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# Pooling job physical exposure data from multiple independent studies in a consortium study of carpal tunnel syndrome

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## Abstract

Pooling data from different epidemiological studies of musculoskeletal disorders (MSDs) is necessary to improve statistical power and to more precisely quantify exposure–response relationships for MSDs. The pooling process is difficult and time-consuming, and small methodological differences could lead to different exposure–response relationships. A subcommittee of a six-study research consortium studying carpal tunnel syndrome: (i) visited each study site, (ii) documented methods used to collect physical exposure data and (iii) determined compatibility of exposure variables across studies. Certain measures of force, frequency of exertion and duty cycle were collected by all studies and were largely compatible. A portion of studies had detailed data to investigate simultaneous combinations of force, frequency and duration of exertions. Limited compatibility was found for hand/wrist posture. Only two studies could calculate compatible Strain Index scores, but Threshold Limit Value for Hand Activity

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*Disclaimer*: The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the NIOSH.

Level could be determined for all studies. Challenges of pooling data, resources required and recommendations for future researchers are discussed.

**Keywords**

methods; ergonomics; NIOSH distal upper extremity consortium; physical exposure data pooling; physical exposure data compatibility; exposure data analysis

## 1. Introduction

The National Institute for Occupational Safety and Health (NIOSH) began funding large-scale prospective cohort studies of upper extremity musculoskeletal disorders (UEMSDs) in 2000. Seven research institutions received funding and designed separate studies to overcome some of the limitations identified in past UEMSD epidemiological studies, such as (i) reliance on retrospective methods (Bernard 1997; Abbas et al. 1998), (ii) use of imprecise and/or unreliable exposure measures (e.g. job titles), (iii) small sample sizes and (iv) samples not representative of workers and industries (Hegmann and Oostema 2008). In addition, the NIOSH studies determined physical exposure for each individual worker rather than assigning the same exposure to all the workers who performed the same job (Moore and Garg 1994). In 2010, six of these seven research institutions formed a consortium to merge their data and create a large and robust pooled data-set to study job physical risk factors for carpal tunnel syndrome (CTS). Unlike a meta-analysis, which is based on an analysis of published data, the consortium aimed to re-analyse primary data (i.e. both published and unpublished original data from the independent studies) using the same variable definitions across the independent studies (Checkoway 1991; Blettner et al. 1999). Some of the advantages of this approach are that it (i) provides evidence for exposure assessment methods that can be assessed by many institutions, (ii) provides detailed data from a diverse group of industries and occupations and (iii) increases statistical power.

This consortium has pooled data on 4123 workers from 54 companies across 10 states. Using standard industrial classification divisions, a majority of workers ($n$ = 2870) were employed in manufacturing or assembling of products, such as automobiles and automobile parts, electric motors, household appliances, furniture, artificial stone, metal and plastic products, commercial lighting, woodworking, books, textiles, glass and window manufacturing, and dairy and food processing to name a few. Other notable groups were services ($n$ = 775, mostly in healthcare, technical professions and general service work), construction ($n$ = 385), agriculture ($n$ = 172), wholesale trade ($n$ = 59) and retail trade ($n$ = 53) (Bao et al. 2006; Armstrong et al. 2008; Dale et al. 2008, 2011; Dartt et al. 2009; Gardner et al. 2010; Burt et al. 2011; Harris et al. 2011; Garg, Hegmann, et al. 2012; Garg, Kapellusch, et al. 2012).

There is a lack of consensus on what measurements, models and sampling strategies to use for collecting and analysing job physical exposure data for epidemiological studies of distal upper extremity (DUE) musculoskeletal disorders (MSDs). For example, it is not clear which measurements of physical exposure variables are more appropriate (e.g. peak force, average force, time-weighted-average force) and what scales to use for these measurements (e.g. Borg CR-10 scale vs. Visual Analog Scale for force; hand activity level (HAL) rating vs. repetitions/min and duration of exertion to quantify hand activity) (Garg and Kapellusch 2009, 2011). Models such as the rapid upper limb assessment (RULA, McAtamney and Corlett 1993), threshold limit value (TLV) for HAL (ACGIH 2002), the strain index (SI, Moore and Garg 1995) and occupational repetitive actions (OCRA, Occhipinti 1998) have been developed for field use, and each provides a single index for estimating biomechanical stresses from multiple physical exposure variables interacting with each other. However, there are only limited studies on the efficacy of these models in determining risk of DUE MSDs (Franzblau et al. 2005; Gell et al. 2005; Werner et al. 2005; Occhipinti and Colombini 2007; Violante et al. 2007; Harris et al. 2011; Bonfiglioli et al. 2012; Garg, Kapellusch, et al. 2012).

Several researchers have suggested sampling techniques that address between-subject variability and within-subject variability (both within a workday and over different workdays) and provide recommendations for efficient sampling techniques for data collection (Hoozemans et al. 2001; Mathiassen, Möller, and Forsman 2003; Loomis and Kromhout 2004; Paquet et al. 2005; Hansson et al. 2006; Mathiassen and Paquet 2010). However, these techniques mostly focus on studying physical exposure variables independently (e.g. hand/wrist posture, repetition, force). Thus, it remains unclear how to utilise these techniques when studying simultaneous combinations of physical exposure variables (e.g. number of exertions at specific force levels in specific postures) or when performing highly detailed sub-task level analyses (i.e. sequences of unique combinations of force, duration of force and hand/wrist posture). This general lack of guidance on selecting combinations of physical exposure measurements, models and sampling methods has been recognised as a barrier to furthering our understanding of risk factors for occupational MSDs (Burdorf 1995; Gerr, Marcus, and Ortiz 1996; Wells et al. 1997; Spielholz et al. 2001; Punnett and Wegman 2004), and remains a significant challenge to those conducting large-scale field research because measurements and models play an important role in selecting appropriate sampling techniques.

For their respective studies, each consortium member independently selected physical exposure measurements, models and data collection strategies that were designed to address their specific research objectives. All member studies ensured that important job physical exposure variables identified in the literature were collected, including measures of force, repetition, hand/wrist posture and hand/arm vibration (Silverstein, Fine, and Armstrong 1987; Chiang et al. 1993; Bernard 1997; Fung et al. 2007; Maghsoudipour et al. 2008; Bonfiglioli et al. 2012; Garg, Kapellusch, et al. 2012).

The physical exposure methods used by the six individual studies were similar, and the studies that started later were able to adopt some of the exposure assessment methods of the earlier studies. For example, all studies included comprehensive video observations of jobs, thus the raw data (i.e. videos) for repetition (frequency and duration of exertion) and posture from all individual studies were homogeneous. However, upon careful inspection, differences were found in how repetition and posture data were extracted from video. These differences (and other differences regarding assessment of force ratings) lead to surprising data heterogeneity, precluding immediate pooling. Given the relatively short-time frame and modest resources of the consortium study, substantial re-analysis of raw data was not practical. Thus, the heterogeneity posed challenges in merging and analysing job physical exposure data.

