Development and Evaluation of a GPS-Based Weeding System for Reducing the Risk of Musculoskeletal Disorders among Agricultural Workers

FINAL PROGRESS REPORT

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PREFACE

This is a report on the goals, methods, implementation and results of the Development and Evaluation of a GPS-Based Weeding System for Reducing the Risk of Musculoskeletal Disorders among Agricultural Workers Project of the University of California Agricultural Ergonomics Research Center, as proposed to and funded by the National Institute for Occupational Safety and Health, Grant # R21-OH009519. This project commenced August 1, 2009, and terminated on July 31st, 2012.

A list of publications resulting from this project is presented at the end of this report. This report is intended to serve as the final project report.

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LIST OF ABBREVIATIONS

AERC: Agricultural Ergonomics Research Center

LBDs: Low Back Disorders

LMM: Lumbar Motion Monitor

MSDs: Musculoskeletal Disorders

NIOSH: National Institute for Occupational Safety and Health

UC: University of California

UCD: University of California, Davis

WCAE: Western Center for Agricultural Equipment

WIB: Worker Interface Box

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ABSTRACT

Weed control is a very important issue for farmers, particularly for those producing vegetable crops. Weeds are currently controlled by chemical herbicides and manual weeding, which is a strenuous task that exposes agricultural workers to various musculoskeletal and low back disorders risk factors. There is clear need to develop new and innovative methods of weed control in order to reduce the risk of musculoskeletal disorders associated with weed control, to reduce the introduction of herbicides into the environment, and to increase the competitiveness of farmers. Hence, the main purpose of this project is to reduce both the risk of musculoskeletal disorders among agricultural workers performing manual weeding tasks, and the amount of chemical herbicides required for weed control by automatically controlling weeds mechanically between crop plants. Several studies were performed to achieve the project's goals. Building upon earlier work by our group, we have successfully further developed a global positioning system (GPS)-based approach that can accurately map the location of each crop plant during transplanting. This accurate information has been combined with an improved mechanical weed knife to develop a GPS-controlled automatic weed knife system for controlling weeds between plants. Compared to traditional manual weeding, this system has been shown to be effective in reducing the required man-hours per hectare by 52%. This level of labor reduction potentially represents a significant savings in the cost of manual labor for hand hoeing, especially for framers who already own and implement GPS-technology in their agricultural practices. To further take advantage of this novel approach by small farmers and/or farmers who do not own a GPS system, the automatic cutting system has been modified in such a way as to allow semi-automatic activation without the need for a GPS system. Studies conducted in this project have shown that this system holds very good promise in replacing the fully-automatic GPS-based system, again reducing the required labor by about 50%. This reduction in labor cost and hours is expected to also reduce workers' exposure to musculoskeletal disorders risk factors. The semi-automatic weeding system requires an operator to observe and occasionally control the opening and closing of the knives system. Studies on the mental workload required by this task have shown that the task places moderate level of mental workload on the operator, with little physical effort. Improvements in interface and workstation designs, as well as in the knives system were recommended or implemented (improved knife system). Lastly, two types of hoes were compared to the traditional weeding hoe for their potential use during close-to-plant weeding. This evaluation showed that manual weeding exhibits high level of risk to the lower back regardless which hoe type is used. However, one type (the "Hula" hoe) may be a good alternative for smaller weeds due to its lighter weight, which will be the case after treatment by either the GPS-controlled or semi-automatic weeding system. Further studies are underway to explore expanding this approach to multiple crop rows in order to maximize its economic and health outcome effectiveness.

