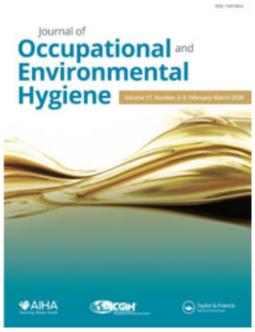

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Biomechanical factors during common agricultural activities: Results of on-farm exposure assessments using direct measurement methods

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ABSTRACT
Agricultural work is associated with increased risk of adverse musculoskeletal health outcomes. The purpose of this study was to quantify exposure to biomechanical factors among a sample (n = 55) of farmers in the Midwest region of the U.S. while they performed a variety of routine agricultural activities, and to compare exposure levels between these activities. Surface electromyography was used to estimate activity levels of the erector spinae, upper trapezius, forearm flexor, and forearm extensor muscle groups. Simultaneously, inertial sensors were used to measure kinematics of the trunk, upper arm, and wrist. In general, lower muscle activity levels, less extreme postures, and slower movement speeds were observed during activities that involved primarily the use of agricultural machinery in comparison to manual activities, suggesting a potential advantage of mechanization relative to musculoskeletal health. Median wrist movement speeds exceeding recently proposed exposure thresholds were also observed during many manual activities, such as milking animals and repairing equipment. Upper arm postures and movement speeds did not appear to confer excessive risk for shoulder-related outcomes (on the whole), but interpretation of the results is limited by a sampling approach that may not have captured the full extent of exposure variation. Not surprisingly, substantial variation in exposure levels were observed within each agricultural activity, which is related to substantial variation in the equipment, tools, and work practices used by participants. Ultimately, the results of this study contribute to an emerging literature in which the physical demands of routine agricultural work have been described on the basis of sensor-based measurements rather than more common self-report or observation-based approaches.

KEYWORDS
Agriculture; ergonomics; kinematics; surface electromyography

Introduction

An increased risk of musculoskeletal health problems has been observed among agricultural workers in comparison to those in many other industries (Leigh and Sheetz 1989; Morse et al. 2007; Walker-Bone and Palmer 2002). Back pain is common among agricultural workers (Osborne et al. 2012a), with indications of increased risk (∼50%) compared to non-farming rural workers (Holmberg et al. 2002). In addition, the prevalence of any shoulder, elbow, or wrist/hand pain has been observed to be significantly greater (∼20%) among those in agriculture compared to those in other industries (Lee et al. 2014). Risk factors for musculoskeletal outcomes in the agricultural setting are fundamentally similar to those among other occupational groups and have been categorized broadly as relating to personal characteristics (e.g., age, body mass, and gender), characteristics of the farm operation (e.g., commodities produced and size of the operation), psychosocial characteristics (e.g., stress and depression), and the physical demands of the work (Davis and Kotowski 2007; Douphrate et al. 2016b; Osborne et al. 2012b). With respect specifically to the physical demands of work, agricultural activities commonly expose workers to the full complement of established biomechanical risk factors for musculoskeletal outcomes (i.e., high muscle forces, non-neutral working postures, and high movement speeds) (Davis and Kotowski 2007; Walker-Bone and Palmer 2002). Understanding patterns of exposure to these biomechanical factors, across a range of body regions and agricultural activities, is an important component of building an empirical basis for prevention activities.

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Supplemental data for this article can be accessed on the publisher's website. AIHA and ACGIH members may also access supplementary material at http://oeh.tandfonline.com/.

Table 1. Classification of common agricultural activities.

Activity classification	Example from on-farm data collection
Field work with a self-powered machine	Using a combine to harvest grain
Repair/service equipment	Servicing hydraulic system of a tractor in a machine shed
Repair/service buildings or structures	Repairing a fence using manual tools
Handle/store harvested crops	Using an auger to transfer grain from a storage bin to a truck
Manual material handling	Lifting bags of fertilizer from a pallet to a storage rack
Powered material handling	Using an end-loader to transfer feed into a mixer
Feed animals	Dispersing feed to chickens by hand from a bucket
Move/load/sort animals	Moving (herding) hogs from barn to pasture
Treat/tag animals	Applying salve to treat wounds on cows
Milk animals	Manually prepping cows for milking and attaching milking units
Paperwork/office	Downloading data to computer and examining

Unfortunately, the use of relatively crude self-report and observation-based exposure assessment methods dominates the practice of measuring biomechanical factors among agricultural workers (Khan et al. 2019a). Notable exceptions include studies of select activities in a few specialized subsectors in which direct measures of muscle activity and/or postures and movement speeds were obtained, such as during apple harvesting (Earle-Richardson et al. 2008; Thamsuwan et al. 2019), grapevine pruning (Balaguier et al. 2017; Kato et al. 2006; Roquelaure et al. 2002), and milking parlor work on dairy farms (Douphrate et al. 2012; 2017; Mixco et al. 2016; Nonnenmann et al. 2010; Pinzke et al. 2001; Stål et al. 1999; 2000). Direct measures have also been used to examine the effects of both administrative and engineering controls to reduce biomechanical loads resulting from stooped working postures common to a number of non-mechanized agricultural activities (Hudson et al. 2014; Meyer and Radwin 2007; Ulrey and Fathallah 2012).

