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Comparisons of physical exposure between workers harvesting apples on mobile orchard platforms and ladders, part 2: Repetitive upper arm motions

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ABSTRACT

Farmworkers are exposed to physical risk factors including repetitive motions. Existing ergonomic assessment methods are primarily laboratory-based and, thus, inappropriate for use in the field. This study presents an approach to characterize the repetitive motions of the upper arms based on direct measurement using accelerometers. Repetition rates were derived from upper arm inclination data and with video recordings in the field. This method was used to investigate whether harvesting with mobile platforms (teams harvesting apples from the platform and the ground) increased the farmworkers' exposure to upper arm repetitive motions compared to traditional harvesting using ladders. The ladder workers had higher repetitive motions (13.7 cycles per minute) compared to the platform and ground workers (11.7 and 12.2 cycles per minutes). The higher repetitions in the ladder workers were likely due to their ability to work independently and the additional arm movements associated with ladder climbing and walking.

1. Introduction

1.1. Migrant farmworkers and work-related issues

The cost and availability of agricultural labor are common and challenging issues in industrial and technologically developed countries. In the United States, most of the rural, American-born workforce are not willing to perform lower paying agricultural work. As a result, Latino migrant workers have been seasonally employed to replace these local American workers (Blank, 1998). As foreigners, migrant farmworkers face hardships because of their low socioeconomic status. During the harvesting season, they are often required to pick a predesignated quota of fruit, which is difficult to achieve, and to work for long hours with few breaks. This highly demanding work puts migrant farmworkers at risk for compromised physical and mental health (Burke Winkelman et al., 2013; Ramos et al., 2015). Despite high work demands, migrant workers may underreport their work-related health conditions because of their undocumented status, lack of access to healthcare, or fear of being replaced by a more productive worker. Holmes (2013) found that they complain less than other workers and use fewer public resources such as clinics, welfare services, and worker compensation services. These results concur with those of Leigh et al. (2014), who estimated the number of nonfatal workplace injuries and illnesses in US crop production to be undercounted by 73.7%. Typically, work-related musculoskeletal disorders develop over time during exposure to one or a combination of physical risk factors, including forceful exertions, awkward postures, and repetitive work (Punnett and Wegman, 2004; Da Costa and Vieira, 2010).

1.2. Harvest-assisted mobile orchard platform

Mechanical semi-automated harvesting is widely used in industrialised orchards to make harvesting more economical by reducing fruit growers' dependence on agricultural workers. A key component of mechanical harvesting in the Washington State tree fruit industry is the harvest-assisted mobile platform, an elevated horizontal surface that

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semi-autonomously moves between two rows of trees. Standing on the platform, workers can continuously pick apples while being transported through the orchard. The major benefit of the mobile platform is an increase in productivity (Auvil et al., 2006) because the workers do not spend time climbing up and down a ladder or walking and transporting picked apples to centrally located apple bins. Another benefit is that platform workers are less vulnerable than ladder workers to falls, the most prevalent accident among orchard workers (Salazar et al., 2005). While on the mobile platforms, workers are attached to the platform by a harness; ladder workers have no such protection since the fall protection is not compatible with ladder use. Their potential for increasing productivity while increasing safety may make mobile platforms a good alternative to ladders. However, a major concern is whether the mobile platforms can cause higher repetitive or prolonged static loading in the workers' body; in other words, the workers may be at greater risk for longer-term, work-related musculoskeletal disorders.

The first part (Thamsuwan et al., in press) of this study already evaluated that the use of mobile platform exposed the workers to lower static loading in upper arm and shoulder than the ladders did. This result could be a factor that suggests ergonomic risk reduction by using the platform. Meanwhile, the risks to musculoskeletal disorders should also account for repetitive motion, which is being included in this paper as the second part of the study. On a contrary, based on the first part of the study, there appeared only marginal exposure to back inclination among all the workers. Thus, the repetition of trunk bending was not studied.