SECTION 1- Findings and Outcomes

Significant Findings

The findings of this project could have important impact on the health and safety of agricultural workers. Based on the multiple studies conducted in this project, the following significant findings can be reported:

- An automatic GPS-based weeding machine was successfully designed and tested, using real-time automatic RTK GPS mapping of crop plants and weed knife path control for mechanical removal of weeds growing between crop plants.
- The GPS-based automatic system significantly reduced the amount of follow-up hand labor. Overall, a 52% reduction in the man-hours per hectare was obtained by using the automatic GPS-based plant mapping and intra-row weeding machine. This reduction is expected to be concurrent with an equal reduction in the exposure to MSD risk factors among workers.
- A non-GPS-based semi-automatic weeding system was successfully developed to tailor to small farmers and/or farmers without GPS capabilities.
- An operator workstation including an interface module was designed and developed to allow the operator to observe and control the knives system operation.
- Operator mental workload during system operation was found to be at moderate levels suggesting the need for modifications, which some were implemented.
- The risk of low back disorders (LBDs) was rather high when using all three types of weeding hoes (a traditional one and two alternative hoes). One hoe type may provide a potential for reduced-risk due to its lighter weight, especially when treating smaller weeds.
- This system is ideal for organic farmers who cannot use chemical herbicides.

Translation of Findings

Implementing the findings of this project should help reduce exposure to both herbicides and MSD risk factors. Based on findings of this research, a few recommendations can be made:

- When a GPS system is available, framers should consider using fully-automatic mechanical weeding systems to reduce the need to apply chemical herbicides and reduce the exposure of workers to the risk musculoskeletal disorders during manual hoeing.
- Smaller farmers and those who do not have the GPS capabilities should consider using the semi-automatic mechanical weeding system to achieve similar results in the reduction of workers exposure to herbicides and musculoskeletal disorders risk factors.
- This approach is recommended for organic farmers who cannot use chemical herbicides.
- System improvements and expansions are still underway to apply the approach into multiple rows.
- The system requires a tractor and implements workstation with a dedicated operator to observe and control the semi-automatic weeding system. Improvements in the design of this workstation are recommended.
- Alternative hoes with lighter weight and different blade type should be considered, especially after mechanically weeding the crop.

Outcomes/Impact

The current practice in agriculture calls for the use of manual hoeing and chemical herbicides for the control of weeds in most vegetable crops. This study presented a successful approach that uses automatic and semi-automatic weeding systems for controlling weeds in vegetable crops, which both have demonstrated significant reduction (about 50%) in weeding time. Therefore, the approach presented in this study, if implemented in agricultural settings, has significant potential outcomes in terms of the impact on agricultural worker risk of exposure to both herbicides and musculoskeletal disorders.

SECTION 2- Scientific Report

Introduction

For decades, agriculture has been ranked among the top US industries with respect to occupational injury and illness rates, which translates into substantial human and economic costs. Similar to other industries, musculoskeletal disorders (MSDs) in agriculture are the most common of all occupational non-fatal injuries and illnesses for farm workers. Looking closer at MSDs in occupational settings, it becomes evident that low back disorders (LBDs) are by far the most prevalent and costly injuries in most industries, including agriculture.

Weed control is a very important issue for farmers, particularly for those producing vegetable crops. Weeds compete with crop plants for space, sunlight, nutrients, and moisture. Weeds are currently controlled by chemical herbicides and manual weeding, which is a strenuous task that exposes agricultural workers to various MSD and LBD risk factors. At this stage, there are limited alternatives to manual hoeing and herbicide application to effectively control weeds in vegetable crops.

There is clear need to develop new and innovative methods of weed control in order to reduce the risk of musculoskeletal disorders associated with weed control, to reduce the introduction of herbicides into the environment, and to increase the competitiveness of farmers. One possible solution is to develop an improved system of mechanical cultivation that will substantially reduce the amount of hand hoeing required. Mechanical cultivation can be improved by developing a system that is capable of cultivating between the crop plants in the row. Combining this mechanical system with an improved tool for manual weed control within the crop plant proximity (instead of hoeing) will assure a substantial decrease in LBD risk to the workers.

The main purpose of this project is to reduce both the risk of musculoskeletal disorders among agricultural workers performing manual weeding tasks, and the amount of chemical herbicides required for weed control by automatically controlling weeds mechanically between crop plants.

