Applied Ergonomics 89 (2020) 103193

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: http://www.elsevier.com/locate/apergo

Comparisons of physical exposure between workers harvesting apples on mobile orchard platforms and ladders, part 1: Back and upper arm postures

Ornwipa Thamsuwan [a,*], Kit Galvin [b], Maria Tchong-French [b], Lovenoor Aulck [c], Linda Ng Boyle [a,d], Randal P. Ching [e], Kevin J. McQuade [f], Peter W. Johnson [b]

[a] Department of Industrial and Systems Engineering, University of Washington, Seattle, WA, USA
[b] Department of Environmental and Occupational Health Sciences, University of Washington, Seattle, WA, USA
[c] Information School, University of Washington, University of Washington, Seattle, WA, USA
[d] Department of Civil and Environmental Engineering, University of Washington, Seattle, WA, USA
[e] Department of Mechanical Engineering, University of Washington, Seattle, WA, USA
[f] Department of Rehabilitation Medicine, University of Washington, Seattle, WA, USA

ABSTRACT

This study compared farmworkers' exposure to non-neutral postures using a new mobile platform apple harvesting method and the traditional method using ladders. Twenty-four workers were recruited and assigned into three groups: ladder workers ($n = 8$) picking apples from full trees using a ladder, mobile platform workers ($n = 8$) picking apples from upper part of the trees while standing on a moving platform, and ground-based mobile platform workers ($n = 8$) picking apples from lower part of the trees which the mobile platform workers left out. Upper arm and back inclinations were continuously monitored during harvesting using tri-axial accelerometers over full work shifts (~8 h). Upper arm posture was characterized as the percentage of time that upper arm flexion and abduction exceeded 30°, 60°, and 90°. Back posture was characterized as the percentage of time that torso angles (sagittal flexion or lateral bending) exceeded 10°, 20°, and 30°. The 10th, 50th, and 90th postural percentiles were also calculated. The platform workers had lower exposures to upper arm flexion and abduction than the ground and ladder workers. There were no differences in torso angles between the ladder and mobile platform workers; however, the ground workers were exposed to more and greater percentages of time in torso flexions.

1. Introduction

1.1. Work-related musculoskeletal disorders in agricultural workers

Agricultural workers suffer from work-related musculoskeletal disorders (WMSDs), with the highest prevalence being in the low back, shoulders, and upper extremities, respectively (Davis and Kotowski, 2007; Osborne et al., 2012). Based on a study of self-reported pain in the USA (Walker-Bone and Palmer, 2002), the prevalence of low back pain was greater in farming (41%) than in other manual (38%) and non-manual (27%) occupations; the prevalence of shoulder pain was also greater in farming (14%) than in other types of manual labor (9.7%) and in non-manual labor (7.1%) occupations. In apple orchards, manual harvesting was reported as the most frequent task (34.5%), and the median duration of the apple harvest typically lasts four weeks for each variety of apple present in an orchard (McCurdy et al., 2003).

Occupational risk factors for low back and shoulder pain include working with moderate to high forces, holding prolonged elevated postures with the back and arms, and using the arms repetitively (English et al., 1995; van der Windt et al., 2000; Leclerc et al., 2004). In apple harvesting, workers are exposed to shoulder stress while reaching to pick apples and to both back and shoulder stress while carrying apple bags or ladders (Fulmer et al., 2002). Research has found that this population is subjected to and holds awkward postures for a greater percentage of time than construction workers and nurses, two groups with the highest WMSD risk (Earle-Richardson et al., 2004).

1.2. Current situation and knowledge gaps in tree fruit industry

The tree fruit industry is important in Washington State, USA. This industry, when compared to others in the state, generates the most revenue and accounts for almost one-third of agricultural product sales in Washington State and is the largest apple supplier in the Unites States (USDA NASS, 2018). Nevertheless, the industry is facing challenges in price competition from foreign producers. In response the financial challenges from foreign producers and to increase profits, the Washington State Tree Fruit Research Commission issued a national roadmap aiming to reduce production costs by focusing on technological

* Corresponding author. #305 - 920 9th St E, Saskatoon, SK S7H 0N1, Canada.
E-mail address: fahornwipa@gmail.com (O. Thamsuwan).

https://doi.org/10.1016/j.apergo.2020.103193
Received 18 March 2020; Received in revised form 10 June 2020; Accepted 11 June 2020
Available online 6 August 2020

Fig. 1. A harvest-assisted mobile orchard platform.

innovations used to automate orchard systems (Seavert, 2005). In industrialized orchards in Washington State, small trees are planted close together and trained onto a trellis to form a continuous fruiting wall to increase production per acre. This orchard layout can easily accommodate new and innovative harvesting systems, such as the mobile platform. This elevated platform moves semi-autonomously through two rows of trees (Fig. 1). This technology has been introduced in some industrialized orchards to make harvesting more robust and economical with the intent to increase productivity and decrease costs. No longer needing to climb ladders, workers using this technology can stand on the platform and continuously pick apples while being semi-autonomously transported through the orchard. A second team of workers harvests the apples remaining on the lower parts of the tree from the ground. Nevertheless, given the usage of these platforms, ergonomics associated with automation in agriculture is still understudied and undervalued. Research is needed to investigate whether they reduce the prolonged static loading or repetitive motions of the shoulders and back or put workers at greater risk for shoulder- and/or back-related discomfort and injury.

1.3. Current methods in assessing postures

Previous studies presented several techniques to assess non-neutral work postures through observational methods of which is a direct measurement, incorporating a computerized system with markers on the body or self-contained battery-powered sensors with built-in memory (Spielholz et al., 2001; Bernmark and Wiktorin, 2002; Amasay et al., 2009; Scibek and Carcia, 2012). However, only a few studies have collected objective posture measurements in this way from agricultural workers in field settings due to the variability in the work environment. One of those few previous studies used accelerometers to collect and characterize the trunk postures of forestry workers performing their various regular tasks such as tree seeding, harvesting, logging, log sorting, and vehicle maintenance (Teschke et al., 2009). Another study collected tri-axial acceleration data of the upper arm and characterized the upper arm posture of milking parlor workers when the workers were standing at fixed positions while the cows were moved to the workers and always at the same height (Douphrate et al., 2012).