While the studies noted above provide useful information, many workers on farm operations in the U.S. Midwest routinely perform a variety of work activities (Fethke et al. 2015a) and, therefore, likely experience a broader range of biomechanical loading patterns than workers in specialized agricultural subsectors. Recently, Khan et al. (2019b) reported directly measured trunk postures and movement speeds among a relatively large sample (n = 49) of agricultural workers in the Canadian prairie (i.e., Saskatchewan), a region with agricultural activity similar in many respects to the U.S. Midwest. In their study, exposures varied substantially between working days categorized as involving predominantly machinery operation, manual tasks, or a mix of the two. In general, postures and movement speeds were less extreme during days with the majority of work time spent operating machinery.

Similar to Khan et al. (2019b), the objective of this study was to characterize the biomechanical loading patterns among a sample of farmers from nine states within the U.S. Midwest as they performed routine agricultural activities. Specifically, we sought to quantify and compare muscular loading and kinematics (i.e., postures and movement speeds) of the trunk, neck/shoulder, and distal upper extremity (i.e., wrist) for agricultural activities consistent with the production agriculture activity categories included in the second decade National Institute for Occupational Safety and Health (NIOSH) National Occupational Research Agenda for Agriculture, Forestry and Fishing (NIOSH 2008).

Methods

Study participants

Participants included in the current analyses were a subset (n = 55) of agricultural workers (n = 518) enrolled in a longitudinal study of musculoskeletal symptoms in nine states within the US Midwest. The procedures used to recruit participants into the longitudinal study have been reported previously (Fethke et al. 2015a). Concurrent with enrollment, all participants were asked to consider participating in the on-farm exposure assessment component of the study. Our goal was to recruit at least 10% of the full cohort for on-farm exposure assessment. The University of Iowa Institutional Review Board approved all on-farm exposure assessment procedures, and these 55 participants provided written informed consent.

On-farm data collection

The approach to data collection is best described as "naturalistic." When scheduling a data collection visit, the study coordinator discussed the agricultural activity or activities to be performed on the day of the visit. Activities (Table 1) were classified based on NIOSH (2008) and as reported previously in Fethke et al. (2015a). After the instrumentation systems were attached and calibrated (details in the following sections), research staff shadowed the participant, making notes regarding each activity performed and collecting video when feasible. Our objective was to collect exposure information for the full duration of each activity on the day of measurement or a maximum of four hours (whichever came first). On average, research staff spent approximately five hours on-farm per visit. The seasonal nature of production agriculture often required multiple visits to obtain measurements for as many activities applicable to the operation as possible. Three visits were made to 8 farms, two visits to 26 farms, and one visit to 21 farms. The total number of activities recorded per participant (across all visits) ranged from one to 10, with a median of four.

Instrumentation and data processing: Muscular loading

Muscular loads of the distal upper extremity, neck/shoulder, and trunk were estimated using surface electromyography (EMG). Specifically, EMG signals were recorded from the dominant side forearm flexors, forearm extensors, and upper trapezius, as well as bilaterally from the erector spinae (T9 level). The T9 level was selected as the erector spinae recording site (vs. the lumbar region) to minimize errors in interpretation as a result of the flexion-relaxation phenomenon (Fethke et al. 2011; Solomonow et al. 2003). A reference electrode was placed over the non-dominant clavicle. Two EMG data logger systems were used during the study: the Myomonitor IV with DE2.3 bipolar electrodes (Delsys Inc., Boston, MA) and the Datalog MWX8 with SX230 bipolar electrodes (Biometrics Ltd., UK). All EMG signals were digitized at 1000 Hz and recorded to flash memory for processing in the laboratory.

All EMG recordings were processed with custom LabVIEW (National Instruments, Austin, TX) and MATLAB (MathWorks, Natick, MA) programs. Visual inspection in both the time and frequency domains was used to assess EMG signal quality, with corrective actions applied as needed using procedures described previously (Douphrate et al. 2016a; Fethke et al. 2011; 2015b; 2016). The EMG recordings were then converted to running root-mean-square (RMS) amplitude using a 100-sample window with a 50-sample overlap (Granzow et al. 2018).