Specific Aims

To achieve the goal of this project the following specific aims were pursued:

Specific Aim 1: Develop a global positioning system (GPS)-based approach that can accurately map the location of each crop plant during transplanting.

Specific Aim 2: Develop a weed knife system to remove weeds growing between the crop plants:

a) Develop a GPS-controlled automatic weed knife for controlling weeds between plants.

b) Develop the cutting system in such a way as to allow manual activation for use by small farmers and/or farmers who do not own a GPS system.

Specific Aim 3: Develop a manual tool to replace traditional hand hoeing for precision weed control in areas close to the crop plant.

Specific Aim 4: Conduct biomechanical and subjective evaluations of the potential reduction in MSDs due to the newly developed approach as compared to the existing manual system.

BACKGROUND AND SIGNIFICANCE

Musculoskeletal Disorders in Agriculture

There is clear and consistent evidence that shows MSDs are the most prevalent and costly of all work related-injuries. These injuries have been positively associated with occupational factors, and rank first in frequency among workers, with approximately half of the nation's workforce being affected (Bernard et al., 1997; NRC/IOM, 2001). Consistent with other industries, MSDs are the most common of all occupational injuries and illnesses for farm workers (McCurdy & Carroll, 2000; McCurdy, Samuels, Carroll, Beaumont, & Morrin, 2003; Villarejo, 1998; Villarejo & Baron, 1999). MSDs in agriculture are commonly reported at rates near or above those of traumatic injury, respiratory illness, pesticide-related injury or illness, dermatological injury or illness, or other types of injuries and illnesses.

Production agriculture ranks among the top ten of industry sub-sectors for back pain (Clemmer, Mohr, & Mercer, 1991; Guo, Tanaka, Halperin, & Cameron, 1999). Strain and sprain is the most common disabling injury in California agriculture, accounting between 31 and 43% of reported injuries (AgSafe, 1992; McCurdy, et al., 2003), and it is the most common injury in the production of fruits and vegetables nationally (33%) (Meyers et al., 2001).

LBDs are a major occupational health concern among the agricultural workforce worldwide. Although, compared to other industries, a limited number of epidemiological studies have exclusively focused on the issue of LBDs (or low back pain) in agriculture; several population- and community-based epidemiological occupational health studies may provide insight about the prevalence and significance of these disorders in agriculture (Al-Arfaj et al., 2003; Allread, Wilkins, Waters, & Marras, 2004; Barrero et al., 2006; Fabunmi, Aba, & Odunaiya, 2005; Kuwashima, Aizawa, Nakamura, Taniguchi, & Watanabe, 1997; Maeda, Okazaki, Suenaga, Sakurai, & Takamatsu, 1980; Manninen, Riihimak, & Heliovaara, 1995; Myers, 1997; Park, Sprince, Whitten, Burmeister, & Zwerling, 2001; Rosecrance, Rodgers, & Merlino, 2006; Shipp et al., 2007; Xiang, Stallones, & Keefe, 1999). Several major points could be concluded from these studies.

Firstly, the prevalence of low back pain in agriculture is consistently high in both developing and developed countries. Secondly, manual agricultural work is the main contributor to the prevalence of LBDs. Thirdly, several studies referred to awkward postures as important factors related to LBDs and other MSDs. Lastly, most studies have suggested the need for better exposure assessment methods, and for developing ergonomic interventions to abate MSDs in general, and LBDs in particular.

Weed Control in Vegetable Crops

Weed control is a very important issue for farmers particularly for those producing vegetable crops. In vegetable crop production, even low numbers of weeds can reduce marketable yield (Bond, 1991) and have a detrimental impact on the competitiveness of producers. For example, (Miyama, 1999) found that weeds left in the seed line of California processing tomatoes reduced the crop yield by over 80% when weed competition occurred over the entire season. Weed control is even more important in organic vegetable crop production. A survey by (Walz, 1999) of over 4,500 certified organic farmers determined:

- Organic crop farmers rated weed management as the number one research priority of 32 possible farming issues.
- 75% of the respondents still rely on hand weeding for weed control.
- Respondents reported that the greatest barrier to transitioning from conventional systems to organic farming was weed control. This barrier was mentioned by over twice as many farmers (28% vs. 11%) as "inability to identify markets for organic products".