In attempt to evaluate the work postures in apple harvesting, a previous study proved the feasibility of the technique using tri-axial accelerometers to collect and characterize postural exposure in both ladder-based and mobile-platform-based apple harvesting (Thamsuwan et al., 2019). In this study, posture data were collected from various types of orchards including conventional ones where workers used ladders to harvest Red Delicious apples from tall and wide trees as well as two different trellised orchards with shorter tree walls where workers harvested Jazz and Gala apples from the mobile platforms. The fact that different apple varieties are grown on trees with different characteristics, e.g. height, and require different harvesting techniques, e.g. strip-picking vs. color-picking, suggested that this study did not provide a fair comparison between the ladder-based and mobile-platform-based apple harvesting. To make a reasonable comparison between the two equipment, posture data should be collected from the same type of orchards where the same types of apples are picked from the trees in the same ages.

1.4. Study objective

The aim of the current study was to overcome the challenge of incomparable dataset in the previous study to determine whether the back and upper arm postures and repetitions for apple harvesting differed for ladder and mobile platform workers. Such exposures among orchard workers using ladder-based and mobile-platform-based harvesting methods were collected and compared within a single orchard. This paper contains part 1 of the current study where workers' exposures to non-neutral back and upper arm posture are being presented, whereas the next paper, part 2 of the study (Thamsuwan et al. in press), describes repetition rates. The postural exposures were characterized in two ways: (1) by the percentage of work time during which the angles of the back and upper arms were greater than certain postural thresholds, and (2) as the 10th, 50th and 90th percentiles of the angles of the back and upper arms.

Table 1
Participants' demographics and anthropometrics: mean (SE).

	Ground	Ladder	Platform	p-value
Age (years)	23.9 (1.4)	32.5 (3.0)	28.3 (3.0)	0.09
Weight (kg)	83.9 (4.9)	71.4 (4.5)	74.7 (2.4)	0.11
Height (cm)	177 (3.3)	170 (2.4)	171 (2.4)	0.16
Arm length (cm)	65.6 (1.6)	63.6 (1.0)	66.1 (1.3)	0.36
Upper arm length (cm)	37.1 (1.0)	35.4 (0.4)	35.7 (0.6)	0.26
Forearm length (cm)	35.4 (1.1)	34.7 (0.5)	35.4 (0.9)	0.80
Number of right-handed workers	7	6	8	–
Experience at study site (seasons)	1.38 (0.26)	2.00 (0.27)	1.25 (0.16)	0.08

2. Methods

2.1. Subjects

Twenty-four workers who were currently working in a trellised orchard and who had at least one season of harvesting experience (i.e., approximately three months) were selected to participate in the study. All the participants were males of Hispanic origin and native Spanish speakers. This study took place in one orchard in Quincy in 2014, which was different from the previous study (Thamsuwan et al., 2019) conducted in several orchards in Yakima region in 2013, when those subjects in each group were recruited separately. Therefore, none of the subjects in this study had previously participated in the previous study.

The participants were firstly recruited from the same orchard at the same time then each participant was assigned to one of the following three groups: (1) platform workers who picked apples at the upper- and mid-level of the trees while standing on a moving platform, (2) ground workers who worked in front or behind the mobile platform and picked apples only at the lower level of the trees, and (3) a separate group of ladder workers who picked apples over the full height of the trees. All subjects participated in the study for one day and only performed their dedicated harvesting tasks. All participants provided informed consent prior to participating and all study procedures involving human subjects were approved by the University of Washington Human Subject's Division Institutional Review Board. The subjects' weight, height, arm length, upper arm length, and forearm length were measured at the end of the work day. Table 1 shows the descriptive statistics of the demographic and anthropometric measures of the participants.

2.2. Apple harvesting tasks

In conventional apple harvesting, an empty bag is attached to the front of the workers' body with shoulder straps (Fig. 2). The workers climb the ladder and pick apples from the highest point of the tree and move down the tree while descending the ladder until the apple bag is filled. With the filled bag, the workers then walk to an apple bin (Fig. 3), dimension: 120 cm × 120 cm x 70 cm, bend over, open the bottom of the apple bag, and gently release, dispense, and disperse the apples into the bin. The workers usually carry up to 20 kg of apples in their bag before they deposit the apples into the bin. As soon as the bag is empty, the work cycle starts again. This work cycle typically takes about 2.5–3 min. When the workers finish picking the apples from one tree, they move to another tree while carrying the ladder with them.

With the new mobile platform technology (Fig. 1), workers do not have to climb a ladder or walk to the bins to unload the harvested apples. They stand on the mobile platform, which slowly moves through the tree canopy. Using the same type of apple bag as the ladder workers, the mobile platform workers pick apples until the bag is full and deposit the apples into a bin located in the center of the mobile platform. One of the mobile platform workers controls the movement and speed of the mobile platform, thus controlling their own work pace. The mobile platform operator only has to control the platform movement intermittently; therefore, this additional task of operating and controlling the platform takes little time and does not distract the workers from their picking task. All mobile platform workers wore harness and were secure to the mobile platform to restrain them from falling.

All the participants picked the same type of apples in the same orchard blocks with the same picking instructions. All the workers were assigned to pick Fuji apples in the same trellised-tree block where all the trees were 7.5 years old. The picking instructions were 'to the second pick for color' referring to the second pass picking apples in an orchard where only apples of a desired color and size are picked. As shown in Fig. 1, the platform (*Bandit Xpress, Automated Ag Systems, Moses Lake, WA, US*) had two raised levels: a lower level in the front and higher level in the back. Four workers stood on the platform, one on each side of the lower level and one on each side of the upper level. A bin for collecting the picked apples was positioned in the middle of the platform between all four workers. Therefore, unlike the ladder and ground workers, the

Fig. 2. A worker picking apples while carrying an apple bag and standing on the ladder as a conventional apple harvesting technique.

Fig. 3. Apple bins between tree rows.

Fig. 4. Accelerometers attached to Participant's Upper Arms and Torso.

platform workers did not have to walk a long distance to fill up the bin and could continuously pick apples. For the ground and ladder workers, the bins were placed along the tree rows; thus, walking to and unloading their apples into these bins constituted part of their work activity. All the participants were paid piece rate according to the number of apples they picked. The study was conducted at a cooperating orchard in the West of Quincy, WA, USA, over a six-day period.

2.3. Instrumentation for field measurement

As shown in Fig. 4, to record upper arm and torso postures over a full work shift (8 h), the participants wore arm bands and a torso strap with a small, wireless tri-axial accelerometer *(G-Links; MicroStrain® Sensing Systems; Williston, VT, USA*) attached to their left and right upper arms and torso. The tri-axial accelerometers were battery powered and had 2 MB of built-in memory. Posture data were continuously recorded with a sampling frequency of 5 Hz.