Muscle activity during agricultural activities was expressed as a proportion of that observed during submaximal, isometric reference voluntary exertions (%RVE). For the upper trapezius, the participant held a load (2 kg) in the hand with the arm abducted to 90° in 20° horizontal adduction, elbow fully extended and forearm pronated (Anton et al. 2007; Fethke et al. 2015b; Mathiassen et al. 1995). For the erector spinae, participants flexed forward to a trunk inclination angle of 30° from vertical and held a load (11.3 kg) with both hands and the arms hanging vertically (Fethke et al. 2011). For the forearm flexors and extensors, participants performed hand grip exertions (89 N) using a calibrated hand dynamometer (GripTrack Commander, J-Tech Medical Industries, Heber City, UT) (Anton et al. 2007; Fethke et al. 2012). Three repetitions of each reference exertion were performed, with a rest period of at least one minute between repeat exertions of a specific muscle group. Participants maintained each reference exertion for 20 s, and the mean RMS amplitude of the middle 10 s of each exertion was calculated. For each muscle, the average of the mean RMS EMG amplitudes from the three reference exertions was used as the RVE activation level. Baseline noise was identified for each EMG channel and quadratically subtracted from all RMS EMG amplitudes (Thorn et al. 2007). The set of EMG summary metrics (for each muscle) included the 10^{th}, 50^{th}, and 90^{th} percentiles of the normalized RMS EMG amplitudes, corresponding respectively to 'static,' 'median,' and 'peak' muscle activity levels (Jonsson 1988).

Instrumentation and data processing: Posture and movement

Postures and movement speeds of the trunk, dominant upper arm, and dominant wrist were estimated using inertial measurement units (IMUs) (Series SXT, Nexgen Ergonomics Inc., Quebec, CA). Each IMU was a small ($48.5 \times 36 \times 12$ mm), wireless, battery powered unit that measured and stored raw acceleration (triaxial, ± 6 g), angular velocity (triaxial, ± 2000° s^{-1}), and magnetic field strength (triaxial, ± 600 μT). Raw IMU data were sampled at 20 Hz. The IMUs were positioned at the (i) anterior thoracic region of the trunk (sternum), (ii) posterior lumbar region of the trunk (near L5/S1), (iii) upper arm (lateral aspect midway between the glenohumeral and elbow joints), (iv) forearm (dorsal surface just proximal of the wrist joint), and (v) hand (dorsal surface). Participants assumed a standard reference anatomical position for IMU calibration, using manufacturer-supplied software and recommended procedures.

All IMU data were processed using custom LabVIEW and MATLAB programs. We derived both posture and movement speed profiles for motions that could be calculated from combinations of accelerometer and gyroscope signals (Table 2; trunk flexion/

Table 2. Posture and movement profiles extracted from recorded inertial measurement unit data.

Body segment	Motion	Sensors involved	Resulting profiles for analysis
Trunk	Flexion/extension[A]	Sternum, L5/S1	Posture and movement speed[C]
Trunk	Lateral bending[B]	Sternum, L5/S1	Posture and movement speed
Dominant upper arm	Elevation	Upper arm	Posture and movement speed
Dominant wrist	Flexion/extension	Hand, forearm	Movement speed only
Dominant wrist	Radial/ulnar deviation	Hand, forearm	Movement speed only

[A]Negative values denote extension; positive values denote flexion.
[B]Negative values denote lateral bending to the left; positive values denote lateral bending to the right.
[C]Movement speed reported as non-directional absolute value of velocity.

extension, trunk lateral bending, and upper arm elevation) using previously reported algorithms (Schall Jr. et al. 2015, 2016b; Chen et al. 2018). Magnetometer data were not used. Wrist posture could not be calculated because, unlike the trunk and upper arm, the orientation of the wrist joint with respect to gravity cannot be assumed. Therefore, we used only the gyroscope signals to calculate wrist movement speed (i.e., the absolute value of velocity) in both the flexion/extension and radial/ulnar deviation movement planes. Similar to the normalized EMG data, the posture and movement speed profiles were summarized using the 10th, 50th, and 90th percentiles. For the trunk and upper arm, we also calculated posture "range" as the difference between the 90th and 10th percentiles.

Statistical analyses

The distributions of all EMG, posture, and movement speed summary metrics were examined using standard descriptive statistics and reported using medians and interquartile ranges. Ultimately, small numbers of measurements (or no measurements) within certain combinations of agricultural activity and farm type restricted our analyses to comparisons between agricultural activities (i.e., collapsing across all farm type categories). Since not all participants were measured during all agricultural activities (because all activities did not apply to all farm operations), our analyses treated the measurements within each agricultural activity as independent from the measurements within every other agricultural activity (i.e., a repeated-measures analysis was not used). Due to violations of parametric assumptions, we used the Kruskal-Wallis omnibus test and, if statistically significant ($p < 0.05$), used the Dwass-Steel-Critchlow-Flinger method (Critchlow and Fligner 1991) for post-hoc pairwise comparisons between agricultural activities. All statistical procedures were performed using SAS (version 9.4, the SAS Institute, Inc., Cary, NC).