This study summarises (i) physical exposure data available from six studies, (ii) processes used to determine job physical exposure data compatibility, (iii) decision-making process for merging job physical exposure data, (iv) final pooled job physical exposure variables available for statistical modelling and analyses and (v) recommendations for 'standard' variables to be collected and models to be used in future field studies of DUE MSDs.

The findings and recommendations from this study may be valuable to those who are planning to conduct future epidemiological studies on job physical exposure and/or to those who are planning to merge physical exposure data from similar but independently designed and conducted studies.

## 2. Job physical exposure risk factors and measures

Job physical exposure risk factors for CTS include force and repetition as well as combinations of these (Silverstein, Fine, and Armstrong 1986, 1987; Chiang et al. 1993; Bonfiglioli et al. 2012; Garg, Kapellusch, et al. 2012). Several studies have also identified posture as a CTS risk factor (Armstrong and Chaffin 1979; de Krom et al. 1990; English et al. 1995; Fung et al. 2007; Maghsoudipour et al. 2008; Tanaka et al. 1995), although NIOSH found insufficient evidence from a comprehensive review in 1997 (Bernard 1997).

Epidemiological studies suggest that interactions between some of these job physical factors (e.g. force and repetition) are likely to pose greater risk for DUE MSDs than for individual physical factors alone (Silverstein, Fine, and Armstrong 1987; Hagberg, Morgenstern, and Kelsh 1992; Moore and Garg 1994; Roquelaure et al. 1997; Rucker and Moore 2002; Garg, Kapellusch, et al. 2012). Two of the most widely used tools to combine job physical exposure factors into a single index are (i) TLV for HAL and (ii) the SI (Dempsey, McGorry, and Maynard 2005). These indices offer summary measures of risk of CTS and other DUE MSDs by combining two or more physical exposure risk factors, with primary emphasis on force and repetition.

## 3. Consortium goals for job physical exposure assessments

The consortium goals for job physical exposure assessments were to provide estimates of force, repetition, posture and composite measures of biomechanical risk factors (or job physical exposure indexes), including the SI and TLV for HAL.

Some workers changed jobs during the follow-up periods (e.g. a worker performed job 1 for $T_1$ months, then job 2 for $T_2$ months and then job '$n$' for $T_n$ months; see Figure 1). Some workers performed jobs with job rotation, and therefore, performed more than one task during a work shift (e.g. a worker performed task 1 for 5 h, task 2 for 3 h). Most tasks consisted of several sub-tasks (see Figure 1). As an example, consider a worker who does assembly of transformers for 5 h/day and operates a grinding machine for 3 h/day. Assembly of a transformer requires 2 exertions (cutting wire) at 60% maximum voluntary contraction

(MVC) of 2 s each with 45° wrist extension, 3 exertions (wrapping wire) at 35% MVC of 1.5 s each with 30° wrist flexion and 5 exertions (driving screws using a powered screw driver) at 15% MVC at 3 s each with neutral wrist; a total of 10 exertions in a 30-s cycle. This task has three sub-tasks: cutting wire, wrapping wire and driving screws. All three sub-tasks require different levels of force (%MVC), durations of force and hand/wrist postures. Tasks such as these are referred to as 'complex tasks' (i.e. task with multiple sub-tasks).

Index methods such as the TLV for HAL and the SI were originally intended to study jobs with a single task and a single sub-task (i.e. mono-task job). Substantial variations in force requirements during a task cycle (i.e. changes in force at the sub-task level) may affect the risk estimates of these models. It is not clear how to adapt these index methods to complex (i. e. multiple sub-tasks) tasks with job rotation (i.e. multiple tasks per job). Options for analysing complex jobs have included (i) simple average for force, posture and duration, (ii) peak/'worst' exposure for force, repetition and posture and (iii) time-or frequency-weighted average for force and posture. Unfortunately, use of average, time/frequency-weighted average and/or peak approaches to summarise exposure at the task or job level may significantly underestimate or overestimate physical exposures (Garg and Kapellusch 2011). Therefore, these approaches may erroneously classify a 'safe' job as 'unsafe' or an 'unsafe' job as 'safe' (Garg and Kapellusch 2011).

In this consortium study, both the health outcome (CTS) and quantified physical exposure are assigned at the worker level. To address the comparative utility of different exposure assessment methods, this consortium proposed analyses based on the (i) peak exposure to an individual variable (e.g. highest force, highest frequency of exertion, worst posture), (ii) typical exposure (i.e. exposure from the task performed most of the time) and (iii) time-weighted average exposure across all tasks. Index exposure methods included (i) TLVs for HAL from typical and peak exposures, (ii) SI scores from typical and peak exposures, (iii) composite SI scores from typical and peak exposures (Garg and Kapellusch 2009), (iv) cumulative SI (integrating all task exposures, Garg and Kapellusch 2009) and (v) a statistically driven CTS risk index that would include practically all forces, frequencies, duty cycles and postures as well as some important interactions between these variables over an entire work shift. The composite SI would account for all exposures within a task and the cumulative SI would account for all tasks performed in a shift. The statistically driven risk index would account for all sub-task exposures across an entire work shift and might provide greater insight into what physical factors (and combinations of physical factors) lead to CTS. Including these numerous exposure analyses would allow this consortium study's results to be compared with results from other studies that use one or more of these similar techniques.

## 4. Formation of job physical exposure team

To accomplish its goals for pooling and quantifying job physical exposure, the consortium formed a sub-committee (job physical exposure team) consisting of four researchers, who had the most expertise in job physical exposure measurement and analysis. The sub-committee members were selected from the studies with the most detailed job physical exposure data. It was recognised that the sub-committee members would have detailed knowledge of their respective studies' data, thus minimising the number of site visits required. The goal of the sub-committee was to comprehensively review job physical exposure data available from each study and make recommendations to the consortium on what data could be pooled. The sub-committee defined four stages of job physical exposure data collection and analysis: (i) data collection, (ii) data processing, (iii) data reduction and (iv) data analysis. Data collection is defined as the collection of field data using methods such as direct measurement, video observation and worker/supervisor interviews. Data processing is the extraction of information in a laboratory from data collected in the field (e.g. review video to determine repetition by counting the number of exertions for a task). Data reduction is assigning a single value to physical exposure from data collection and extraction (e.g. identifying peak force, time-weighted-average force, worst hand/wrist posture, SI score from six different task variables and TLV for HAL for a task). The final stage is data analysis, which refers to the statistical analysis of reduced data.

The specific responsibilities of this sub-committee were (i) perform a detailed methodological assessment of the exposure data (methods used for data collection, data processing and data reduction), (ii) identify workers whose daily exposure was too varied to accurately quantify physical exposure (e.g. machine repair and maintenance work) or who were missing data for a portion of their work shift, (iii) identify differences in definitions of variables, (iv) propose consistent definitions for pooling of data, (v) prepare a detailed report of physical exposure data for the consortium showing compatibility of data as well as any additional work required from each individual study to make data compatible and (vi) provide a prioritised list of job physical exposure variables to be pooled based on information collected from each individual study.