2.4. Calculating postural exposure of back and upper arm

Similar to the previous study (Thamsuwan et al., 2019), upper arm elevation relative to the gravity (Θ_{VS}) was calculated as shown in eq. (1). In addition to that, this study defined upper arm posture based on three anatomical planes: flexion (arm forward) and extension (arm backward) on the sagittal plane; abduction (arm toward the side) and adduction (arm away from the side) in the frontal plane, to provide more detailed information on the ergonomic exposure at shoulder in relation to the nature of the work. The flexion/extension angles were angles between the projection of the upper arm to the sagittal plane and the vertical gravity line. The abduction/adduction angles were angles between the

Table 2
Median (IQR) of the APDF parameters of upper arm and torso angles in degrees. Positive values indicate arm flexion, arm abduction, and torso flexion.

	Ground	Ladder	Platform	p-value Method	Arm[a]
Upper Arm Exposure					
Sample size (N)	7	6	8		
Arm Flexion					
10th Percentile					
Non-dominant Arm	−8.6 (5.9)	−11.5 (41.1)	−20.5 (15.7)	0.41	**0.05**
Dominant Arm	−3.1 (14.7)	−4.2 (21.6)	−4.7 (24.6)	0.83	
50th Percentile					
Non-dominant Arm	14.9 (6.4)	11.3 (41.3)	−0.7 (18.0)	0.32	**0.01**
Dominant Arm	23.4 (12.4)	26.0 (18.7)	18.8 (25.7)	0.95	
90th Percentile					
Non-dominant Arm	40.6 (8.1)	39.6 (45.9)	24.2 (18.8)	0.29	**0.005**
Dominant Arm	50.5 (15.6)	54.9 (13.1)	43.7 (20.9)	0.45	
Arm Abduction					
10th Percentile					
Non-dominant Arm	0.2 (4.7)	−11.8 (14.4)	−5.4 (16.5)	0.23	0.66
Dominant Arm	0.1 (19.1)	−8.0 (22.8)	−2.3 (16.2)	0.96	
50th Percentile					
Non-dominant Arm	15.4 (5.6)	6.7 (11.3)	11.0 (16.0)	0.40	0.70
Dominant Arm	18.9 (24.0)	11.9 (18.9)	13.7 (11.5)	0.93	
90th Percentile					
Non-dominant Arm	35.1 (6.1)	40.4 (11.4)	28.9 (19.1)	0.68	0.41
Dominant Arm	39.4 (29.5)	38.1 (20.1)	34.1 (10.6)	0.71	
Arm Elevation					
10th Percentile					
Non-dominant Arm	10.5 (5.7)	11.8 (9.1)	12.2 (5.6)	0.91	**0.02**
Dominant Arm	14.2 (7.3)	16.6 (5.3)	14.7 (11.1)	0.37	
50th Percentile					
Non-dominant Arm	25.5 (7.9)	25.7 (15.5)	26.5 (8.8)	0.47	**0.0004**
Dominant Arm	34.1 (7.6)	35.5 (6.7)	32.0 (18.2)	0.59	
90th Percentile					
Non-dominant Arm	49.6 (7.2)[a]	54.4 (13.2)[b]	47.6 (11.2)[a]	**0.0003**	**0.0002**
Dominant Arm	57.0 (10.1)	62.5 (10.2)	53.2 (10.1)	0.15	
Trunk Flexion					
Sample size (N)	8	7	8		
10th Percentile	−13.8 (10.4)	−20.9 (11.4)	−29.4 (10.5)	0.08	N/A
50th Percentile	13.6 (4.7)[a]	0.3 (16.1)[b]	3.2 (5.9)[b]	**0.03**	N/A
90th Percentile	28.2 (5.6)[a]	13.8 (14.1)[b]	19.2 (8.3)[b]	**0.02**	N/A

[a, b] indicates the results of the post hoc analysis, i.e. pair-wise comparison, between the exposures across the worker groups. Worker groups with same letter means that they did not have significantly different exposures to non-neutral posture. The sample size for the Wilcoxon Signed Rank Test for the difference between two dependent groups (non-dominant and dominant arms) were N = 21 (i.e. 7 from ground, 6 from ladder, and 8 from platform workers).

[a] The sample size for the Wilcoxon Signed Rank Test for the difference between two dependent groups (non-dominant and dominant arms) were N = 21 (i.e. 7 from ground, 6 from ladder, and 8 from platform workers).

projection of the upper arm to the frontal plane and the vertical gravity line. The angles of flexion (Θ_{AFL}) and abduction (Θ_{AAB}) are determined by eq. (2)and eq. (3), respectively.

$$\theta_{VS} = \tan^{-1}\left(\frac{\sqrt{x^2+y^2}}{z}\right) \tag{1}$$

$$\theta_{AFL} = \tan^{-1}\left(\frac{x}{z}\right) \tag{2}$$

$$\theta_{AAB} = \tan^{-1}\left(\frac{y}{z}\right) \tag{3}$$

Where

x accelerations of upper arm in forward direction
y = accelerations of upper arm in sideway direction
z = accelerations of upper arm in upward direction

Similar to upper arm angles, torso inclination was defined in terms of the degree the torso deviated from the vertical line in the sagittal plane and the coronal plane. The torso inclination angles were calculated as the torso forward flexion (Θ_{TFL}) according to eq. (4), with positive values in the x-axis in the forward direction, and positive values in the z-axis in the downward or gravity direction.

$$\theta_{TFL} = \tan^{-1}\left(\frac{x}{z}\right) \tag{4}$$

The postural exposures in upper arms were characterized by the 10th, 50th, and 90th percentile angles and in terms of the percentage of work time during which the upper arm flexion and abduction angles were above the designated threshold values of 30°, 60°, and 90°. The exposures to torso inclination were characterized by the 10th, 50th, and 90th percentile angles and the percentage of time during which torso flexion exceeded 10°, 20°, and 30°. The 10th and 90th percentiles of the postural exposures represented the minimum and maximum, respectively. The 50th percentile was a measure of central tendency.