Results

For the 55 participants included in the current analysis, the mean age was 57.7 ± 9.7 years (vs. 61.1 ± 12.8 years for the full cohort (Fethke et al. 2015a)), the mean body mass index was $29.9 \pm 5.6\,\text{kg·m}^{-2}$ (vs. $29.0 \pm 4.9\,\text{kg·m}^{-2}$), 53 (96%) were male (vs. 94%), all were Caucasian (vs. 99.6%), 49 (89%) reported farming as his/her primary occupation (vs. 71%), and 45 (82%) self-identified as the farm owner/operator (vs. 80%). Participants' operations were categorized by the types of commodities produced. Twenty-four operations (44%) produced two commodities (e.g., grain and beef), 15 (27%) produced grain only (e.g., corn and/or soybeans), 11 (20%) produced three or more commodities, 4 (7%) produced specialty commodities (e.g., fruits/vegetables), and 1 (2%) produced only beef.

The numbers of on-farm measurements obtained by agricultural activity and also by farm type are provided in Table 3. In total, 224 task-based measurements of muscle activity and 232 task-based measurements of posture/movement were obtained. Random instrumentation failures (e.g., loss of contact between the electrode and skin) led to the lower number of EMG measurements. Approximately half of all on-farm measurements involved the operation of agricultural machinery. Machine operation occurred in all or nearly all measurements of *field work with a self-powered machine* and *powered material handling*, and in about 80% of measurements of *handle/store harvested crops*, but was much lower (or 0%) for other activities.

In general, the exposure measurements were characterized by substantial variability across all activities (Table 4) and both between and within specific activities (supplemental Tables S1–S10). Across all muscle activity and posture/movement summary metrics, 96 of 119 (81%) statistically significant post-hoc pairwise comparisons included *field work with a self-powered machine* (supplemental Tables S1–S10). In the majority (92%) of these comparisons, the exposure level was lower during *field work with a self-powered*

Table 3. Number and duration of on-farm exposure measures, by agricultural activity and farm type (a/b/c, where a = # of trunk and dominant upper arm posture and movement speed measures, b = # of muscle activity measures, and c = # involving machinery operation[A]).

	Farm type						
Agricultural activity	Grain only	Beef only	Specialty	2 comm.	≥3 comm.	*Totals*	*Duration (min)*[B]
Field work with a self-powered machine	15/13/15	-/-/-	1/1/1	16/14/20	10/9/8	*42/37/44*	*76.2 [47.2, 98.6]*
Repair/service equipment	9/10/1	-/-/-	2/1/-	16/17/4	8/8/-	*35/36/5*	*44.6 [24.5, 82.0]*
Repair/service buildings/structures	5/5/2	1/1/-	2/2/-	8/10/2	5/4/-	*21/22/4*	*54.9 [37.7, 79.2]*
Handle/store harvested crops	4/3/3	-/-/-	2/2/1	11/10/11	8/7/5	*25/22/20*	*57.0 [34.9, 92.2]*
Manual material handling	3/3/-	-/-/-	3/3/-	9/9/-	7/6/-	*22/21/-*	*16.4 [6.0, 37.0]*
Powered material handling	4/4/4	-/-/-	2/2/2	13/14/14	5/5/4	*24/25/24*	*30.2 [12.9, 51.1]*
Feed animals	-/-/-	1/1/-	-/-/-	15/17/12	7/7/1	*23/25/13*	*29.3 [19.4, 46.6]*
Move/load/sort animals	-/-/-	1/1/-	-/-/-	7/7/1	6/6/-	*14/14/1*	*17.4 [10.8, 30.5]*
Treat/tag animals	-/-/-	-/-/-	-/-/-	7/8/1	7/6/-	*14/14/1*	*24.0 [11.3, 61.2]*
Milk animals	-/-/-	-/-/-	-/-/-	4/3/-	4/3/-	*8/6/-*	*44.6 [24.5, 82.0]*
Paperwork/office	1/1/-	-/-/-	-/-/-	3/1/-	-/-/-	*4/2/-*	*33.9 [21.0, 46.8]*
Totals	*41/39/25*	*3/3/-*	*12/11/4*	*109/110/65*	*67/61/18*	*232/224/112*	*40.7 [17.0-75.1]*

[A]Tasks involving machinery operation also included measurement of whole-body vibration; results are reported in Fethke et al. (2018)
[B]Sampling duration reported for muscle activity measures as median [interquartile range], in minutes.