## 5. Comprehensive review of available physical exposure data

Prior to commencing the study, the consortium, via telephone discussions and conference calls, had performed a review of field data collection forms, data processing protocols and data reduction strategies and protocols for important job physical exposure variables collected for each individual study. These important job physical exposure variables, the methods used to collect these variables (field observation, direct measurement, videotaping) and data extraction from video analysis are summarised in Table 1. On the basis of these early discussions, the consortium members believed that there was a high level of compatibility in job physical exposure variables across the six studies.

To gain more specific and detailed knowledge on these variables and how they were measured, the sub-committee members travelled to the site of each individual study and met with that study's researchers for 2 days. The objectives of these visits were to (i) comprehensively review physical exposure data collection methods and protocols, (ii) determine job physical exposure variables available for pooling, (iii) determine the scope and feasibility of any additional analysis work needed for data compatibility, (iv) determine the types of workers studied and (iv) determine the approximate number of workers with complete job physical exposure data. During the visits, the sub-committee carefully reviewed all data for a random sample of workers from that study (typically 10–15 workers).

The focus was to define and document variables and data collection strategies related to the exposures identified in Table 1.

Upon completing the individual study visits, the sub-committee met in-person for 1 week to carefully review and evaluate (i) the study-specific methods used to collect data, (ii) important job physical exposure variables available from each study and (iii) compatibility of variables and their definitions from different studies. The committee summarised their findings to the consortium. Those included (i) a comprehensive summary of the data available from each study, (ii) what additional work needed to be performed at each site to make data compatible and (iii) a priority list for job physical exposure variables that were either available from most studies or could be obtained with a reasonable amount of additional work performed by each individual study's personnel.

From the inception of the study, it took 32 months to finalise the pooled data-set of job physical exposure variables. During this time, the sub-committee spent a total of 35 days (144 person-days) meeting with representatives from each individual study, reviewing pooled data, requesting revisions to data to meet consortium definitions and finalising the pooled data-set (Figure 2). In addition, it is estimated that researchers from individual studies spent a total of 132 person-days (22 person-days for each study) to prepare physical exposure data for pooling. These time estimates are for senior researchers and do not include time spent by research assistants or travel time. Major findings from the data pooling process are summarised in Tables 2–9.

## 6. Assessment and summary of available job physical exposure data

Although all six studies followed a similar construct for organising job physical exposures and changes to those exposures with time (Figure 1), their precise variable definitions, protocols and methods of measurement varied. Two of the six studies (B and E) had detailed job physical exposure analyses available at the sub-task level. Those two studies characterised a subtask by hand force, number of exertions, duty cycle for that force and hand/wrist posture. In an effort to make an efficient use of available resources, two of the six studies (A and C) extracted sub-task data only for 'significant exertions' (Table 2). With minor differences, significant exertions were defined as those exertions requiring either a grip force ≥45 N or a pinch force ≥9 N; however, no specific force ratings were assigned to those significant exertions. Study B had both comprehensive sub-task data and significant exertion data.

Five of the six studies collected job physical exposure data for both hands and one study for only the dominant hand (Study D). Study A collected data for both hands with the exception of HAL, which was collected only on the active hand (i.e. the hand that is performing the most work within the task).

Study F used a slightly different construct for their data collection. This study defined 'critical concerns' (CC) within a job rather than explicit tasks and/or sub-tasks. CCs were groups of tasks or activities identified subjectively by the ergonomist in the field as activities with the greatest physical stress that occurred for the longest duration of the workday or involving the highest level of force. For example, one of the Study F jobs was 'rough carpenter' and one of the CCs for the job of rough carpenter was 'assembly with wood', performed on average for 2.5 h/day, and requiring frequent use of a nail gun and hammer. Worksite visits for Study F captured video samples of all tasks performed during the visit and worker interviews for ratings of hand force on typical work tasks and description of tasks, materials and equipment. Although much of Study F's reduced data were incompatible with the other studies, the raw data collected were determined to be broadly consistent. The job physical exposure committee suggested that with recoding of data in a format consistent with other studies, a subset of workers from Study F would qualify for pooling of physical exposure data.

Table 2 provides a summary of how each study characterised physical exertions. Not surprisingly, there were both consistencies and differences in measuring force, repetition and hand/wrist posture among different studies. For example, five of the six studies (A, B, C, E and F) used a rating scale to rate force, one study (D) used surface electromyography to study force at the task level. Fortunately, Study D also conducted a sub-study of their workers. This sub-study was performed on a select number of workers and included task analysis using the SI methodology (Moore and Garg 1995). It was decided that sub-study workers from Study D should be included for pooling of job physical exposure data for certain analyses at the task level. The following sections describe similarities and differences among individual studies for estimating force, repetition and hand/wrist posture.

### 6.1. Measurements of force

Individual studies utilised one or more of five different instruments and methods for estimating hand force. These were (i) Borg CR-10 scale (Borg 1982, five studies), (ii) Borg RPE (rating of perceived exertion) scale (i.e. 6–20 scale, Borg 1970, one study), (iii) 10-point visual analog scale (one study), (iv) matching grip/pinch force (Casey, McGorry, and Dempsey 2002; Bao and Silverstein 2005, four studies) and (v) surface EMG (one study). Force ratings were provided by analysts and/or workers. Regarding peak force requirements of a task, all six studies included worker force ratings (Table 3). Five out of six studies used the Borg-CR 10 scale for worker peak force ratings. Study D used the Borg RPE scale. Study D's ratings were converted from the Borg RPE scale to the Borg CR-10 scale by matching verbal anchors (see Appendix). Four of the six studies (A, B, E and F) also estimated peak force requirements of a task using analyst ratings on the Borg CR-10 scale either during field data collection or from reviewing video in the laboratory (Table 3). Four studies (A, B, C and E) had matching peak grip/pinch forces (peak obtained from matching grip/pinch forces for sub-tasks). All studies measured maximum grip and pinch strengths in neutral hand/wrist posture using grip and pinch dynamometers. Therefore, peak matching grip/pinch forces could be converted to %MVC with the limitation that the maximum grasp strength was not recorded in the same hand/wrist posture(s) that was used for applying matching grasp force(s). In this regard, only Study A measured maximum grip/pinch strengths in the same hand/wrist postures (and grip/pinch span) as the postures used to apply the matching forces.