2.5. Accelerometer-data processing

The data collected from the tri-axial accelerometers were processed and analyzed using an interactive graphical software program (*LabVIEW, 2014; National Instruments; Austin, TX, USA*). To reduce instrumental noise, raw data were filtered using a dual-pass 1-Hz low-pass Butterworth filter. After the filtered signals of the upper arm and torso

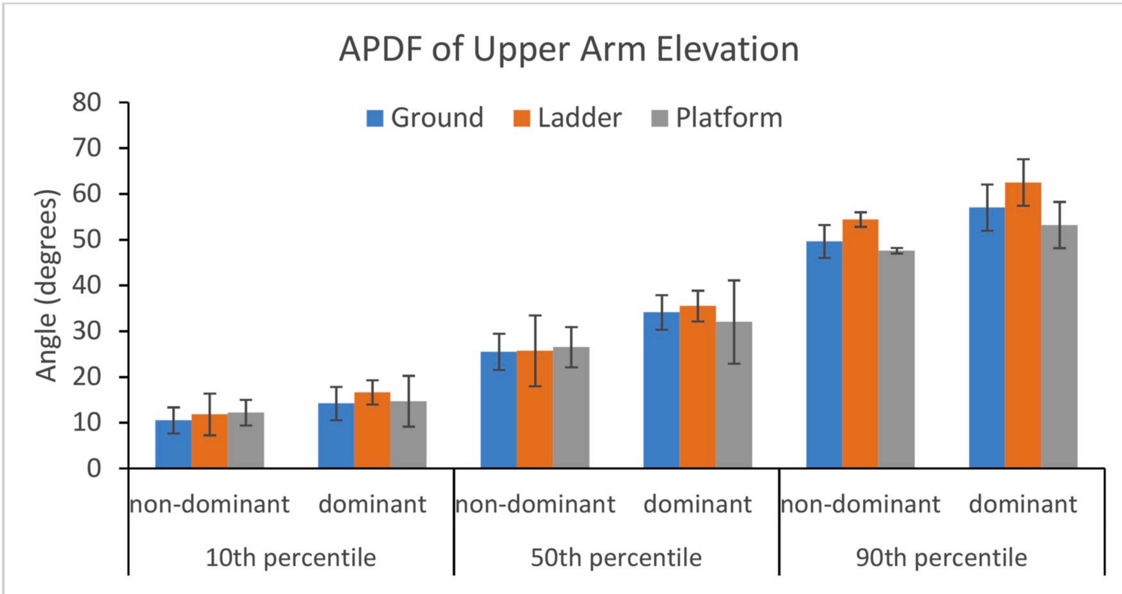

Fig. 5. Median of the APDF parameters of upper arm elevation angles; error bars are IQR.

Table 3
Median (IQR) of the exposure to non-neutral postures of upper arms and torso in percentage of work time.

	Ground	Ladder	Platform	p-value Method	p-value Arm[a]
Upper Arm Exposure					
Sample size (N)	7	6	8		
Arm Flexion					
% time above 30°					
Non-dominant Arm	23.5 (8.3)	22.7 (54.8)	6.6 (14.8)	0.28	**0.005**
Dominant Arm	37.5 (27.8)	43.0 (24.8)	31.0 (38.2)	0.85	
% time above 60°					
Non-dominant Arm	4.7 (1.8)	3.6 (11.3)	1.5 (2.0)	0.14	**0.03**
Dominant Arm	5.0 (3.5)	7.8 (5.5)	3.4 (4.7)	0.26	
% time above 90°					
Non-dominant Arm	1.3 (0.6)[a]	0.7 (1.3)[a,b]	0.4 (0.4)[b]	**0.04**	0.06
Dominant Arm	1.6 (1.2)[a]	2.3 (0.9)[a]	0.6 (0.5)[b]	**0.03**	
Arm Abduction					
% time above 30°					
Non-dominant Arm	15.1 (7.3)	17.0 (5.6)	9.4 (25.8)	0.86	0.29
Dominant Arm	22.6 (35.2)	20.1 (18.8)	14.3 (11.4)	0.83	
% time above 60°					
Non-dominant Arm	3.4 (1.0)	5.0 (2.1)	1.8 (1.6)	0.08	0.97
Dominant Arm	2.4 (4.6)	4.5 (4.1)	1.9 (0.9)	0.32	
% time above 90°					
Non-dominant Arm	1.3 (0.8)[a]	1.3 (0.4)[a]	0.4 (0.3)[b]	**0.005**	0.84
Dominant Arm	0.9 (0.9)[a]	1.8 (1.1)[a]	0.6 (0.3)[b]	**0.01**	
Arm Elevation					
% time above 30°					
Non-dominant Arm	38.4 (22.9)	39.3 (38.1)	39.7 (23.5)	0.49	**0.0009**
Dominant Arm	58.7 (21.5)	63.4 (16.2)	55.4 (39.7)	0.58	
% time above 60°					
Non-dominant Arm	5.7 (2.0)[a]	7.8 (6.4)[b]	3.6 (3.1)[c]	**0.0001**	**0.004**
Dominant Arm	8.5 (5.2)	11.6 (6.9)	5.9 (4.0)	0.12	
% time above 90°					
Non-dominant Arm	1.1 (0.6)[a]	1.5 (0.5)[a]	0.5 (0.5)[b]	**0.0001**	0.14
Dominant Arm	1.7 (1.5)[a]	2.3 (1.8)[a]	0.7 (0.8)[b]	**0.002**	
Trunk Flexion					
Sample size (N)	8	7	8		
% time above 10°	59.2 (11.0)[a]	18.7 (35.5)[b]	31.8 (18.7)[b]	**0.04**	N/A
% time above 20°	32.0 (15.4)[a]	5.1 (14.5)[a]	9.0 (12.5)[b]	**0.04**	N/A
% time above 30°	7.0 (8.8)[a]	1.3 (2.9)[a,b]	0.6 (1.3)[b]	**0.05**	N/A

[a, b] indicates the results of the post hoc analysis, i.e. pair-wise comparison, between the exposures across the worker groups. Worker groups with same letter means that they did not have significantly different exposures to non-neutral posture. The sample size for the Wilcoxon Signed Rank Test for the difference between two dependent groups (non-dominant and dominant arms) were N = 21 (i.e. 7 from ground, 6 from ladder, and 8 from platform workers).

accelerations in each of the three directions (x-y-z) were obtained, the acceleration data were calibrated; in other words, offset by the accelerations in three directions while the participants were standing straight with arm hanging vertically in the gravity direction. Then the upper arm angle and torso angles were calculated using equations (1) and (2), as described in the previous section. Since apple harvesting is a bilateral task and to account for the hand dominance, the upper arms were labeled as dominant and non-dominant arms instead of left and right arms. For each participant, two-time segments – the working period before and after the lunch break – were extracted from the full-day measurements. Then the 10th, 50th, and 90th percentile of postural angles and the percentage of time spent working in the various upper arm and torso postural exposure categories were calculated.