1.3. Current methods in assessing repetitive motion

Repetition in the upper arms can be characterized based on the change of the upper arm inclination angle relative to the shoulder glenohumeral joint. Observation-based methods like "PATH: posture, activity, tools and handling" (Buchholz et al., 1996) or video-based image processing technology (Chen et al., 2013; Greene et al., 2017) can be used to determine repetition cycles at certain time points or as snapshots of the ergonomic assessment. However, these observational methods can be time consuming and, with or without videotaping, may lead to systematic biases (Jackson et al., 2016). For example, workers could change the way they normally work because researchers are observing them. To overcome these drawbacks, less invasive, direct measurements are preferred.

Objective direct measurements incorporate either a computerized system with markers on the relevant body segments (Ahmed and Babski-Reeves, 2012; Patrizi et al., 2016) or self-contained, battery-powered sensors with built-in memory (Scibek and Carcia, 2012; Spielholz et al., 2001). One commonly used method to measure posture and repetition is a motion tracking system in which optical or electromagnetic sensors follow markers placed on a subject. Although these systems have been found to be highly accurate (Merriaux et al., 2017; Fuller et al., 2009; Lowe, 2004), the methods are limited to laboratory or controlled indoor settings.

Another way to directly collect the movement of upper arms, as well as other body segments, is to use accelerometers that measure angles with respect to gravity. This technique has been used in the clinical assessment of the shoulder's range of movement (Green et al., 2005; Johnson et al., 2001; Kolber and Hanney, 2012; Triffitt et al., 1999) but has not been explored for investigating work repetition. A previous study (Spielholz et al., 2001) collected the postures of the distal upper extremities (hand, wrist, and forearm) using electrogoniometers and electrotorsiometers, and derived repetition rates from the postural excursion data. In the study by Spielholz et al. (2001), one repetition cycle was defined as a movement passing a pre-defined neutral postural cut point, ending in a non-neutral posture, and passing back through the neutral postural cut point. This method using a neutral anatomical cut point is reliable for assessing repetitive motions of the distal upper extremities.

1.4. Study objective

This second part of the study aimed to develop a systematic method for quantifying the repetition of the upper arms and to apply this method to determine whether there are differences in upper arm repetitions between ladder- and mobile platform-based fruit harvesting methods. This method for quantifying the repetition in the upper arms was tailored for field-based assessments, which involve a wide range of unconstrained arm movements throughout the day. A computational algorithm was developed to count cyclic upper arm motions collected from accelerometers attached to the orchard workers' upper arms while the workers were harvesting fruit. The results from this method were introduced along with ones from a subset of time-motion analyses from video, a method that has been historically well established and is widely accepted for assessing repetitions (Penglaou and Nadler, 1957).

2. Methods

2.1. Subjects

Participants were identical to the study Part 1. That is, twenty-four participants had harvesting experience, were Latino males and native Spanish speakers. Similar to Part 1, the participants were equally divided into three work groups based on the apple harvesting method they employed: (1) a ladder work group that picked apples over the full height of the trees ($n = 8$), (2) a platform work group that picked apples at the upper and mid-level of the trees while standing on a moving platform ($n = 8$), and (3) a complementary group of ground workers that either worked in front or behind the mobile platform and only picked apples from the lower level of the trees ($n = 8$). Table 1 shows the demographic and anthropometric information of the subjects. All the participants participated in the study for one day, only performed their dedicated harvesting task, and received piece rate pay according to the number of apple bins they filled. All participants were 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.

2.2. Upper arm repetition

The data collection for the postures (Part 1) and repetition rates (Part 2) were conducted on the same day and with the same accelerometers. The number of upper arm repetitions, in repetitions per minute, in the dominant and non-dominant arms were compared using two different computational methods: (1) the repetition rates counted from video observations, and (2) an algorithm designed to count upper arm repetitions from accelerometer data. In addition to repetition rates, the harvesting productivity of the three harvesting methods was compared.