Three out of six studies (B, D and E) estimated 'overall' hand force for a task (Table 4). Overall force is a construct that represents an analyst's judgement of the collective force demands of a task; it is neither peak force, nor average force, nor frequency-weighted-average or time-weighted-average force. Overall force is required to calculate the SI score (Moore and Garg 1995). Two of these four studies (D and E) had analysts rate overall forces (Table 4). Study E also had overall force rating from the workers. Two out of these three studies (B and E) had force ratings for all sub-tasks in a task. In order to make use of these sub-task data, the physical exposure committee developed an algorithm that estimates overall force for a task based upon the frequency and duration of exertions at sub-task level forces. On the basis of our experience, many ergonomists find estimating overall force challenging when forces change substantially during an exertion cycle, and rating of overall force by different ergonomists may lead to under or over estimation of overall force for the task. It is believed that this algorithm should minimise biases associated with estimating overall force.

At the sub-task level, there was lack of compatibility of force data among the studies. Three studies (A, B and E) had analyst sub-task force ratings, but only two of those studies (B and E) had data for all sub-tasks within a task. Two studies had worker force ratings (A and B), but only for significant exertions (Table 5). Four studies (A, B, C and E) had matching grip/pinch forces, but again only for a portion of subjects and/or a portion of sub-tasks.

### 6.2. Measurements of repetition and duration

All six studies assigned ratings for HAL for all tasks either in the field by observing the tasks (three studies) or by analysing videos in the laboratory (six studies, Table 6). There were some differences in the HAL measurements provided by different studies. Analysts assigned HAL ratings in the field using the HAL verbal anchor scale (Latko et al. 1997) for studies A, B and C. Analysts from studies D, E and F observed task video in the laboratory and assigned HAL ratings using the verbal anchor scale. In addition, four studies (A, B, C and E) calculated HAL ratings using frequency of exertion and duty cycle (from sub-task analyses) using the HAL tabulation table (ACGIH 2002). Study C also collected HAL ratings from workers using the HAL verbal anchor scale.

Temporal exertion patterns were determined by detailed time studies of task video by five studies (A–E). These analyses provided frequency of exertion, duty cycle and speed of work, required for SI calculations (Table 6). Four of the six studies performed sub-task analyses of video to determine frequency of exertion, and exertion(s) duty cycle (% duration of exertion for all sub-tasks) (Table 7). These data along with force and posture estimates could be used to quantify job physical stresses to DUE for each sub-task as well as to compute composite SI scores (Garg and Kapellusch 2009).

### 6.3. Measurements of posture

Different studies used different methods to estimate hand/wrist postures, and duration of time spent in a given posture. Two studies (C and D) rated hand/wrist posture at the task level and two studies at the sub-task level (B and E) using the SI posture rating scale (Table 8). Three studies (A–C) used a random sampling technique to estimate absolute hand/wrist posture, as a function of time. The remaining studies (D–F) collected percentage of time spent in pre-defined categories of hand/wrist postures. However, these studies used different categories. Relative to anatomical neutral, Study D categorised hand/wrist postures either as neutral (i.e. flexion/extension ± 30°) or non-neutral (flexion ≥ 30° or extension ≥ 30°). Study E used the categories of neutral (i.e. flexion/extension ± 30°), flexion < 50°, flexion ≥ 50°, extension < 50° and extension ≥ 50°. Study F used categories that were substantially different from studies D and E (flexion 0–30°, flexion < 60°, flexion ≥ 60°, extension 0–45°, extension < 60°, extension ≥ 60°). Because of large variation in posture categories used for the different studies, the consortium decided to categorise posture based on a ‘common denominator’ approach that allowed for pooling of posture data from most of the studies. For this purpose, categories selected were (i) neutral (i.e. flexion/extension ± 30°), (ii) flexion > 30° and (iii) extension > 30°.

## 7. Pooled data available for physical exposure modelling

A meeting of consortium members was held to review the sub-committee report and recommendations and determine what job physical exposure variables and index measures were feasible for pooling of data from the six individual studies. It was agreed that for pooling of job physical exposure variables and indexes: (i) data should be available from a minimum of three studies and (ii) due to very limited resources, re-analysis time required should be minimal. On the basis of these discussions, the consortium agreed to perform selected analyses to quantify physical exposure from the pooled data. Table 9 provides a summary of the pooled physical exposure measures. Each major category of exposure is briefly discussed below.

### 7.1. Force

The pooled data provide four different estimates of hand force. These are summarised in Table 9 and include estimates of both highest hand force and overall hand force required for a task. The highest force requirements of a task can be estimated from (i) worker peak force rating (six studies), (ii) analyst peak force rating (four studies) and (iii) as %MVC from matching grip/pinch force and maximum grip/pinch strength (four studies). Only three studies could provide analyst overall force ratings in addition to the peak ratings.

### 7.2. Repetition

Four different estimates of the repetitiveness of a task can be pooled, including: (i) analyst HAL rating using the verbal anchor (all six studies), analyst HAL rating using the HAL table (four studies), (iii) number of exertions per minute regardless of the force level of exertions (five studies) and (iv) number of significant force exertions per minute (four studies) (Table 9).

### 7.3. Duty cycle

Two different estimates of duty cycle could be pooled: (i) duty cycle for all exertions and (ii) duty cycle for significant force exertions.

### 7.4. Hand wrist posture

Due to lack of compatibility on hand/wrist posture between the different studies, only a few simple analyses can be performed on hand wrist posture. These include whether a worker is exposed to (i) extension > 30° (data from five studies), (ii) extension > 50° (data from four studies) and (iii) flexion > 30° (data from five studies) as well as the percentage of total time spent on each of these categories (Table 9).

### 7.5. Interactions between physical exposure variables

Data from three of the consortium studies (A, B and E) can be used to investigate interactions between high force and high repetition at the task level. These interactions will be studied by accounting for a number of exertions with (i) force rating on Borg CR-10 scale ≥2 (light) and force rating ≥4 (somewhat hard).

### 7.6. Vibration

Five of the six studies collected data on exposure to hand/arm vibration. Similar to other physical factors, methods and definitions for studying vibration varied between studies. The pooled data are a categorical 'yes/no' variable with affirmative answers for those workers with visible hand/arm vibration and/or use of vibratory hand-tools.

### 7.7. Computation of index measures

There is sufficient agreement in data collected by the individual studies to provide four different estimates of TLV for HAL (Table 9). Those estimates include TLV for HAL from (i) worker peak force and analyst verbal anchor HAL rating (all six studies), (ii) worker peak force and tabular HAL rating (four studies), (iii) analyst peak force and verbal anchor HAL rating (four studies) and (iv) analyst peak force and tabular HAL rating (three studies).

Regarding the SI, necessary data to compute SI scores are available from only three of six studies (B, D and E).

### 7.8. Sub-task analyses

Sub-task analyses investigate the effect of unique combinations of force, repetition and posture on exposure–response relationships. All six studies (with the possible exception of Study F that studied CC as opposed to specific tasks) have the necessary raw information for sub-task analyses available on video. However, at present only two studies (B and E) have completely extracted force, repetition and posture for every sub-task performed from those videos. Studies A, C and D have varying degrees of partial sub-task data contained in their time-studies of tasks, but a substantial amount of time and resources (beyond the scale of this consortium project) would be required to complete sub-task data extraction for these three studies. Thus, sub-task analyses using models such as the proposed composite SI and cumulative SI (Garg and Kapellusch 2009), and the proposed statistically driven CTS risk index are not currently possible without substantial additional work by researchers from each individual study.