2.6. Statistical analysis

Due to equipment failures, 21 sets of bi-lateral measurements were collected from the upper arms ($n = 7$ from ground, $n = 6$ from ladder, and $n = 8$ from platform workers) and included in the final analysis. Almost complete torso postural exposures were collected from all three groups ($n = 8$ from ground, $n = 7$ from ladder, and $n = 8$ from platform workers). Since each group of participants used only one harvesting method, the comparison across harvesting methods did not use a repeated-measures design. The distribution of the data passed neither normality test nor the equality of variances across the groups, the data was analyzed using Kruskal-Wallis tests. The dominant and non-dominant arms were treated as repeated measures and were compared using Wilcoxon Signed-Rank tests.

3. Results

3.1. Upper arm postural exposure

The postures (Table 2 and Fig. 5) and the percentage of time above postural thresholds (Table 3 and Fig. 7) show statistically significant differences in arm flexion and elevation between the non-dominant and dominant arms; however, there was no significant difference between the non-dominant and dominant arm abduction. The 10th percentile (minimum) of the upper arm flexion/extension suggested that the workers had their non-dominant arms in greater extension angles than their dominant arms. The 50th and 90th percentiles (median and maximum) of the upper arm flexion and elevation angles were greater in the workers' dominant arm than those in their non-dominant arm (Table 2). Participants spent more time with their dominant arm flexed and elevated above 30° and 60° than with their non-dominant arm flexed and elevated above the same thresholds (Table 3). The percentage of time the arms were flexed above 90° almost reached significance between the dominant and non-dominant arm.

As shown in Table 2, there were no significant differences in the 10th, 50th, and 90th percentile flexion-extension and abduction/adduction upper arm angles across the three harvesting methods, except the 90th percentile of dominant arm elevation. On the other hand, as shown in Table 3, the platform works significantly reduced the percentage of work time during which the non-dominant and dominant upper arm were flexed, abducted and elevated above 90°.

3.2. Back postural exposure

The 10th, 50th, and 90th percentiles of torso inclination angles are presented in Table 2 and Fig. 6, indicating the ground workers worked with more forward flexion in the 50th and 90th percentiles of angles than the ladder and platform workers. The percentage of work time during which torso forward flexion was greater than the angle thresholds of 10°, 20°, and 30° are shown in Table 3 and Fig. 8. The ground workers spent more time working with torso forward flexion over 10°, 20°, and 30° than both the platform and ladder workers, and more time with torso forward flexion over 30° than the platform workers.

4. Discussion

4.1. Implications of research findings for the industry

This study presented an objective method for measuring work postures using accelerometers. Non-neutral postures of the upper arms and back were assessed using different angular thresholds of upper arm and torso inclination angles. The study identified differences in the percentage of time spent above various defined angle thresholds between the dominant and non-dominant arms. Mobile platform use reduced the percentage of time workers were exposed to the most extreme postures (% time arms were above 90°) but did not substantially change the percentage of time during which the upper arms were used at the lower levels of arm elevation.

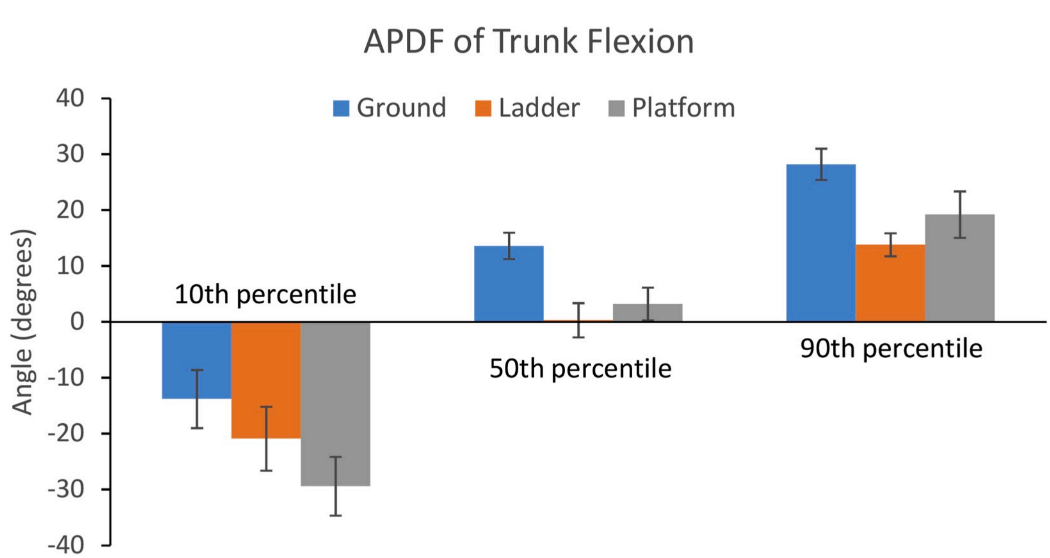

Fig. 6. Median of the APDF parameters of upper trunk flexion angles; error bars are IQR.

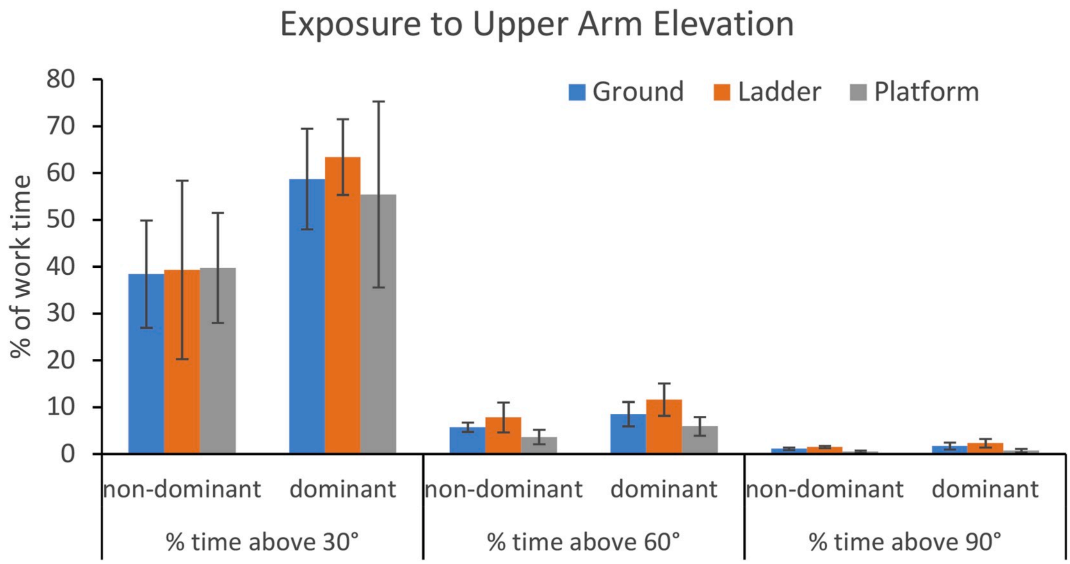

Fig. 7. Median of the exposure to upper arm elevation; error bars are IQR.