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

2.3. Counting repetition cycles from video

For characterizing upper arm repetitions using the video, eight workers in each group (ladder, platform, and ground) were videotaped for 5 sessions, each lasting 5–6 min, while they were performing their work, which was the typical amount of time it took to fill up and empty two consecutive bags of apples. The video recording time started when a subject finished emptying a bag of apples into a bin and ended after two bags of apples were filled and the second bag of apples was emptied into the bin. Within this time interval, repetition cycles of arm movement were counted by a single trained observer to avoid systematic bias.

The video analysis was considered to yield the true group average for the dominant and non-dominant arm repetition rates for the ladder, platform, and ground workers. These video-based repetition rates were then used to evaluate methods employed by the computational program for deriving and counting the dominant and non-dominant upper arm repetitions from the accelerometer data.

2.4. Characterizing repetition cycles from accelerometer data

In addition to the video observations, small wireless tri-axial accelerometers *(G-Links; MicroStrain® Sensing Systems; Williston, VT, USA)*, as described in Part 1, were attached to the participants' left and right upper arms. The accelerometers were battery-powered and had 2 MB of built-in memory. The movement of the upper arms was continuously recorded at the sampling frequency of 5 Hz and then was filtered using a dual-pass 1-Hz low-pass Butterworth filter.

Upper arm posture was calculated as a concentric cone of the upper arm about the shoulder, relative to the vertical line, and denoted as an inclination angle (Θ_{VS}) calculated using eq. (1), where x, y, and z represent the accelerations of the upper arm in forwards, sideways, and vertical directions, respectively.

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

The repetition rate was calculated using a computer algorithm that continuously measured the changes of the upper arm angles (Θ_{VS}) with respect to time. As shown in Fig. 1, local maxima and minima were determined when the slope of the upper arm's postural profile changed from positive to negative and vice versa. When the difference between successive local minimum and maximum was smaller than 1°, the two data points were treated as part of one movement cycle. One cycle of motion was counted when a difference in the angles between successive local maxima and minima was greater than a movement threshold, denoted as Φ. For a given Φ, the number of upper arm movements equal to or greater than Φ were tabulated from the dominant and non-dominant arms over the entire work shift and then normalized to repetitions per minute. Because the different Φ would yield different repetition rates, the values of Φ needed to be validated.

Since the aim of this study was to develop a computational method for quantifying work repetition, the purpose of the computational algorithm was to determine if there was an appropriate value of Φ that matched the video-based technique for measuring upper arm repetition during apple harvesting activity. The repetitions in the dominant and non-dominant arms were derived using various Φ thresholds and then compared to the repetition results from the video-based observations. The values of Φ evaluated in this study ranged from 5° to 30° in increments of 5°.

2.5. Calculating productivity

At the end of each work day, the number of apples the participants harvested was recorded by counting the number of bins they filled. Since the work hours were slightly different across the measurement days, the productivity was calculated in terms of the number of apple bins per worker-hour, as well as the number of apples per person-minute. Given that each bin weighed 315 kg and a Fuji apple weighs approximately 154 g, a bin represented the equivalent of 2045 apples, which equates to 1023 repetitions per arm.

Platform and ground workers shared apple bins among four workers; therefore, they worked as a team. On the other hand, ladder workers worked individually; that is, they did not share bins. All the participants were paid piece rate and were paid by the number of bins that they filled with apples.