Table 4. Median [interquartile range] muscle activity levels (part a) and posture and movement speed levels (part b) across all participants, farm types, and agricultural activities.

a) Muscle activity	Erector Spinae, L		Erector Spinae, R		Upper Trapezius		Flexors		Extensors	
10^{th} percentile, %RVE	16.5	[11.4, 25.6]	19.0	[12.4, 28.5]	5.5	[2.8, 9.2]	5.7	[2.7, 10.8]	3.4	[1.9, 6.1]
50^{th} percentile, %RVE	46.0	[32.9, 58.7]	48.8	[35.3, 61.6]	26.4	[17.7, 40.1]	30.4	[15.7, 52.5]	19.4	[11.2, 34.3]
90^{th} percentile, %RVE	109.8	[79.4, 141.6]	112.0	[85.7, 136.8]	80.0	[59.3, 107.3]	163.0	[90.5, 302.0]	91.1	[61.9, 149.0]
b) Posture and movement	Trunk Flex/Ext		Trunk Lateral Bend		Upper Arm		Wrist Flex/Ext		Wrist Rad/Uln	
Postures										
10^{th} percentile, °	9.0	[1.6, 20.0]	−11.1	[-16.2, -6.6]	15.3	[7.9, 24.3]				
50^{th} percentile, °	22.0	[12.9, 34.4]	0.0	[-4.4, 4.0]	35.6	[26.1, 46.2]				
90^{th} percentile, °	39.3	[28.5, 52.5]	10.5	[6.1, 16.1]	67.9	[53.7, 83.2]				
Range (90^{th}-10^{th} percentiles), °	29.6	[18.8, 39.3]	21.1	[17.5, 26.7]	53.6	[40.5, 64.5]				
Movement speeds										
10^{th} percentile, $°\cdot s^{-1}$	1.1	[0.8, 1.6]	1.2	[0.8, 1.8]	1.7	[1.2, 2.4]	1.7	[1.2, 2.5]	1.1	[0.7, 1.7]
50^{th} percentile, $°\cdot s^{-1}$	8.8	[6.7, 11.8]	10.3	[7.5, 14.2]	14.3	[10.4, 19.8]	13.5	[8.9, 19.1]	10.2	[6.9, 14.2]
90^{th} percentile, $°\cdot s^{-1}$	35.7	[27.7, 44.3]	42.4	[33.0, 55.6]	61.6	[46.0, 74.0]	74.7	[52.5, 94.9]	52.8	[37.8, 68.2]

machine than during the comparison activity. Exceptions involved the 10^{th} and 50^{th} percentiles of trunk flexion/extension angle, the 10^{th} percentile of trunk flexion/extension movement speed, and the 10^{th} percentile of upper arm angle, for which exposure levels were greater during *field work with a self-powered machine* than during some other activities.

Differences in exposure levels between agricultural activities are depicted in Figures 1–3. For brevity and clarity of presentation, each figure shows the median summary metric value across all activities (as reported in Table 4) and median summary metric values for (i) *milk animals*, (ii) *repair/service equipment*, (iii) *manual material handling*, and (iv) *field work with a self-powered machine* (as reported in supplemental Tables S1–S10).

With regard to muscle activity (Figure 1), *field work with a self-powered machine* led to lower normalized EMG levels in comparison to most other activities. For the 50^{th} and 90^{th} percentile EMG summary metrics, the median levels during *field work with a self-powered machine* were 23–37% less than the median levels across all activities combined. Several differences in EMG levels between *field work with a self-powered machine* and other activities were statistically significant in post-hoc analyses, particularly for the 50^{th} and 90^{th} percentile EMG summary metrics (see supplemental Tables S6–S10). Other notable observations across all activities include (i) somewhat greater 10^{th} percentile levels of both the left erector spinae (16.5 %RVE) and right erector spinae (19.0 %RVE) in comparison to the other muscles (3.4–5.7 %RVE) and (ii) a larger difference between the 10^{th} and 90^{th} percentile activity levels of the forearm flexors in comparison to the other muscles.

Figure 2 shows the median 10^{th}, 50^{th}, and 90^{th} posture percentiles for trunk flexion/extension, trunk lateral bending, and upper arm elevation angles. As suggested above, both the median 10^{th} and 50^{th} percentiles of the trunk flexion/extension angle and the median 10^{th} percentile upper arm elevation angle were greater during *field work with a self-powered*

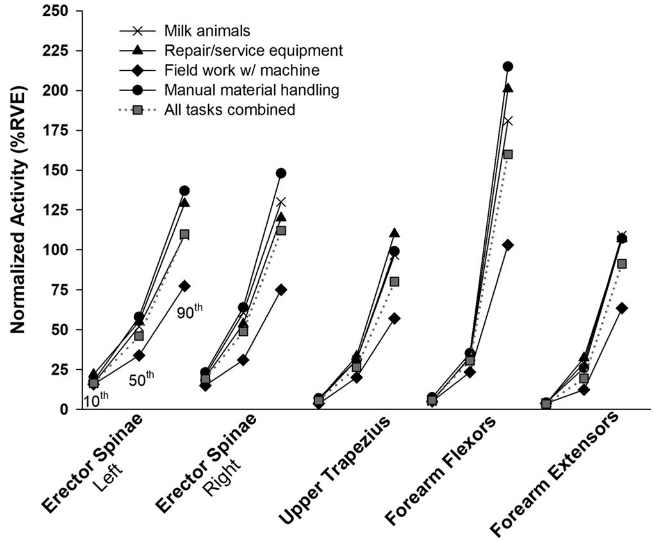

Figure 1. Group median normalized muscle activity level percentiles (10th= 10th percentile, 50th = 50th percentile, 90th = 90th percentile).