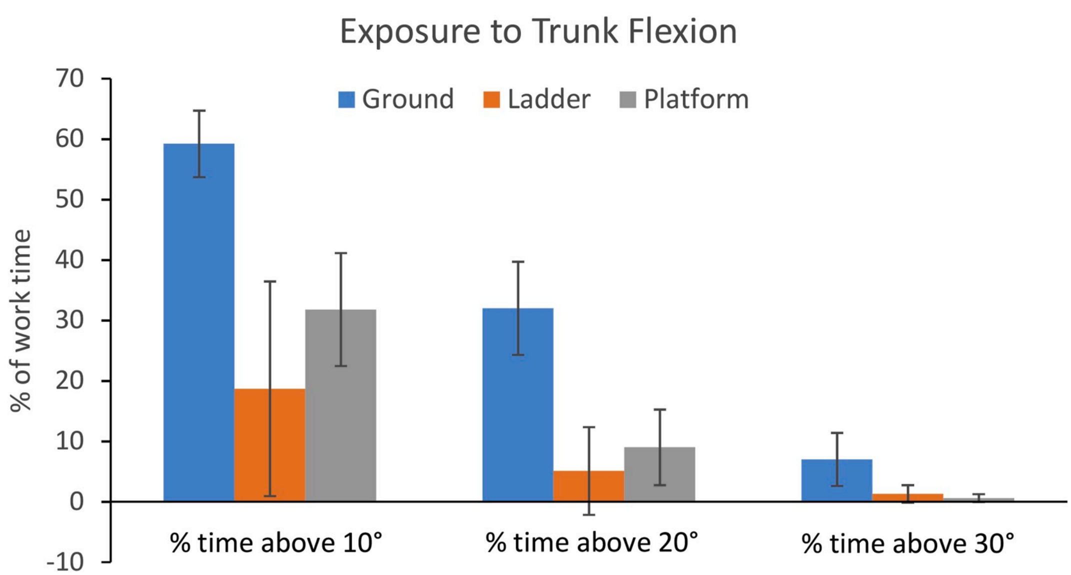

Fig. 8. Median of the exposure to trunk flexion; error bars are IQR.

Although the platform was found to significantly reduce the percentage of time in more extreme postural exposures, the difference may not always be meaningful due to the small percentage of time the workers engaged these postures, particularly for the upper arm at higher angle thresholds. For instance, for overhead work where the upper arm angles were above 90°, the percentage of time difference between the platform and ladder methods was very little (~1%). The roughly 1% reduction in the percentage of time the arms were above 90° is equivalent to 5 min of the platform workers' regular 8-h work day. Accordingly, the practical interpretation of these results has to be made carefully. However, the results indicate that platforms do not appear to increase postural risks, which was a concern given that platform workers are almost constantly working in the tree canopy.

Although the platform could reduce the percentage of time in torso flexion, relative to working on a ladder, the platform also requires a group of ground workers to walk and pick apples from the lower levels of the tree. This study demonstrated that the ground workers had the greatest exposure in terms of the percentage of time spent in torso flexion. Therefore, if mobile platforms were to be implemented, job rotation between the platform and ground work would be advisable.

The mobile platform did not appear to increase postural exposures and the subsequent risks for WMSDs. In addition, relative to ladder work, the mobile platforms can reduce the risk of acute injuries because the workers wear integral fall-restraint devices built into the platform. However, ladders may still be necessary for certain harvesting situations, for example, when the orchard terrain is heavily sloped and unsuitable for mobile platforms. In such cases, job rotation could be carried out between ladder- and mobile platform-based work and between platform- and ground-based works.

In general, considering postures as one of ergonomic risk factors to musculoskeletal disorders, this study showed that none of the worker groups had a high risk to shoulder injuries since the 90th percentiles of their upper arm flexion, abduction, and elevation were less than 60° with an exception for the dominant arm of ladder workers. However, in terms of trunk flexion and extension, the APDF results (Table 2) suggested that the ladder workers had only little extreme trunk posture as the 10th and 90th percentiles of their trunk flexion/extension stayed within the range of −20° and 20°. In contrast, the ground workers occasionally had high-risk trunk flexion (90th percentile angle > 20°) and the platform workers sometimes had high-risk trunk extension (10th percentile angle < −20°).

4.2. Comparing postures to previous studies

Upper arm results were somewhat different from those of a previous study of apple orchard workers in New York State (Earle-Richardson et al., 2005). In this 2005 study, different designs of apple buckets were evaluated while workers were harvesting apples from ladders; the researchers observed, sampled, and tracked the various work postures of the workers. In their study, both upper arms were in a neutral region (<60°) 40% of the work time; one upper arm was above 60° about 30% of the time; and both upper arms were above 60° about 30% of the time. The non-neutral upper arm postures assessed through this visual observation method indicated that at least one arm was elevated above 60° (60% of work time) for more time than in the current study (at most 5.7 + 7.8 + 4.1 + 4.6 = 22.2% of work time). Our results and the discrepancy with the New York study suggest that the threshold of 60° for defining a non-neutral upper arm position may not be sufficient. Our study providing the 30° threshold could advance understanding of the health effect of the harvesting technique.

The results of the back postural exposure among the ladder workers in our study were also slightly different from those of the New York study. In our study, the ladder workers bent their backs more than 20° for 15.3 (Standard Error 9.0) % of work time. In the New York study, the workers bent their backs more than 20° for 23% of their work time. The source of the slight difference could either be due to measurement methods, differences in ladder harvesting techniques, or a combination of both.

In addition to the comparison with previous studies on orchard workers, the results were compared to other industries with similar work postures. The exposure to non-neutral posture of upper arm and trunk, i.e. the percentage of time in awkward posture region, in orchard workers appeared to be much lower than arm elevation and trunk flexion in construction workers who did overhead work, climbed a ladder to reach a ceiling or sustained awkward trunk postures to install drywalls(Sengupta Dasgupta et al., 2014). However, the percentages of time when an arm was raised above 60° and 90° in the current study were fairly close to the construction electricians, but how much the arms were elevated, i.e. the 90th percentile of arm elevation angle, was not as high as ones in the electricians(Moriguchi et al., 2013).