## 8. Discussion

The full consortium will provide a large and rich job physical exposure data-set to study job physical exposure risk factors for CTS. However, the most detailed and complex analyses of physical exposure measures will be available on only a subset of the data. Different measures of force and repetition will allow us to investigate which of these measures are the best predictors of risk of CTS. For example, do the force ratings from workers predict risk of CTS better than the analysts' force ratings? Similarly, does HAL calculated using frequency and duration of exertion provide a better estimate of repetition than HAL rated using the verbal anchor scale (Harris et al. 2011)? These are important issues for providing recommendations for future job analyses as different estimates of force and repetition are expected to have an effect on whether a job is classified as 'safe' or 'unsafe' (Garg and Kapellusch 2011).

Previous research has shown that there is lack of agreement on different measures used to quantify force and repetition. For example, Wurzelbacher et al. (2010) determined HAL ratings using two different methods: (i) HAL 10-point visual analog rating scale and (ii) HAL rating from a table combining frequency of exertion and duty cycle. These two HAL ratings were combined with analyst, field-rated peak force rated on Borg CR-10 scale to compute two separate TLVs for HAL. The authors reported that the two methods to calculate TLV for HAL had 12% agreement for tasks below action limit (AL), 10% agreement between AL and TLV and 51% agreement above TLV. Similarly, correlation between observer and worker peak force ratings was 0.47 with 26% agreement. Percent agreement improved to 33% when the worker force ratings were normalised to 50th percentile study population strength. TLVs for HAL calculated using the 10-point verbal anchor scale for HAL and the worker and analyst peak force ratings had 17% agreement for tasks below AL, 7% agreement for tasks between AL and TLV and 39% agreement for tasks above TLV.

Results such as these suggest that small methodological differences in physical exposure data collection and/or analysis may lead to different risk classifications for workers and thus, could affect the association between job physical exposure and risk of CTS. Therefore, when pooling physical exposure data from different studies, it is important that variable definitions and methods used for data collection are essentially identical (Friedenreich 1993).

Physical exposure data are complex and require a comprehensive understanding of data collection methods and data collected to determine compatibility among varied sources. Based on initial discussions between different individual study researchers, it was believed that job physical exposure data among different studies were largely homogeneous. However, detailed (in-person) discussions of job physical exposure data with individual study researchers revealed a surprising amount of heterogeneity among the methods used to collect, process and reduce data into specific variables. For example, during initial discussions, each study indicated that they collected hand force data. During study site visits, we found that all studies had worker peak force rating at the task level, but studies had used different force scales to collect the data (Borg CR-10 scale, Borg RPE scale). Only four studies had analyst peak force ratings, some collected in the field, others estimated from video. Only three studies had task level overall force ratings, but again using different approaches.

Fortunately, with some assumptions and/or additional analyses, it is possible to create equivalency between the varied measures of many of the physical exposure variables. For example, regarding worker peak force rating, an algorithm was used to convert Borg RPE rating to Borg CR-10 rating. Similarly, with some additional work, all studies could provide analyst peak force rating, based upon video observation.

In order to pool certain data, such as analyst's peak force rating and HAL rating, we have assumed that these ratings are the same whether assigned in the field while observing a task or assigned in a laboratory based on reviews of videotapes (see Tables 3 and 6). Both field peak and laboratory peak force ratings are available from one study (Table 3) and the consortium may be able to determine the differences between the two methods of assigning peak force rating. The advantage of assigning peak force rating in the field is that it is based upon observation of a task in real time. Furthermore, the observer might be able to perform a task and experience the amount of force required. The disadvantage is that the analysts are collecting a large volume of differing data in a very short period of time and this could lead to an error of haste or omission. Analysts might also be biased by inadvertent discussions with workers. However, when assigning peak force rating from a review of video, the analyst has time to carefully consider his/her decision, but may not have access to data that might influence hand force (for example, hardness of the material being cut or how hard it is to grip/pinch a tool during use). On the basis of our experience, we believe that force ratings provided by an analyst either in the field or in the laboratory based on their combined field and video observations may be lower than those provided by an analyst based on video observation only (Bao et al. 2010). We are unable to test this assumption; however, studies on a subset of data could be designed to specifically test it. Ideally, we believe the same analyst who observed the task and collected data in the field should subsequently assign their force rating based upon video review.

Another potential error arises from use of different force scales. One of the studies used Borg RPE scale to assign force, whereas others used Borg CR-10 scale. Force ratings from RPE scale were converted into CR-10 scale by matching the verbal anchors (see Appendix). At present it is not clear whether there are any errors involved in making such conversions.

Three of the six studies defined 'significant exertions' based on grip/pinch force during field observations of tasks. Significant exertions were identified using observer subjective judgements to decide whether an exertion was above or below a certain force level (individual studies used different levels of force to classify significant exertions, see Table 2). This may lead to more exertions being classified as significant than would be if every exertion were measured objectively (Bao et al. 2009). One study had analyst force ratings for all exertions of any intensity. In order to make these four studies compatible, the consortium plans to use force ratings on the Borg CR-10 scale to stratify all efforts into two separate groups, significant and non-significant exertions. Although the error associated with this conversion is unknown, we plan to use guidance from the study that has analyst force ratings on the Borg CR-10 scale for all significant exertions to minimise error.

All physical exposure variables (e.g. force, repetition, posture) were assigned by different analysts employed for the different studies, using study-specific methods. The consortium believes that training new analysts and re-analysing a sufficiently large pool of example tasks from each study in order to determine inter-rater reliability is not feasible. Any differences in job physical exposure variables due to inter-rater reliability should lead to a bias towards null and we do not believe that any such bias will not be a major problem within the pooled data-set.

Although challenges of epidemiologic studies of pooled data have been discussed (Blettner et al. 1999; Friedenreich 2002), those discussions have focused predominantly on the eventual statistical analyses and the relative strengths and weaknesses of the pooling approach. To our knowledge, research groups have not published their specific experiences with merging of data, nor the specific resources and methods required to do so. In that regard, the lessons learned from this process are that pooling of job physical exposure data from different individual study groups is a complex, time-consuming process and requires substantial resources. Detailed, face-to-face discussions although time consuming are necessary to determine compatibility of job physical exposure data and assumptions needed for data merging. Re-analysis of video data is often not feasible, as it requires a tremendous amount of time and personnel. Our consortium underestimated the complexity, time and resources required to pool physical exposure data from the individual studies. Similarly, we were overly optimistic that the individual study researchers would be able to re-analyse their data to make them compatible without the commensurate resources.