In general, current weed control practice relies on a combination of manual weeding and herbicide application.

Manual Weeding

Manual weeding is a tedious, menial task that is often conducted in an uncomfortable environment. The MSD risk factors of manual weeding include repetitive gripping (66 times/min); high pinch forces; contact stress on the non-dominant hand from the plant and on the dominant hand from the tool; cold ambient temperatures depending on the time of year, and more importantly prolonged trunk flexion angles. This may explain why farm laborers who find alternative employment in construction, retail or other industrial sectors are unlikely to return to farm labor jobs. With 75% of the organic farmers relying solely on manual weeding (in addition to all the conventional farmers also using manual weeding), the industry is dependent on the availability of workers willing to undertake such work. Note that many organic farmers also rely on hand weeding (pulling of weeds using bare hands, while in a stooped posture), which has been shown to substantially increase the risk of LBD among farmworkers (Ramahi & Fathallah, 2006). Further, the task requires larger numbers of individuals for a fairly short period of time, exacerbating the problem.

While neither the US Department of Labor nor Agriculture tracks the percentage of the Nation's 961,000 hired farm laborers (NASS, 2008) specifically involved in hand hoeing, an estimate can be determined from published information on hand hoeing costs per acre, the hourly wage earned by farm laborers and the total acreage used to produce vegetables in the US. For example, hand hoeing had a typical cost of $84 per acre in processing tomatoes in California in 2001 (Miyao, Klonsky, & De Moura, 2001). The US Dept. of Labor, Bureau of Labor Statistics lists the 2001 median hourly wage for laborers hired for weeding tasks using hoes as $6.97/hour (BLS, 2001). Thus the number of man-hours required for hand hoeing in California processing tomatoes is 12 man-hours/acre. In 2002, there were 3,698,744 acres of vegetables harvested in the US (NASS, 2003). Assuming that other vegetable crops in the US have manual hoeing requirements similar to California processing tomatoes, this equates to 44 million man-hours annually nationwide. Note that in California the minimum wage has risen to $8/hour in 2008; which makes this estimate a rather conservative one. Finding effective means for reducing the exposure to MSD risk factors among this working population may have a large positive impact on the workers and the industry.

Herbicide Application

In addition to the potential risk of musculoskeletal disorders associated with weed control, conventional farming practices often depend upon the use of herbicides for weed control. Pesticides are used by farmers to improve productivity and to remain competitive in the world market. The popularity of pesticides is evidenced by the $9.3 billion spent on pesticides by US farmers in 2006 (USDA, 2007) despite growing concerns about the detrimental impact that pesticides have on the environment and human health (Halberg, 1987; Mott, 1991).

Data on herbicide use by vegetable crop farmers indicates that herbicide use in vegetable crops is steady or increasing (CDPR, 2007). For example, the number of acres treated by herbicides in processing tomatoes has doubled from 0.3 million in 1993 to about 0.6 million in 2005. During this same time period, the amount of California processing tomatoes harvested only increased from 7,931,988 tons in 1993 to 9,599,213 tons in 2005 (PTAB, 2007) showing that the herbicide use rate has increased over the past decade. In addition to environmental concerns about herbicide use, the long-term sustainability of herbicide-based weed control is uncertain due to problems with herbicide resistance and the high cost of developing new herbicides. Historically there is a low adoption rate of methods to reduce herbicide resistance which may be due to farmers' focus on optimizing short-term economic returns (Beckie, 2006), or their inability to assess the risk of resistance development (Rotteveel, de Goeij, & van Gemerden, 1997) or unrealistic expectations that new herbicide technology will continually be forthcoming (Llewellyn, Lindner, Pannell, & Powles, 2002). Thus, herbicides should not be viewed as a sustainable resource. With the costs of bringing a new herbicide to market in the US at $150 to $180 million in 2005 (Beckie, 2006) the development of new herbicides is not guaranteed.

