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Radio frequency identification to measure the duration of machine-paced assembly tasks: Agreement with self-reported task duration and application in variance components analyses of upper arm postures and movements recorded over multiple days

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ABSTRACT

Technical advances in inertial measurement units (IMUs) with data logging functionality have enabled multi-day collection of fullshift upper arm postures and movements. Such data are useful for characterizing job-level exposures and, when coupled with task-level information, can inform interventions to mitigate high-exposure tasks. Previously reported methods for capturing task-level information, however, were limited primarily to self-report diaries or direct observation. In this study of machine-paced manufacturing workers (n = 6), a low-cost radio frequency identification (RFID) system was used to collect information about when, and for how long, specific assembly tasks were performed during up to 14 consecutive work shifts (76 total work shifts across the six participants). The RFID data were compared to information collected with a self-report diary using Bland-Altman analyses. In addition, the RFID data were paired with IMU data to identify task-level exposures from within full-shift recordings of upper arm postures and movements. These data were then used to estimate the relative contributions of between- and within-worker sources of variance to overall variance in posture and movement summary measures using hierarchical random-effects analysis of variance (ANOVA) techniques. Average estimates of daily task duration based on RFID data were comparable to estimates obtained by self-report (mean bias < ± 1 minute) but with substantial variability (limits of agreement > ± 100 minutes). In addition, the ANOVA models containing task-level information suggested a substantial amount of the overall exposure variance was attributed to repeated observations of the same task within a work day. These findings (i) suggest that while the RFID system used in this study performed adequately, further refinement, validation, and/or alternative strategies may be needed and (ii) underscore the importance of repeated full-shift and task-based measurement approaches in characterizing physical exposures, even in machine-paced environments.

1. Introduction

Occupational exposure to non-neutral upper arm postures has been associated with upper extremity musculoskeletal disorders (Gerr et al., 2014; Gold et al., 2009; Häkkänen et al., 2001; Punnett et al., 2000), although the wide variety of methods used to estimate exposure has contributed to uncertainty regarding dose-response relationships. Contemporary ergonomics exposure science generally accepts that direct measurement methods produce exposure information of greater accuracy and precision in comparison to self-report and observation-based methods (Burdorf and van der Beek, 1999; Dale et al., 2011; Trask et al., 2012; van der Beek and Frings-Dresen, 1998). Technological advances in commercially available sensor systems are also expected to lead to greater use of direct measurement in modern occupational safety and health practice (Reid et al., 2017).

The proliferation and low-cost of inertial measurement units (IMUs) with embedded data logging functionality have made field-based measurement of full-shift upper arm postures and movements across multiple work days logistically feasible in many occupational contexts. Several studies examining the statistical performance of exposure sampling strategies defined full-shift information as the “true” exposure for comparison purposes (Mathiassen et al., 2003, 2012; Svendsen et al., 2005; Trask et al., 2008). When full-shift exposure data are collected across multiple work days, the resulting information can be used

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to estimate exposure variability both between-workers and within-worker (e.g., between-days-within-worker), which is believed to have important implications on the risk of musculoskeletal outcomes (Mathiassen, 2006). Such information is also useful to inform the design of exposure assessment studies and to assess potential bias of risk estimates in epidemiologic studies (Loomis and Kromhout, 2004).

While full-shift exposure data are relatively easy to collect from a technical perspective, practitioners frequently require information about task-level exposures in order to efficiently allocate resources when designing and implementing interventions. For example, modern manufacturing enterprises often rotate workers through two or more tasks in any given work day, in part, as an administrative control to prevent musculoskeletal outcomes (Jorgensen et al., 2005). While the effectiveness of task rotation for primary prevention is not fully established (Leider et al., 2015; Padula et al., 2017), physical workload at the task level is commonly used as an input to task rotation design and scheduling models (Otto and Battaïa, 2017; Yoon et al., 2016). However, methods used to extract task-level information (e.g., task start and stop times) from continuous full-shift exposure measurements are somewhat crude, such as the use of self-report diaries (Gerr et al., 2014; Svendsen et al., 2005; Wahlström et al., 2010); resource-intensive, such as the use of direct observation (Fethke et al., 2015; Granzow et al., 2018; Mathiassen et al., 2005); or potentially disruptive to production, such as actively marking events into a data logging system (Douphrate et al., 2016).

Radio frequency identification (RFID) technology has the potential to simplify the process of measuring task-level information. The basic components of a simple RFID system include a "tag" used to identify an object and a "reader" for retrieving information encoded on the tag. A transceiver within a reader emits radio waves that activate the internal microchip within a tag, allowing access to the encoded data (usually in the form of a unique identification code). In a manufacturing environment, RFID readers installed at assembly workstations and tags assigned to workers represent a system for tracking when and for how long specific workers perform specific tasks. Pairing data from an RFID system with data from full-shift exposure measurements (e.g., upper arm postures and movements via IMUs) can then minimize the burden of exposure assessment both to participants (by eliminating the need to self-report task information) and to research staff (by eliminating the need to directly observe participants' tasks). Over multiple days of data collection, the resulting information can also facilitate analyses of both between- and within-worker components of exposure variability.