2.6. Statistical analysis

To analyze and compare the repetition rates derived from the full-shift accelerometer data, and the repetition rates derived from the 5 representative video segments from each subject, harvesting method and arm (dominant and non-dominant) were the main effects. Two-way ANOVAs were used to determine if there were differences between the harvesting methods and the dominant and non-dominant arms. The difference in productivity across the three harvesting was tested using a one-way ANOVA, with the harvesting method as a fixed effect and the participant as a random effect nested within the harvesting method. In

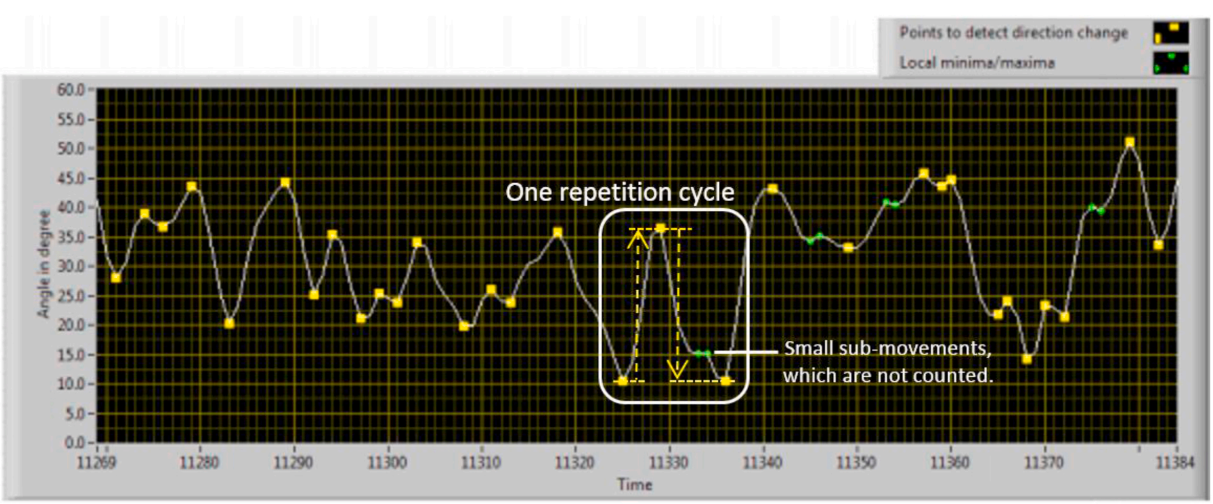

Fig. 1. Upper arm angle signal showing repetition cycles of one subject picking apples for 115 s.
Remarks: Round marks were the twisting motion (stem breaking) not included in the detecting cycle; square marks were the rest of the local minima and maxima considered in the detecting cycle.

Table 2
Arm repetition rates in cycles per minute from the video recordings by harvesting method.

	Mean (SE)			p-value	
	Ground N = 8	Ladder N = 8	Platform N = 8	Harvesting Method	Arm
Non-Dominant	15.1 (0.9)	13.1 (0.9)	16.4 (1.2)	0.18	0.02
Dominant	13.6 (0.9)	12.8 (0.7)	11.3 (1.8)	0.55	
Average	14.4 (0.8)	13.0 (0.7)	13.9 (0.8)	0.61	

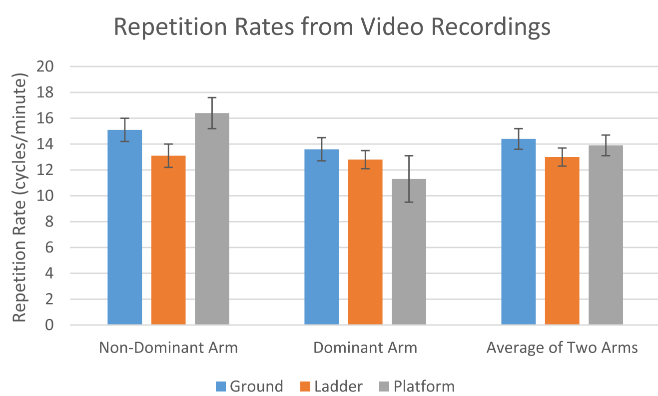

Fig. 2. Arm repetition rates in cycles per minute from the video recordings.

addition, Tukey's from post-hoc analysis HSD tests were used to determine if there were significant differences across the groups.