4.3. Study limitations

The data collection tool, the accelerometer-based inclinometer, is limited as it cannot capture different angles in horizontal planes. In other words, the internal and external rotation of the shoulders and torso twisting could not be measured. All information measured by the accelerometer was relative to gravity. The lack of information about the arm and torso posture in the horizontal plane may limit clinical implications because potentially hazardous extremes of shoulder (internal and external rotation) and torso twisting could not be identified. Not having information on internal and external shoulder rotation and torso twisting could also hinder the design or redesign of the platform to improve work postures. Moreover, the sensors similar to the accelerometer-based inclinometers used in the study were found to underestimate the true arm angles when the arm flexion or abduction was above 60° (Jackson et al., 2015). Additionally, it was found that the accuracy of arm inclination angles derived from accelerometer-based measurement was adversely affected by increased motion speed, that is, when the motion speed was increased from 15 to 30 cycles per minute (Chen, 2017). Still, based on part 2 of this current study, the repetition rates were approximately less than 15 cycles per minute (Thamsuwan et al., in press), implying smaller errors.

There is also another limitation in relation to instrumental error. Once the accelerometers were attached, participants tried moving their arm and trunk to ensure that the sensors would not move and that the participants maintain their full range of motion. Despite the secure mounting that allowed workers to move their body as if there had been no sensor, accelerometers at the torso, which were attached by harness (Fig. 4), could have moved while participants were working, especially when adjusting their apple bag after emptying it. The calibration for sensor mounting position was only conducted prior to the work session, but neither during nor after harvesting, so it was unknown when the sensors have already shifted from the calibrated orientation. This might have caused an error in the results. As shown in Table 2, the 10th percentile angles of trunk flexion/extension were negative, i.e. there were higher extension exposure than what should have been.

Finally, some caution should be applied to generalizability. The study was conducted in a trellised orchard, which is one standard type of orchard in Washington State but may not be typical of orchards in other parts of the USA or the world. The difference in the exposure profile in this study from one in New York State was due to not only harvesting methods and measurement technique, but also the trellising systems.

4.4. Future research

Inertial measurement units (IMUs) can help overcome the inability of accelerometer-based inclinometry to characterize the shoulder internal/external rotation by adding gyroscopes and magnetometers to the sensor unit (Wang et al., 2015; Valenti et al., 2015; Ricci et al., 2016). Previous studies have measured postures using IMUs and incorporating the gyroscope's angular velocity data into their posture calculation algorithms and have demonstrated that this IMU-based inclinometry technique could reduce the posture estimation errors in accelerometer-based inclinometry (Bergamini et al., 2014; Chen et al., 2018). Therefore, IMUs, which provide angular velocities in addition to acceleration, may replace the accelerometer-based inclinometers in the future.

Developing techniques to assess physical exposures in field settings is one essential step for developing standards and recommendations for evaluating work practices as well as technological interventions. The methods developed in this study have implications for future studies that attempt to generate results and conclusions to support the healthy work environment of farmworkers. Exposure to non-neutral postures is one among several physical risk factors at workplace. While part 1 of the study described in this paper showed that mobile platforms do not appear to increase the orchard workers' exposure to awkward posture associated with apple harvesting, part 2 of study (Thamsuwan et al., in press) presents the repetitive motion of apple harvesting, which is another ergonomic risk factor that should also be considered when deciding whether an intervention should be used. The next study could focus on how to help workers use the mobile platforms more efficiently. Other research questions that could be addressed include the following: How do farm owners and farmworkers understand the benefits of technology such as mobile platforms in terms of health, besides economic advantage? What are the constraints that prevent the extensive use of the mobile platform? Qualitative research may play an important role in figuring out the way to implement new technology.

5. Conclusion

Applying the methodology developed and validated in the previous study (Thamsuwan et al., 2019) to characterize the postures of workers harvesting apples, this study was able to compare the upper arm and back inclination of workers harvesting apples while using ladders and mobile elevated orchard platforms. The platform workers had lower exposures to upper arm flexion and abduction than the ladder workers whereas there were no differences in back inclination between the ladder and platform workers. Therefore, this study suggested, when possible, mobile platforms may be implemented to improve the ergonomics of apple harvesting.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work was supported by the CDC-NIOSH Cooperative Agreement #5 U54 0H007544-11 and the Washington State Medical Aid and Accident Fund. The authors would like to thank the platform manufacturer and all the study participants. We also thank Scott Driscoll, the orchard manager from the collaborating orchard, and the research team members, including Maria Negrete, Pablo Palmández, Margaret Hughes, and Katherine Gregersen for their support in data field collection, and Patrik Rynell for his support in the development of a data processing program.