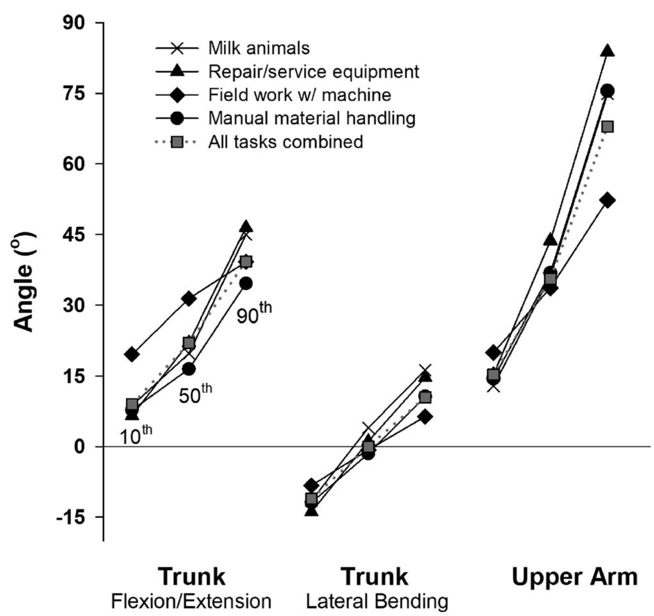

Figure 2. Group median trunk and upper arm posture percentiles (10th= 10th percentile, 50th = 50th percentile, 90th = 90th percentile).

machine than during other activities. This pattern did not hold for the median 90th percentile values, however, implying greater static but lower peak trunk and upper arm postures during *field work with a self-powered machine* in comparison to most other activities.

As might be expected, observed movement speeds generally increased from the trunk, to the upper arm, to the wrist (Figure 3). As with EMG levels, the lowest 90th percentile movement speeds (all body areas) were observed during *field work with a self-powered machine*. The greatest 90th percentile wrist speeds (in both flexion/extension and radial/ulnar deviation) were observed during *milk animals*.

Discussion

Direct measurement of muscle activity and kinematic information is common in field-based studies of physical workload (although rarely in agricultural settings), with the underlying assumption that differences in exposure levels between activities implies differences in the risk of musculoskeletal outcomes. However, results of analyses of associations between summary exposure metrics of direct measures and musculoskeletal symptoms (or disorders) are mixed. For example, Gerr et al. (2014) did not observe associations between EMG levels (upper trapezius, forearm

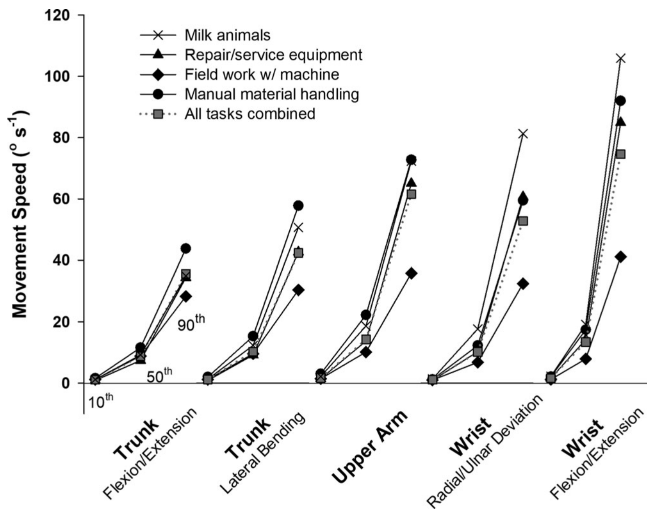

Figure 3. Group median movement speed percentiles (10th= 10th percentile, 50th = 50th percentile, 90th = 90th percentile).

extensors, forearm flexors) and the incidence of either neck/shoulder or hand/arm outcomes in a prospective study of manufacturing workers. On the other hand, Nordander et al. (2013) and Nordander et al. (2016) synthesized exposure and outcome prevalence data from a large number of observational studies among a variety of occupational groups and reported several statistically significant associations. Summary metrics associated with distal upper extremity symptom prevalence included the 10th and 90th percentile forearm extensor EMG levels and the 50th percentile wrist flexion/extension speed (Nordander et al. 2013). Summary metrics associated with shoulder symptom prevalence included the 10th percentile upper trapezius EMG level and the 50th percentile upper arm movement speed (Nordander et al. 2016).