## 8.1. Recommendations for measuring and modelling physical exposure variables

To further our understanding of DUE MSDs risk factors, it would be helpful if researchers could better (i) contrast their results with others or perform meta-analyses of results and (ii) pool their data with other studies to achieve greater statistical power and diversity of workers (as is being done for this consortium study). To facilitate these objectives, we need uniform data and data collection methods for MSD studies. Ideally, a committee of experts on DUE MSDs should convene to establish guidelines that future researchers can follow for collecting and analysing data. Until such guidelines are developed, we are providing the following recommendations based upon our experience and professional judgement.

**8.1.1. Data collection strategies—**In Figure 1, we showed our conceptual structure of physical exposure with respect to time. Workers are described as performing jobs. A job consists of one or more tasks. Each task is made up of sub-tasks, in which a sub-task is a sequence of unique force, duration of force and posture combinations. A worker’s job can change over time, requiring a re-evaluation of physical exposure. Two types of physical exposure variation can be defined: between subjects and within subject (Loomis and Kromhout 2004). Between-subjects variation is due to (i) different workers performing different jobs and/or (ii) different workers performing the same job using different techniques/tools. Within-subject variation is due to (i) a worker performing more than one task within a day (commonly referred to as job rotation), (ii) variation of physical demands between task cycles and/or (iii) a change in either one or more tasks or job physical demands with time (i.e. job change).

Several sampling techniques have been published to address between-and within-subject variation (Hoozemans et al. 2001; Mathiassen, Möller, and Forsman 2003; Paquet et al. 2005; Hansson et al. 2006; Mathiassen and Paquet 2010). However, most sampling techniques have been developed to estimate mean exposure within a workday, perhaps implying it is the most appropriate estimate of risk for MSDs. In the context of DUE MSDs, this assumption is essentially untested. However, low-back-pain studies have shown that averaging does not predict risk well (e.g. Herrin, Jaraiedi, and Anderson 1986; Marras et al. 1993; Norman et al. 1998). It is worth noting that the *ad hoc* committee for the Revised NIOSH Lifting Equation did not believe that averaging of variables or Lifting Indexes was an appropriate method. In response they replaced averaging of variables in 1981 Guide (NIOSH 1981) with an incremental stress approach in the Revised Equation to calculate Lifting Index for complex tasks (composite lifting index) (Waters, Putz-Anderson, and Garg 1994).

Until the scientific community has a better understanding of risk factors and the variables to measure those risk factors, selection of appropriate sampling techniques will remain a difficult proposition. Whatever sampling strategy a researcher selects, we recommend that data be collected for all tasks performed in order to account for potential within-worker variation. If the research purpose is to study how specific combinations of force, duration of force and posture influence development of DUE MSDs, or to design safe, productive jobs, then we advise detailed, sub-task level analyses.

**8.1.2. Variables to study DUE MSDs—**DUE MSD research suggests that certain combinations (interactions) of force, repetition, posture and hand/wrist vibration are important risk factors (Garg and Kapellusch 2011). Physical exposure models used to study DUE MSDs in the field include RULA, OCRA, TLV for HAL and SI (Dempsey, McGorry, and Maynard 2005). In North America, TLV for HAL and SI appear to be most commonly used. Our recommendations for variables to study DUE MSDs are summarised in Table 10. We have focused on key task level physical exposure variables, their combinations, TLV for HAL and SI.

## 9. Conclusions

Through careful investigation and analysis, the physical exposure sub-committee of this consortium was able to resolve many of the differences in both measurements and measurement protocols between individual studies. This study allows the consortium to merge many important job physical exposure variables into a single pooled data-set. The observed heterogeneity among seemingly homogeneous job physical exposure variables within this consortium highlights that standardised tools, methods to assess physical exposures for epidemiological MSD studies and detailed instructions on how to use and apply those tools and methods are badly needed. Using our experience and professional judgement, we have provided recommendations for measuring and modelling physical exposure variables that may be useful to researchers studying DUE MSDs. Studies such as this consortium study and the studies of the underlying members have great potential to help determine what physical factors are most important to study, and suggest how they should be measured in the future.

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## Appendix: Algorithm for converting Borg RPE rating to Borg CR-10 rating

Borg RPE (i.e. 6–20 scale) was converted to Borg CR-10 (i.e. 0–10 scale) using the scales' respective verbal anchors as guidance. Table A1 shows the Borg CR-10 scale and its equivalent Borg RPE ratings.

**Table A1**

Borg RPE to Borg CR-10 rating conversion using verbal anchors.

| Borg CR-10 rating | Verbal anchor | Borg RPE rating |
|---|---|---|
| 0 | Nothing at all | 6 |
| 0.5 | Very, very light | 7 |
| 1 | Very light | 8–9 |
| 2 | Light | 10–11 |
| 3 | Moderate | 12 |
| 4 | Somewhat hard | 13 |
| 5 | Hard | 14–15 |

| **Borg CR-10 rating** | **Verbal anchor** | **Borg RPE rating** |
|---|---|---|
| 6 | | 16 |
| 7 | Very hard | 17 |
| 8 | | 18 |
| 9 | | 19 |
| 10 | Very, very hard | 20 |

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### Practitioner Summary

There is a need for standardised measures and measurement protocols of physical exposure for the upper extremity. This study may provide guidance for those planning to conduct an epidemiological study on quantified job physical exposures, or planning to merge physical exposure data from similar studies with some methodologic differences.

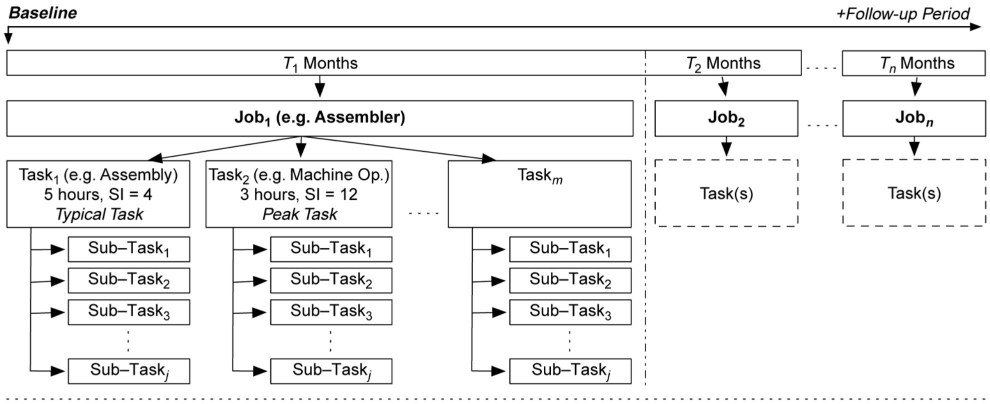


**Figure 1.**

Job physical exposure hierarchy of worker, job(s), task(s) and sub-task(s) with respect to time.