References

Amasay, Tal, Zodrow, Keely, Kincl, Laurel, Hess, Jennifer, Karduna, Andrew, 2009. Validation of tri-axial accelerometer for the calculation of elevation angles. Int. J. Ind. Ergon. 39 (5), 783–789. https://doi.org/10.1016/j.ergon.2009.03.005.
Bergamini, Elena, Ligorio, Gabriele, Summa, Aurora, Vannozzi, Giuseppe, Cappozzo, Aurelio, Sabatini, Angelo Maria, 2014. Estimating orientation using magnetic and inertial sensors and different sensor fusion approaches: accuracy assessment in manual and locomotion tasks. Sensors (Switzerland) 14 (10), 18625–18649. https://doi.org/10.3390/s141018625.
Bernmark, Eva, Wiktorin, Christina, 2002. A triaxial accelerometer for measuring arm movements. Appl. Ergon. 33 (6), 541–547. https://doi.org/10.1016/S0003-6870(02)00072-8.
Chen, Howard, 2017. The Effects of Movement Speeds and Magnetic Disturbance on Inertial Measurement Unit Accuracy: the Implications of Sensor Fusion Algorithms in Occupational Ergonomics Applications. University of Iowa. https://doi.org/10.17077/etd.29a72vle.
Chen, Howard, Schall, Mark C., Nathan, Fethke, 2018. Accuracy of angular displacements and velocities from inertial-based inclinometers. Appl. Ergon. 67, 151–161. https://doi.org/10.1016/j.apergo.2017.09.007.
Dasgupta, Priyadarshini Sengupta, Fulmer, Scott, Jing, Xiao Lu, Punnett, Laura, Kuhn, Sarah, Buchholz, Bryan, 2014. Assessing the ergonomic exposures for drywall workers. Int. J. Ind. Ergon. 44 (2), 307–315. https://doi.org/10.1016/j.ergon.2013.11.002.
Davis, Kermit G., Kotowski, Susan E., 2007. Understanding the ergonomic risk for musculoskeletal disorders in the United States agricultural sector. Am. J. Ind. Med. 50 (7), 501–5111. https://doi.org/10.1002/ajim.20479.
Douphrate, David I., Fethke, Nathan B., Nonnenmann, Matthew W., Rosecrance, John C., Reynolds, Stephen J., 2012. Full shift arm inclinometry among dairy parlor workers: a feasibility study in a challenging work environment. Appl. Ergon. 43 (3), 604–613. https://doi.org/10.1016/j.apergo.2011.09.007.
Earle-Richardson, Giulia, Scott, Fulmer, Jenkins, Paul, Mason, Christine, Bresee, Corinne, May, John, 2004. Ergonomic analysis of New York apple harvest work using a posture-activities-tools-handling (PATH) work sampling approach. J. Agric. Saf. Health 10, 163–176.
Earle-Richardson, Giulia, Jenkins, Paul, Scott, Fulmer, Mason, Christine, Burdick, Patrick, May, John, 2005. An ergonomic intervention to reduce back strain among apple harvest workers in New York state. Appl. Ergon. 36, 327–334. https://doi.org/10.1016/j.apergo.2004.12.003.
English, C.J., Maclaren, W.M., Court-Brown, C., Hughes, S.P., Porter, R.W., Wallace, W. A., Graves, R.J., Pethick, A.J., Soutar, C.A., 1995. Relations between upper limb soft tissue disorders and repetitive movements at work. Am. J. Ind. Med. 27, 75–90.
Fulmer, Scott, Punnett, Laura, Tucker Slingerland, D., Earle-Richardson, Giulia, 2002. Ergonomic exposures in apple harvesting: preliminary observations. Am. J. Ind. Med. 42, 3–9. https://doi.org/10.1002/ajim.10087.
Jackson, Jennie A., Mathiassen, Svend Erik, Wahlström, Jens, Per, Liv, Forsman, Mikael, 2015. Is what you see what you get? Standard inclinometry of set upper arm elevation angles. Appl. Ergon. 47, 242–252. https://doi.org/10.1016/j.apergo.2014.08.014.
Leclerc, A., Chastang, J.-F., Niedhammer, I., Landre, M.-F., Roquelaure, Y., 2004. Incidence of shoulder pain in repetitive work. Occup. Environ. Med. 61, 39–44.
McCurdy, Stephen A., Samuels, Steven J., Carroll, Daniel J., Beaumont, James J., Morrin, Lynne A., 2003. Agricultural injury in California migrant hispanic farm workers. Am. J. Ind. Med. 44, 225–235. https://doi.org/10.1002/ajim.10272.
Moriguchi, Cristiane Shinohara, Carnaz, Letícia, Veiersted, Kaj Bo, Hanvold, Therese N., Hæg, Liv Berit, Hansson, Gert åke, Coury, Helenice Jane Cote Gil, 2013. Occupational posture exposure among construction electricians. Appl. Ergon. 44 (1), 86–92. https://doi.org/10.1016/j.apergo.2012.05.002.
Osborne, Aoife, Blake, Catherine, Fullen, Brona M., Meredith, David, Phelan, James, McNamara, John, Cunningham, Caitriona, 2012. Prevalence of musculoskeletal disorders among farmers: a systematic Review. Am. J. Ind. Med. 55 (2), 143–158. https://doi.org/10.1002/ajim.21033.
Ricci, Luca, Taffoni, Fabrizio, Formica, Domenico, 2016. On the orientation error of IMU: investigating static and dynamic accuracy targeting human motion. PloS One. https://doi.org/10.1371/journal.pone.0161940.
Scibek, Jason S., Carcia, Christopher R., 2012. Assessment of scapulohumeral rhythm for scapular plane shoulder elevation using a modified digital inclinometer. World J. Orthoped. 3 (6), 87–94. https://doi.org/10.5312/wjo.v3.i6.87.
Seavert, C.F., 2005. Remaining globally competitive in the U.S. Tree fruit industry with the national tree fruit technology roadmap. Acta Hortic. 671, 407–411.
Spielholz, P., Silverstein, B., Morgan, M., Checkoway, H., Kaufman, J., 2001. Comparison of self-report, video observation and direct measurement methods for upper extremity musculoskeletal disorder physical risk factors. Ergonomics 44, 588–613. https://doi.org/10.1080/00140130118050.
Teschke, Kay, Trask, Catherine, Johnson, Pete, Chow, Yat, Village, Judy, Koehoorn, Mieke, 2009. Measuring posture for epidemiology: comparing inclinometry, observations and self-reports. Ergonomics. https://doi.org/10.1080/00140130902912811.
Thamsuwan, Ornwipa, Galvin, Kit, Tchong-French, Maria, Kim, Jeong Ho, Johnson, Peter W., 2019. A feasibility study comparing objective and subjective field-based physical exposure measurements during apple harvesting with ladders and mobile platforms. J. Agromed. 24 (3), 268–278. https://doi.org/10.1080/1059924X.2019.1593273.
Thamsuwan, Ornwipa, Kit Galvin K, Maria Tchong-French, Lovenoor Aulck, Linda Ng Boyle, Randal P Ching, Kevin J McQuade, and Peter W Johnson. (in press). "Comparisons of physical exposure between workers harvesting apples on mobile orchard platforms and ladders, Part 2: repetitive upper arm motions." *Appl. Ergon.*.
USDA NASS, 2018. Crop Production 2017 Summary. *National Agricultural Statistics Service*. https://doi.org/10.1017/s0007114510001479.
Valenti, Roberto G., Dryanovski, Ivan, Xiao, Jizhong, 2015. Keeping a good attitude: a quaternion-based orientation filter for IMUs and MARGs. Sensors (Switzerland) 15 (8), 19302–19330. https://doi.org/10.3390/s150819302.
van der Windt, D.A., Thomas, E., Pope, D.P., de Winter, A.F., Macfarlane, G.J., Bouter, L. M., Silman, A.J., 2000. Occupational risk factors for shoulder pain: a systematic Review. Occup. Environ. Med. 57 (7), 433–442. https://doi.org/10.1136/oem.57.7.433.
Walker-Bone, K., Palmer, K.T., 2002. Musculoskeletal disorders in farmers and farm workers. Occup. Med. 52 (8), 441–459. https://doi.org/10.1093/occmed/52.8.441.
Wang, Li, Zhang, Zheng, Sun, Ping, 2015. Quaternion-based kalman filter for AHRS using an adaptive-step gradient descent algorithm. Int. J. Adv. Rob. Syst. 12 (9) https://doi.org/10.5772/61313.