3. Results

3.1. Video-based repetition rates

As shown in Table 2 and Fig. 2, the videos revealed that the non-dominant arm had higher repetition rates than the dominant arm (*p-value* = *0.02*); however, the differences were only significant for the platform (*p-value* = *0.05*) and ground workers (*p-value* = *0.04*). The repetition rates in the dominant and non-dominant arms were not significantly different in the ladder workers (*p-value* = *0.36*). The reason for this difference was that apple picking required stem-clipping often with the dominant hands. The upper arm repetition rates were slightly higher in the platform and ground workers when compared to the ladder workers, especially in the non-dominant arm; however, these small differences were not significant. When the repetition rates from both arms were pooled and averaged, there were no significant differences between the harvesting methods.

3.2. Accelerometer-derived repetition rates

Using the computational program, as the threshold of the change of the upper arm angle (Φ) increased from 5° to 30°, the calculated repetition rates decreased, as shown in Table 3 and Fig. 3. Regardless of the Φ used in the analysis, the repetition rates of the non-dominant arm and the repetition rates based on the average of both arms were greater in the ladder workers. In particular, the differences were statistically significant when Φ ranges from 15° to 30°. However, the harvesting methods did not significantly affect the repetition rates in the dominant arm.

3.3. Observed productivity

The group means (standard error) of the ground ($n = 8$), ladder ($n = 8$), and platform ($n = 8$) workers' productivity recorded at the end of the work shift were 0.70 (0.06), 0.80 (0.13), 0.64 (0.04) bins per person-hour. Converting to the average apples per minute picked by each hand, these were equivalent to 11.9 (1.4), 13.6 (3.1), 10.9 (1.0) repetitions per minute for the ground, ladder, and platform workers, respectively. Productivity was significantly different across the three groups (*p-value* = *0.004*). Furthermore, from post-hoc analysis with Tukey's HSD test, the ladder workers were more productive than the ground workers (*p-value* = *0.05*) and the platform workers (*p-value* = *0.003*).

4. Discussion

4.1. Comparing repetition rates between accelerometer data and video

Based on the repetition rates counted from the video, the results from the computational program revealed that a value of $\Phi = 20°$ best

Table 3
Computer algorithm-based arm repetition rates in cycles per minute by harvesting method.

Angle Threshold Φ	Location	Mean (SE)			p-value	
		Ground N = 7*	Ladder N = 6**	Platform N = 8	Method	Arm
5°	Non-Dominant	29.7 (0.8)	30.1 (0.6)	28.6 (1.1)	0.45	
	Dominant	29.3 (0.7)	30.3 (0.5)	29.1 (1.0)	0.55	0.84
	Average	29.5 (0.7)	30.2 (0.6)	28.9 (1.0)	0.26	
10°	Non-Dominant	22.5 (0.7)	23.7 (0.4)	21.5 (1.0)	0.17	
	Dominant	23.1 (0.6)	24.0 (0.4)	22.6 (1.0)	0.41	0.25
	Average	22.8 (0.7)	23.8 (0.4)	22.1 (1.0)	0.07	
15°	Non-Dominant	16.4 (0.6) [a]	18.2 (0.3) [b]	15.6 (0.8) [a]	0.04	
	Dominant	17.5 (0.6)	18.4 (0.4)	17.0 (1.0)	0.37	0.09
	Average	16.9 (0.6) [a, b]	18.3 (0.4) [b]	16.3 (0.9) [a]	0.02	
20°	Non-Dominant	11.6 (0.5) [a]	13.7 (0.3) [b]	10.8 (0.7) [a]	0.002	
	Dominant	12.9 (0.6)	13.6 (0.3)	12.5 (0.9)	0.42	0.05
	Average	12.2 (0.6) [a]	13.7 (0.3) [b]	11.7 (0.8) [a]	0.004	
25°	Non-Dominant	8.1 (0.4) [a]	10.4 (0.2) [b]	7.3 (0.5) [a]	<0.0001	
	Dominant	9.3 (0.6)	9.9 (0.3)	8.9 (0.7)	0.42	0.05
	Average	8.7 (0.5) [a]	10.1 (0.2) [b]	8.1 (0.6) [a]	0.0005	
30°	Non-Dominant	5.7 (0.3) [a]	7.9 (0.2) [b]	4.9 (0.4) [a]	<0.0001	
	Dominant	6.6 (0.5)	7.1 (0.2)	6.2 (0.6)	0.38	0.10
	Average	6.2 (0.4) [a]	7.5 (0.2) [b]	5.5 (0.5) [a]	<0.0001	