Expanding on the Nordander et al. studies, Balogh et al. (2019) recently proposed exposure thresholds of $60°\cdot s^{-1}$ for the 50th percentile upper arm movement speed and $20°\cdot s^{-1}$ for the 50th percentile wrist flexion/extension movement speed (for an 8-hr shift). In the current study, the median 50th percentile upper arm movement speed across all activities ($14.3°\cdot s^{-1}$, IQR $10.4\text{-}19.8°\cdot s^{-1}$) was much lower than the proposed threshold. Likewise, the upper bounds of the IQRs around the activity-specific median 50th percentile upper arm movement speed values were all less than $30°\cdot s^{-1}$, implying that (on the whole) the upper arm movement speeds measured in this study do not confer excessive risk for shoulder-related musculoskeletal outcomes. However, the median 90th percentile upper arm movement speeds did exceed $60°\cdot s^{-1}$ for all but two activities (*field work with a self-powered machine* and *handling/storing harvested crop*). Consequently, longer sampling durations and/or sampling across multiple days may reveal median 50th percentile upper arm movement speed levels closer to the proposed threshold.

In contrast to the upper arm, the median 50th percentile wrist flexion/extension movement speed approached the proposed $20°\cdot s^{-1}$ threshold for *milk animals* ($19.2°\cdot s^{-1}$, IQR = $15.5\text{–}30.9°\cdot s^{-1}$), and the upper bounds of the IQRs around the median 50th percentile values exceeded $20°\cdot s^{-1}$ for more than half of the activities. While Balogh et al. (2019) did not propose exposure thresholds for EMG-based metrics, increasing upper trapezius activity levels were associated with increased prevalence of neck/shoulder outcomes (e.g., rotator cuff tendonitis and tension neck syndrome), and increasing forearm extensor activity levels were associated with increased prevalence of distal upper extremity outcomes (e.g., carpal tunnel syndrome [CTS]).

Additional epidemiological analyses support a relationship between wrist movement speed and distal upper extremity outcomes. Two recent studies are particularly relevant. Lund et al. (2019) reported mean wrist movement speeds (in flexion/extension) for 30 occupational groups ranging from $3.6°\cdot s^{-1}$ (for office workers) to $37.6°\cdot s^{-1}$ (for "slaughterhouse" workers). Farmers were included among the occupational groups, with a mean wrist movement speed of $14.6°\cdot s^{-1}$, a value consistent with the measurements of the current study. Furthermore, the risk of CTS increased as wrist movement speed increased, with those exposed at levels above $11.1°\cdot s^{-1}$ experiencing more than twice the incidence rate as those exposed at levels below $6.1°\cdot s^{-1}$. In addition, Heilskov-Hansen et al. (2016) recently reported, among house painters, a 37% increase in the incidence rate of CTS diagnosis for every $1°·s^{-1}$ increase of the 50^{th} percentile wrist movement speed (in flexion/extension). In that study, the median 50^{th} percentile wrist movement speed in flexion/extension was $15.6°·s^{-1}$, a value also consistent with the measurements of the current study.

Interestingly, neither the Nordander et al. (2013, 2016) studies nor Balogh et al. (2019) supported an association between upper arm posture percentiles and the prevalence of shoulder symptoms. In contrast, multiple reviews (van der Molen et al. 2017; van Rijn et al. 2010) and individual studies suggest a relationship between the percent time with "extreme" upper arm posture (typically defined as 60° or 90° of shoulder flexion or upper arm elevation) and shoulder outcomes. In Svendsen et al. (2004), for example, the odds of disabling shoulder pain among machinists, mechanics, and painters (workers with non-routinized tasks, similar to agricultural workers) with 3–6% and 6–9% of work time spent with the dominant upper arm elevated $>90°$ were 2.1 and 3.5 times greater, respectively, compared to those with $<3\%$ of work time spent with the dominant upper arm elevated $>90°$. In the current study (data not shown), activities with $>3\%$ of work time with the upper arm elevated $>90°$ included *treat/tag animals* (median = 3.4%), *manual material handling* (4.1%), *milk animals* (5.4%), and *repair/service equipment* (7.8%), which suggests that workers who spend relatively greater amounts of time in these activities may experience a greater risk of shoulder outcomes.