Note: A worker performs ‘*n*’ jobs throughout the study, for a period of months ($T_1$, $T_2$, …, $T_n$). Each job consists of ‘*m*’ tasks (Task$_1$, Task$_2$, …, Task$_m$). Each task consists of ‘*j* ‘ sub–tasks (Sub–Task$_1$, Sub–Task$_2$, Sub–Task$_3$, …, Sub–Task$_j$).

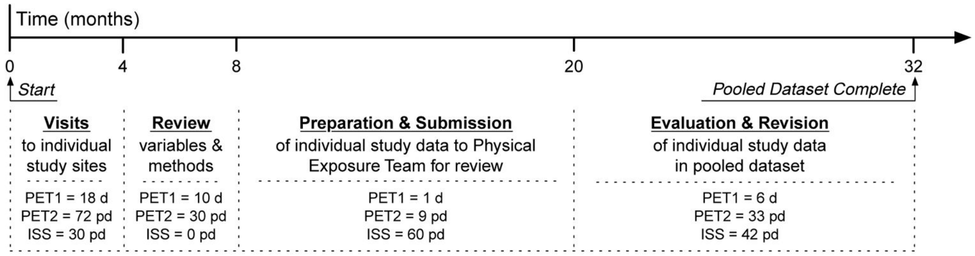


**Figure 2.**

Timeline and effort required to produce final pooled data-set for the consortium study of CTS.

PET1:Physical Exposure Team face-to-face meetings: visiting study sites, reviewing data, determining data compatibility, preparing reports, providing feedback, and reviewing pooled data - measured in days* (d)

PET2: Physical Exposure Team time commitment (PET1) measured in person-days* (pd)

ISS: Time commitment of key personnel at individual sites to review, prepare, reanalyze and provide data to the consortium - measured in person-days* (pd)

*Times are for senior researchers and do not include time spent by research assistants or travel time

## Table 1

Summary of data collection methods used by each individual study.

| Individual study | Grip force | Efforts per minute | Duration of exertion | HAL | Speed of work | Wrist posture | Vibration |
|---|---|---|---|---|---|---|---|
| A | D,M | V | V | D,V | – | V | D,M |
| B | Q,D,M | D,V | D,V | D,V | D | D,V | D,V |
| C | Q,M,V | D,V | D,V | D,V | D | D,V | D |
| D | M | V | V | V | V | V | D,V |
| E | M | D,V | D,V | D,V | D | D,V | D,V |
| F | Q,V | – | V | V | V | D,V | Q,V |

Note: Q, questionnaire; D, direct observation; M, measurement; V, video analysis.

**Table 2**

Definition of effort for each study.

| Individual study | Definition of effort |
|---|---|
| A[a] | Individual exertions were marked by the presence of 'significant events[b]'<br>Significant event: ≥45 N grip or ≥9 N pinch<br>Non-significant event: anytime the hand contacts an object for a 'work purpose' |
| B | Individual exertions were marked by the presence of 'significant events[b]'<br>Significant event: ≥45 N grip or ≥9 N pinch<br>Non-significant event: anytime the hand contacted an object for a 'work purpose' that required <45 N grip and <9 N pinch force |
| C | Individual exertions were marked as 'significant force', 'light force' or 'nothing'<br>Significant force: ≥40 N grip or ≥10 N pinch<br>Light force: <40 N grip or <10 N pinch<br>Nothing: no force applied |
| D[c] | Main study: no formal definition of exertion was used, data were collected using surface EMG<br>Sub-study: any hand action material to performing the job that has an applied force ≥9 N. Only dominant was measured |
| E | Individual exertions were stratified by Borg CR-10 force rating, all exertions were force rated and counted |
| F | No formal definition. Identified Critical Concerns (CC). CCs could be efforts, sub-tasks, groups of sub-tasks or whole tasks depending on job requirements |

[a] Site A collected data on both hands with the exception of HAL, which was collected only for the active hand (i.e. the hand that is performing the most work within the task).

[b] 'Significant event' refers to an effort requiring a certain minimum level of force. The minimum level varied from study to study. 'Non-significant' refers to efforts below the minimum force level and it does not imply that these efforts are not important with regard to risk of developing CTS.

[c] Site D data are from both a 'main study' (funded by NIOSH), and a 'sub-study' consisting of data collected from videotapes by a doctoral student for her dissertation.

**Table 3**

Task level peak force measurements available from each study.

| | | Analyst Borg CR-10 rating | | | Grip/pinch force | |
|---|---|---|---|---|---|---|
| **Individual study** | **Worker Borg CR-10 rating** | **Field rated** | **Laboratory rated** | **Surface EMG** | **Matched** | **Maximum[a]** |
| A | Yes | Yes | – | – | Yes[b] | Yes |
| B | Yes | Yes | – | – | Yes | Yes |
| C | Yes | – | – | – | Yes | Yes |
| D | Yes[b,c] | – | – | Yes | – | Yes |
| E | Yes | Yes | Yes | – | Yes[b] | Yes |
| F | Yes | – | Yes | – | – | Yes |

[a]Maximum grip/pinch force measured in neutral wrist posture using grip (73 mm span) or pinch dynamometer.

[b]Data available for a portion of workers.

[c]Measured on Borg RPE scale (i.e. 6–20 scale) and converted to Borg CR-10 using an algorithm developed by this consortium's exposure committee.

## Table 4

Task level overall[a] force measurements available from each study.

| | | Analyst Borg CR-10 rating | | | |
|---|---|---|---|---|---|
| Individual study | Worker Borg CR-10 rating | Field measured | Laboratory estimated | Sub-task algorithm[b] | Surface EMG |
| A | – | – | – | – | – |
| B | – | – | – | Yes | – |
| C | – | – | – | – | – |
| D | – | – | Yes[c] | – | Yes |
| E | Yes | Yes | Yes | Yes | – |
| F | – | – | – | – | – |

[a]Overall force is a construct that represents an analyst's judgement of the collective force demands of a task; it is neither peak force, nor average force, nor frequency weighted or time weighted average force.

[b]Sub-task algorithm developed by the physical exposure committee that estimates overall force for a task based upon the frequency and duration of exertions at sub-task level forces.

[c]Data available for a portion of workers.

## Table 5

Sub-task level force measurements available from each study.

| Individual study | Worker Borg CR-10 rating | Analyst Borg CR-10 rating | | Surface EMG | Grip/pinch force | |
|---|---|---|---|---|---|---|
| | | Field rated | Laboratory rated | | Matched | Maximum[a] |
| A | Yes[b] | Yes[b] | – | – | Yes[b] | Yes[b] |
| B | Yes[b] | – | Yes | – | Yes[b] | – |
| C | – | – | – | – | Yes[b] | – |
| D | – | – | – | Yes | – | – |
| E | – | – | Yes | – | Yes[b,c] | – |
| F | – | – | – | – | – | – |

[a]Maximum grip/pinch strength measured in the same posture and at the same span as the matched grip/pinch force estimate.

[b]Data available for a portion of sub-tasks determined by individual analysts to be important for influencing risk of DUE MSD.