*, ** the number of subjects were fewer than 8 as measured due to accelerometers' data quality loss in the field measurement.
[a, b] indicates the results of the post hoc analysis, i.e. pair-wise comparison, between the repetition rates across the worker groups. Worker groups with same letter means that they did not have significantly different repetition rates. E.g. at **Φ** = 15°and the average of both arms, the difference between ground ([b]) and ladder ([b]) and the difference between ground ([a]) and platform ([a]) were insignificant, but the difference between ladder ([b]) and platform ([a]) were statistically significant.

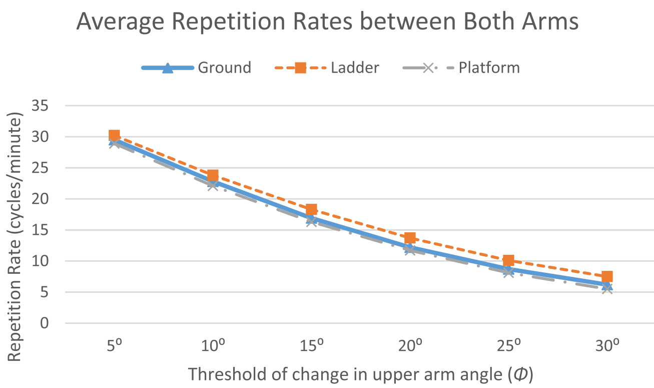

Fig. 3. Average repetition rates between both arms, derived from accelerometer data.

approximated the upper arm repetition rates for the platform-related work (platform and ground workers). The discrepancies between the video-based and accelerometer-based results on which arms had higher repetition than the other were due to the fact that the participants used dominant arms on other activities besides picking and those movement cycles were only counted in the accelerometer-based paradigm. The average (dominant and non-dominant arm) repetition rates computed from the program using $\Phi = 20^\circ$ were 12.2, 13.7, and 11.7 cycles per minute for the ground, ladder, and platform workers, respectively. Moreover, by interpolation, the repetition rates calculated when $\Phi = 17.5^\circ$ were 14.5, 16.0, and 14.0 cycles per minute for the ground, ladder, and platform workers, respectively. These interpolated Φ repetition rates were very close to the video-based repetitions for the ground and platform workers (14.4 and 13.9 cycles per minute, respectively). However, the repetitions rates from the accelerometer and video-derived measures were not as closely matched (16.0 vs. 13.0 repetitions per minute). This is because the video results did not include the repetition unrelated to picking motions. The selection of the Φ based on video for ladder workers would have been biased.

4.2. Comparing repetitions to work productivity

The comparison between the accelerometer-derived and video-based repetitions were relatively consistent and similar for the platform and ground-based work but did show some discrepancies for the ladder-based work and with respect to the trends between the dominant and non-dominant hands. However, the group trends with the accelerometer-derived repetition results were more in line with the objective measures of productivity. Workers harvesting apples using ladders had higher productivity than the ground and platform workers. The ladder workers' higher productivity might be attributable to two factors: first, they picked apples at their own pace, and, second, they were able to take quick breaks as needed to recover when they felt tired. In contrast, the platform workers were obligated to follow the movement of the platform.