In this study, a low-cost, passive RFID system was used to track when and for how long manufacturing workers performed different assembly tasks during up to 14 consecutive work shifts. We had two primary analytic objectives. First, we examined the agreement in measures of task duration obtained using the RFID system to those obtained with a self-report diary. Second, we paired the RFID data with IMU data to extract task-level information from full-shift recordings of upper arm postures and movements, and then used these data to estimate the relative contributions of between- and within-worker sources of variance to overall variance in posture and movement summary measures.

2. Methods

2.1. Study participants

A sample of eight assembly workers was recruited from a household appliance manufacturer. No participant reported (i) a history of orthopedic surgery involving the upper extremity or (ii) pain in the upper extremity in the two weeks prior to enrollment. The University of Iowa Institutional Review Board approved all study procedures, and written informed consent was obtained. Of the eight participants, one left the study due to voluntary termination of employment and one was moved to a different assembly area in the facility. Six participants completed the data collection procedures. Five of the six participants were female. The mean age was 48 years (range: 21–63 years), mean height was 168.9 cm (range: 157.5–182.9 cm), and mean BMI was 29.7 kg/m^2 (range: 22.6–46.3 kg/m^2).

2.2. Facility and work description

The study facility employed more than 2000 production workers. The machine-paced production areas were arranged by "lines" corresponding to distinct product families. Each line was further arranged by "areas" corresponding to specific subassembly processes. Finally, each area was composed of several "tasks" to which individual workers were assigned. Each task was performed according to standardized production instructions. Tasks generally required manual manipulation of product parts and the use of tools (powered and/or manual). The task workstations were not height-adjustable. Machine-pacing was generally consistent from day-to-day during study activities (cycle time of approximately 35 s). The area in which study participants worked contained 10 tasks, and participants rotated between tasks generally at scheduled breaks during the work shift. The number of tasks any one participant performed per shift ranged from two to five. Many participants also performed the same task at different times during a shift.

2.3. Data collection instruments

Upper arm elevation was measured across each complete work shift using an IMU (GT9X Link, Actigraph, LLC., Pensacola, Florida). The IMU fit into a plastic housing accessory, which was attached using a Velcro® strap to the lateral aspect of the upper arm midway between the acromion and the lateral epicondyle. The IMU included a 3-axis accelerometer, gyroscope, and magnetometer that measured linear acceleration (± 16 g), angular velocity (± 2000 deg/sec), and magnetic field strength (± 4800 µT). Raw IMU data were sampled at 100 Hz and stored to onboard flash memory in the proprietary Actigraph file format. At the end of each work shift, the files were transferred to a computer using ActiLife software (version 6.11.9, Actigraph, LLC., Pensacola, FL). The raw IMU data were then exported to comma-separated text files for processing using custom programs in MATLAB (The MathWorks, Inc., Natick, MA) and LabVIEW (National Instruments, Austin, TX).

At the completion of each shift, participants entered in a preprinted diary (i) each task performed during the shift and (ii) an estimate of the total time spent performing each task. Participants were not asked to specify the temporal sequence of tasks. Each task workstation was also equipped with an RFID reader constructed using off-the-shelf components available through Adafruit Industries, LLC, including a microcontroller (Arduino Uno R3), an RFID "shield" (PN532 NFC/RFID Controller Shield), and a data logging/storage component (Data Logging Shield). Each RFID reader was battery operated and housed within a custom 3D-printed case. Each participant was assigned a unique RFID tag (Mifare Classic) attached to a lanyard worn around the neck. When an RFID tag was positioned near (approx. 5 cm) a reader, the reader "scanned" the tag ID number and logged the ID number and a timestamp to the compact flash card. Participants were instructed to scan the RFID tag when they began working at a particular task and again when they finished working at the task. Thus, each RFID reader generated a text file with information about which participant(s) performed the task (based on tag ID numbers) and for how long (based on timestamps). Prior to the start of each data collection day, the RFID and IMU systems were synchronized by using a common computer to initialize the devices.

2.4. Data processing

Due to widespread local magnetic field disturbances in the manufacturing environment, the IMU magnetometer data were not usable. Therefore, the IMU accelerometer and gyroscope measurements were combined using a custom complementary weighting algorithm to calculate upper arm elevation relative to gravity. In this study, 0° of elevation indicates alignment with gravity and the distal aspect of the