[c]Data are available for a portion of total workers studied.

**Table 6**

Task level repetition measurements available from each study.

| | HAL rating | | | | | | |
|---|---|---|---|---|---|---|---|
| **Individual study** | **Worker field rated** | **Analyst field rated** | **Analyst laboratory rated** | **Table calculated** | **Frequency of exertion** | **Duty cycle** | **Speed of work (SI)** |
| A | – | Yes | – | Yes | Yes | Yes | – |
| B | – | Yes | – | Yes | Yes | Yes | Yes |
| C | Yes | Yes | – | Yes | Yes | Yes | Yes |
| D | – | – | Yes | – | Yes[a] | Yes[a] | Yes |
| E | – | – | Yes | Yes | Yes | Yes | Yes |
| F | – | – | Yes | – | – | – | – |

[a]Measured using the Strain Index rating scale.

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**Table 7**

Sub-task level repetition measurements available from each study.

| Individual study | Frequency of exertion | Duty cycle | Duration per exertion |
|---|---|---|---|
| A | Yes | Yes | Yes |
| B | Yes | Yes | Yes |
| C | Yes | Yes | Yes |
| D | – | – | – |
| E | Yes | Yes | Yes |
| F | – | – | – |

## Table 8

Task level posture measurements available from each study.

| | Duration of time in posture | | Number of exertions in posture | | |
|---|---|---|---|---|---|
| Individual study | Rated into categories | Discrete estimate | Rated into categories | Discrete estimate | SI posture rating |
| A | – | Yes | – | Yes | – |
| B | – | Yes[a] | – | Yes[a] | Yes[a] |
| C | – | Yes | – | Yes | Yes |
| D | Yes[b] | – | Yes[b] | – | Yes |
| E | Yes[a,c] | – | Yes[a,c] | – | Yes[a] |
| F | Yes[d] | – | Yes[d] | – | – |

[a] Posture and force measurements linked at the sub-task level.

[b] Neutral (i.e. flexion/extension ± 30°), flexion ≥ 30°, extension ≥ 30°.

[c] Neutral (i.e. flexion/extension ± 30°), flexion < 50°, flexion ≥ 50°, extension < 50°, extension ≥ 50°.

[d] Flexion 0–30°, flexion < 60°, flexion ≥ 60°, extension 0–45°, extension < 60°, extension ≥ 60°.

## Table 9

Summary of planned physical exposure measurements for pooled analyses (all measurements made or summarised at task level).

| Exposure | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Force | | | | | | |
| Peak worker Borg CR-10 rating | Yes | Yes | Yes | Yes | Yes | Yes |
| Peak analyst Borg CR-10 rating | Yes | Yes | – | – | Yes | Yes |
| Peak %MVC from matching grip/pinch force[a] | Yes | Yes | Yes | – | Yes | – |
| Overall Borg CR-10 rating from sub-task algorithm | Yes | Yes | – | – | Yes | – |
| Repetition | | | | | | |
| Analyst HAL rating (verbal anchor scale) | Yes | Yes | Yes | Yes | Yes | Yes |
| Analyst HAL rating (from HAL table) | Yes | Yes | Yes | – | Yes | – |
| Total exertions per minute at any force level | Yes | Yes | Yes | Yes | Yes | – |
| Total exertions per minute with analyst Borg CR-10 ≥ 2 | Yes | Yes | – | – | Yes | – |
| Total exertions per minute with analyst Borg CR-10 ≥ 4 | Yes | Yes | – | – | Yes | – |
| Total exertions per minute with significant force | Yes | Yes | Yes | – | Yes | – |
| Duty cycle of all exertions | Yes | Yes | Yes | Yes | Yes | – |
| Duty cycle of all exertions with analyst Borg CR-10 ≥ 2 | Yes | Yes | – | – | Yes | – |
| Duty cycle of all exertions with analyst Borg CR-10 ≥ 4 | Yes | Yes | – | – | Yes | – |
| Duty cycle of all exertions with significant force | Yes | Yes | Yes | – | Yes | – |
| Posture | | | | | | |
| Extension ≥ 30° (yes/no and percent of time) | Yes | Yes | Yes | Yes | Yes | – |
| Extension ≥ 50° (yes/no and percent of time) | Yes | Yes | Yes | – | Yes | – |
| Flexion ≥ 30° (yes/no and percent of time) | Yes | Yes | Yes | Yes | Yes | – |
| Vibrating tools | | | | | | |
| Yes/no | Yes | Yes | – | Yes | Yes | Yes |
| Composite indexes | | | | | | |
| ACGIH TLV for HAL (worker force, verbal anchor HAL) | Yes | Yes | Yes | Yes | Yes | Yes |
| ACGIH TLV for HAL (worker force, tabular HAL) | Yes | Yes | Yes | – | Yes | – |
| ACGIH TLV for HAL (analyst force, verbal anchor HAL) | Yes | Yes | – | – | Yes | Yes |
| ACGIH TLV for HAL (analyst force, tabular HAL) | Yes | Yes | – | – | Yes | – |
| 1995 Strain Index | – | Yes | – | Yes | Yes | – |

[a]%MVC determined by comparing matched grip/pinch force to subject's neutral maximum grip/pinch force.

**Table 10**

Recommendations for physical exposure variables to study DUE MSDs.

| Variable | Scale | Rating from worker (W) or analyst (A) | Field observation (F) or video analysis (V) | Variable used for |
|---|---|---|---|---|
| Peak force | Borg CR-10 | W | F | TLV for HAL |
| Peak force | Borg CR-10 | A | F and V (see Section 8, para 6) | TLV for HAL |
| Overall force[a] | Borg CR-10 | A | F and V (see Section 8, para 6) | SI |
| HAL rating | HAL scale | A | V | TLV for HAL |
| Cycle time | s | A | F or V | SI |
| Exertions/min | Number/min | A | V | SI |
| Duty cycle | % | A | V | SI |
| Speed of work | SI categories | A | F or V | SI |
| Hand/wrist posture (SI) | SI categories | A | V | SI |
| Hand/wrist posture (general) | Neutral, flexion[b] ≤ 30, 31–50, >50<br>Extension[b] ≤ 30, 31–50, >50 | A | V | Posture analysis |
| Hours of task/day | h | W, supervisor | F | SI |
| Exertions/min at each force level | Number/min | A | F and V (see Section 8, para 6) | Sub-task or force-repetition combination |
| Duration per exertion at each force level | s | A | F & V (see Section 8, para 6) | Sub-task or force-duration combination |
| Exertions/min in a given general hand/wrist posture | Number/min | A | V | Sub-task or posture-repetition combination |
| General posture at each force level | % time in general posture categories and number of exertions in each posture category | A | V | Sub-task or force-posture combination |

[a] Overall force is a construct that represents an analyst's judgement of the collective force demands of a task; it is neither peak force, nor average force, nor frequency-weighted or time-weighted average force.

[b] Flexion/extension measured from anatomical neutral.