While some prospective studies have reported associations between non-neutral trunk work postures (e.g., $>45°$ or 60° of trunk flexion) and low back symptoms (Coenen et al. 2013; Hoogendoorn et al. 2000; Jansen et al. 2004; Van Nieuwenhuyse et al. 2006) others have not (Lagersted-Olsen et al. 2016), and several reviews on the topic offer conflicting evidence (Bakker et al. 2009; da Costa and Vieira 2010; Griffith et al. 2012; Khan et al. 2019a; Roffey et al. 2010; Wai et al. 2010). Instead, dynamic and/or cumulative aspects of low back biomechanical loading have been reported as potentially more important factors to consider when identifying workers at risk of developing adverse low back health outcomes (Coenen et al. 2013; Davis and Marras 2000; Fathallah et al. 1998; Marras et al. 2010), in part because compressive and shear forces increase as a result of increases in movement velocity (Marras and Granata 1997). Results of the current study suggest that *manual material handling* activities may place farmers at increased risk of low back outcomes relative to some other work activities as a function of increased trunk flexion and lateral bending speeds. This is further supported by elevated EMG levels for *manual material handling* activities (the 90^{th} percentile left erector spinae as well as the 50^{th} and 90^{th} percentile right erector spinae). However, the use of submaximal isometric reference exertions (i.e., RVE) for the purpose of EMG normalization limits the extent to which the observed EMG levels relate to capacity, and thus to risk. We considered but ultimately elected to forego maximum voluntary contractions (i.e., MVC) primarily to minimize the possibility of injury during normalization procedures (Attebrant et al. 1995; Bao et al. 1995; Mathiassen et al. 1995; Nieminen et al. 1993), which was desirable given participants' mean age of nearly 58 years.

Consistent with Khan et al. (2019b) our results suggest that biomechanical demands are lower during tasks involving the operation of agricultural machinery (e.g., *field work with a self-powered machine* and *powered material handling*) in comparison to primarily manual tasks. However, the current analyses did not consider the potential risks for musculoskeletal outcomes associated with whole-body vibration. Interestingly, the median 10^{th} and 50^{th} percentiles of trunk flexion/extension angles were greatest during activities with frequent machine use, which is a direct consequence of the seated postures adopted during machine operation (Amari et al. 2015; Eger et al. 2008; Fethke et al. 2018; Raffler et al. 2010). The role of trunk posture relative to low back outcomes in the context of concurrent exposure to whole-body vibration has been examined for decades, and the ISO issued a technical report to provide guidance for measuring and reporting of trunk postures among seated machine operators (ISO 2012). Although the current study was designed and initiated prior to release of the ISO technical report, we do report trunk flexion/extension as the angle of the IMU located on the sternum relative to the angle of IMU located on the low back. This approach differs from many recent field-based studies using a single accelerometer or IMU located on the trunk and reporting trunk flexion/extension angles relative to gravity (Afshari et al. 2014; Fethke et al. 2011; Khan et al. 2019b; Lagersted-Olsen et al. 2016; Schall Jr et al. 2016a; Villumsen et al. 2017; Wahlström et al. 2016). However, the angle of the trunk relative to gravity does not fully capture the kinematics of seated postures, in which the pelvis tilts rearward and the lumbar curvature is flattened, particularly in situations involving forward leaning and/or the absence of a backrest with lumbar support.

The dataset generated during the current study includes quantitative information about biomechanical factors among a relatively large sample of farmers performing a wide variety of activities. However, this strength also presents some important challenges in terms of interpreting the results. During the course of data collection, we observed substantial variation in the tools, equipment, and work practices among participants when performing activities classified identically. This between-worker variation is reflected in the observed variability of the summary metrics and, in turn, limited the power to detect statistical differences between the agricultural activities. Statistical power was also limited in that not every participant was measured on every agricultural activity, partly because not every activity applied to every farm operation. Therefore, we could not apply within-worker analytic procedures (i.e., repeated measures) that maximize statistical power. In addition, we were not able to ascertain the relative contributions of between-worker, between-days-within-worker, or within-worker sources of variability to the observed exposure variance, which is useful when designing interventions and/or exposure assessment strategies for epidemiological studies. Furthermore, the current analyses did not consider certain aspects of biomechanical loading that may increase the risk of musculoskeletal health outcomes, such as joint angular acceleration (Marras and Schoenmarklin 1993), periods of muscle rest (Veiersted et al. 1990), or an explicit interaction between posture/movement and muscle activation (e.g., movement speeds above the proposed thresholds concurrent with high muscle activity levels). Finally, the study sample was relatively homogeneous, which may limit the generalizability of the observed results to the broader agricultural workforce. However, demographic characteristics of producers in the nine study states are similar to those of the study sample (e.g., average age ∼57 years and >99% Caucasian), with the exception of gender (about 65% male) (United States Department of Agriculture 2019).

Conclusions

Our findings indicated that more than half of the agricultural activities observed in this study exceeded recently proposed exposure thresholds for wrist movement speed, suggesting potentially excessive risk for distal upper extremity musculoskeletal outcomes among farmers. Upper arm movement speeds measured in this study did not meet the recently proposed upper arm velocity exposure threshold criterion, although several non-mechanized activities may increase the risk of shoulder-related musculoskeletal outcomes. In addition, *field work with a self-powered machine* generally required lower muscular loads and lower peak kinematic loading in comparison to most other activities, indicating a potential advantage of mechanization but at a cost of greater static kinematic characteristics and, implicitly, increased exposure to whole-body vibration. Overall, the substantial variability in biomechanical loading between and within agricultural activities indicates a need for sampling strategies designed to more fully capture the temporal patterns of farm work.

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