The results were compared to previous work where overall productivity was recorded. A 2014 report in Washington State found that the average apple harvesting rate of a worker performing a first pick (picking apples for the first time based on color and size) on a mobile platform was 45 apples per minute (Karkee et al., 2014). In other words, approximately 22.5 apples were picked by each hand in a 1-min period. This apple-picking rate was higher than that of the platform workers in the current study, which was 21.8 apples per minute or 10.9 repetitions per minute for each arm, as described in section 3.4. Additionally, in both studies, repetitions could have been impacted by the speed of the moving platform. In our study, workers operated the platform themselves, so the speed of the platform depended on the picking speed of the slowest person on the team. In other orchards, the platforms might be operated by a supervisor or worker designated to only operate the platform, so the platform in the 2014 Washington study could have moved faster than the one in the current study.

4.3. Methodological considerations

The repetition assessment method developed in this study differs from other studies that used the number of movements passing an anatomically-based cut point (Spielholz et al., 2001). Most previous studies have been conducted in well-controlled laboratory settings in which the participants performed designated, postural-constrained tasks rather than their daily activities. In contrast, the repetitions evaluated in this study were from actual field work, which involves a great deal of postural variation due to the nature of the apple-picking task (i.e., the apples on trees are at various heights and the arms do not return to the same set angle in every cycle). Assessing repetitions through the changes in the upper arm angle was thus more applicable in this study.

This computational method did not work as well for ladder-based apple picking tasks due to the variety of non-apple picking related movements (e.g., climbing ladders, walking, and carrying ladders, etc.) These tasks involve upper arm movements and may partially contribute to the higher acclerometer-based repetition rates of the ladder workers. When repetitions were counted using accelerometer data, these movements were not separated from the picking motions but were excluded in the videos. The other activities involved with ladder-based harvesting may explain some of the repetition differences between the acclerometer- and video-based measures in the ladder workers.

4.4. Study limitations

The study has some systematic biases. Videotaping or the presence of the researchers in the field might have altered the way the participants worked compared to when their work is not monitored. In addition, even though this study was well controlled, some caution should be expressed with respect to generalizability. The study was conducted in a trellised orchard with trees averaging 2.4 m in height. This is a modern type of orchard used in Washington State, and it may be different from typical orchards in other parts of the country or world. In the cooperating orchards in this study, apple trees were grown as tree walls and limited to a maximum height, i.e., as a trellised orchard. However, in other orchards, trees are generally and naturally taller and broader, and because the growth of the branches is not constrained, the trees are typically wider and cover a greater area. Moreover, the type of apples harvested and the picking method should also be taken into consideration when comparing studies. For example, Red Delicious apples are harvested using the strip picking technique; that is, all the apples are picked at once and without the workers' mental effort to judge whether the apples are of the correct color. Gala apples are harvested using a color picking technique; that is, apples with the right color are picked, but the others are left on the trees until their color is appropriate for picking. Fuji apples, which were harvested in this study, are also harvested using color picking and, since their skins are delicate, their stems have to be clipped to prevent them from scratching or damaging the skin of the other apples when they are put in the same bin for transportation. These differences demonstrate the complexity and care needed when comparing apple harvesting studies. Overall, this study provided a very fair and controlled comparison of the harvesting methods (the newly developed mobile platform and the traditional ladder), but caution is necessary when comparing the results from this study to those from other apple harvesting studies.

5. Conclusion

The assessment techniques developed in this study were used to compare various picking methods. This study found that the workers who picked apples from the mobile platform and from the ground had lower repetition rates than those of the workers who used ladders within the same given work period. This suggests the reduction of workers' daily exposure to repetitive motion by the use of mobile platform. The accelerometer-based assessment method for determining repetitive exposures developed in this study may be used in other types of work and contribute to the body of work related to repetition and musculoskeletal health.

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.

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