of video display units: A three-year prospective study. *Scandinavian Journal of Work, Environment & Health*, *35*, 134–144.

Latko, W. A., Armstrong, T. J., Foulke, J. A., Herrin, G. D., Rabourn, R. A., & Ulin, S. S. (1997). Development and evaluation of an observational method for assessing repetition in hand tasks. *American Industrial Hygiene Association Journal*, *58*, 278–285.

Latko, W. A., Armstrong, T. J., Franzblau, A., Ulin, S. S., Werner, R. A., & Albers, J. W. (1999). Cross-sectional study of the relationship between repetitive work and the prevalence of upper limb musculoskeletal disorders. *American Journal of Industrial Medicine*, *36*, 248–259.

Leclerc, A., Chastang, J. F., Niedhammer, I., Landre, M. F., Roquelaure, Y., & Study Group on Repetitive Work. (2004).

Incidence of shoulder pain in repetitive work. *Occupational and Environmental Medicine*, *61*, 39–44.
Leclerc, A., Landre, M. F., Chastang, J. F., Niedhammer, I., Roquelaure, Y., & Study Group on Repetitive Work. (2001). Upper-limb disorders in repetitive work. *Scandinavian Journal of Work, Environment & Health*, *27*, 268–278.
Mathiassen, S. E., & Winkel, J. (1991). Quantifying variation in physical load using exposure-vs-time data. *Ergonomics*, *5*, 1455–1468.
Mathiassen, S. E., Winkel, J., & Hagg, G. M. (1995). Normalization of surface EMG amplitude from the upper trapezius muscle in ergonomic studies: A review. *Journal of Electromyography and Kinesiology*, *5*, 197–226.
McAtamney, L., & Corlett, N. E. (1993). RULA: A survey method for the investigation of work-related upper limb disorders. *Applied Ergonomics*, *24*, 91–99.
Meyer, R. H., & Radwin, R. G. (2007). Comparison of stoop versus prone postures for a simulated agricultural harvesting task. *Applied Ergonomics*, *38*, 549–555.
Meyers, A. R., Gerr, F., & Fethke, N. B. (2014). Evaluation of alternate category structures for the Strain Index, an empirical analysis. *Human Factors, 56*, 131–142.
Miranda, H., Viikari-Juntura, E., Martikainen, R., Takala, E. P., & Riihimaki, H. (2001). A prospective study of work related factors and physical exercise as predictors of shoulder pain. *Occupational and Environmental Medicine*, *58*, 528–534.
Moore, J. S., & Garg, A. (1995). The Strain Index: A proposed method to analyze jobs for risk of distal upper extremity disorders. *AIHA Journal*, *56*, 443–458.
Punnett, L., Gold, J., Katz, J. N., Gore, R., & Wegman, D. H. (2004). Ergonomic stressors and upper extremity musculoskeletal disorders in automobile manufacturing: A one-year follow up study. *Occupational and Environmental Medicine*, *61*, 668–674.
Roquelaure, Y., Mariel, J., Dano, C., Fanello, S., & Penneau-Fontbonne, D. (2001). Prevalence, incidence and risk factors of carpal tunnel syndrome in a large footwear factory. *International Journal of Occupational Medicine and Environmental Health*, *14*, 357–367.
Shiri, R., Viikari-Juntura, E., Varonen, H., & Heliovaara, M. (2006). Prevalence and determinants of lateral and medial epicondylitis: A population study. *American Journal of Epidemiology*, *164*, 1065–1074.
Silverstein, B. A., Bao, S. S., Fan, Z. J., Howard, N., Smith, C., Spielholz, P., . . . Viikari-Juntura, E. (2008). Rotator cuff syndrome: Personal, work-related psychosocial and physical load factors. *Journal of Occupational and Environmental Medicine/American College of Occupational and Environmental Medicine*, *50*, 1062–1076.
Sluiter, J. K., Rest, K. M., & Frings-Dresen, M. H. (2001). Criteria document for evaluating the work-relatedness of upper-extremity musculoskeletal disorders. *Scandinavian Journal of Work, Environment & Health*, *27*(Suppl. 1), 1–102.
Smith, C. K., Silverstein, B. A., Fan, Z. J., Bao, S., & Johnson, P. W. (2009). Psychosocial factors and shoulder symptom development among workers. *American Journal of Industrial Medicine*, *52*, 57–68.
Solidaki, E., Chatzi, L., Bitsios, P., Markatzi, I., Plana, E., Castro, F., . . . Kogevinas, M. (2010). Work-related and psychological determinants of multisite musculoskeletal pain. *Scandinavian Journal of Work, Environment & Health*, *36*, 54–61.
Spielholz, P., Silverstein, B., Morgan, M., Checkoway, H., & Kaufman, J. (2001). Comparison of self-report, video observation and direct measurement methods for upper extremity musculoskeletal disorder physical risk factors. *Ergonomics*, *44*, 588–613.
Thomsen, J. F., Mikkelsen, S., Andersen, J. H., Fallentin, N., Loft, I. P., Frost, P., . . . Overgaard, E. (2007). Risk factors for hand-wrist disorders in repetitive work. *Occupational and Environmental Medicine*, *64*, 527–533.
U.S. Bureau of Labor Statistics. (2012). *Nonfatal occupational injuries and illness requiring days away from work, 2011* (USDL-12-2204). Washington, DC: Author.
Veiersted, K. B., Westgaard, R. H., & Andersen, P. (1990). Pattern of muscle activity during stereotyped work and its relation to muscle pain. *International Archives of Occupational & Environmental Health*, *62*, 31–41.
Violante, F. S., Armstrong, T. J., Fiorentini, C., Graziosi, F., Risi, A., Venturi, S., . . . Mattioli, S. (2007). Carpal tunnel syndrome and manual work: A longitudinal study. *Journal of Occupational and Environmental Medicine/American College of Occupational and Environmental Medicine*, *49*, 1189–1196.
Waris, P., Kuorinka, I., Kurppa, K., Luopajarvi, T., Virolainen, M., Pesonen, K., . . . Kukkonen, R. (1979). Epidemiologic screening of occupational neck and upper limb disorders: Methods and criteria. *Scandinavian Journal of Work, Environment & Health*, *5*(Suppl. 3), 25–38.
Watson, D., Clark, L. A., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: The PANAS scales. *Journal of Personality and Social Psychology*, *54*, 1063–1070.
Werner, R. A., Franzblau, A., Gell, N., Ulin, S. S., & Armstrong, T. J. (2005). Predictors of upper extremity discomfort: A longitudinal study of industrial and clerical workers. *Journal of Occupational Rehabilitation*, *15*, 27–35.
Yen, T. Y., & Radwin, R. G. (2000). Comparison between using spectral analysis of electrogoniometer data and observational analysis to quantify repetitive motion and ergonomic changes in cyclical industrial work. *Ergonomics*, *43*, 106–132.
Zipp, P. (1982). Recommendations for standardization of lead positions in surface electromyography. *European Journal of Applied Physiology*, *50*, 41–54.

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