One of the indirect benefits of this project is reducing the use of pre-plant soil fumigation, which reduces the number of farm workers in the field exposed to pre-emergence pesticides and fumigants.

Need for Alternative Weeding Methods

Clearly, there is a need to develop new and innovative methods of weed control in order to reduce to the risk of musculoskeletal disorders associated with weed control, to reduce the introduction of herbicides into the environment, and to increase the competitiveness of farmers. One possible solution is to develop an improved system of mechanical cultivation that will substantially reduce the amount of hand hoeing required. Mechanical cultivation can be improved by developing a system that is capable of cultivating between the crop plants in the row.

Global Positioning System-Based Weeding Control System

One of the recent innovations in agricultural technology has been the adaptation of global positioning system (GPS) technology originally developed for the military. The availability of such systems for civilian use has opened the possibility for locating almost any object on Earth to varying degree of accuracy. Inexpensive hand-held GPS devices can provide accuracy in the range of 10 to 66 feet, which are suitable for recreational and sports purposes. Some of the hand-held devices include a Wide Area Augmentation System (WAAS), a satellite-based system capable of delivering accuracy to within about 10 feet. These systems are increasingly accepted in agriculture for scouting purposes such as locating patches of weeds or grid points. Differential GPS (DGPS) units, which use free Coast Guard beacons where available or for-fee satellite correction from vendors, can provide accuracy to less than 3.3 feet. These systems cost about $3,000-$5,000 and are widely used in precision farming for mapping yield, soil electrical conductivity and variable-rate application of agricultural chemicals. At the high end of the spectrum are ultra-precise GPS units, known as real-time kinematics GPS or RTK GPS, which can provide accuracy to within about 0.4 inches "on-the-go". These systems consist of a rover (a mobile unit) and a local base station; they cost about $40,000 to $50,000 (Abidine, Heidman, Upadhyaya, & Hills, 2004).

It is clear that the development of RTK GPS technology has made it technically feasible to determine the location of plants or equipment in agricultural fields at an accuracy of a few centimeters. The RTK GPS technology has been developed into commercial products for automatic steering of tractors allowing precision close cultivation between crop rows to be realized. Farmers are beginning to adopt RTK GPS technology for tractor autosteering. However, for most farmers, their use of RTK GPS technology is limited to primary tillage and cultivation of weeds that are outside the crop row (Abidine et al., 2004- Discussed further in the Preliminary Studies Section). However, the technology has not been used for removing weeds along the seed line. The technology proposed in this research will allow farmers to better utilize their RTK GPS investment by expanding its usage into other farming tasks, thereby reducing the exposure of farm workers to MSD risk factors involved in tasks such as manual weeding, as well as increasing their competitive advantage over less technologically advanced food producers in other parts of the world.

Study Significance and Innovation

The research proposed here will develop an automatic system capable of mechanical weed control between the crop plants in the row. While such an automated system may sound ambitious, many of the concepts and components have already been developed and field-tested by this project's research team. For example, we have successfully developed an automatic seed location mapping system using RTK GPS to record the latitude and longitude of each corn seed planted directly in an agricultural field with an accuracy of between 3 and 4 cm (Ehsani, Upadhyaya, & Mattson, 2004). The expertise gained from this prior development in corn will be valuable in extending the technology to specialty crop production for transplant applications. One added benefit of this research project is that the mechanical weed control portion of the project will also be suitable for automatic thinning of direct-seeded crops (i.e. where the seed is placed directly in the soil) that have been planted with an RTK GPS seed planter, giving additional utility to the system for those growers planting both direct-seeded and transplanted crops.

This project will develop two innovative technologies. One will be to develop a RTK GPS-based system that can accurately map the location of each crop plant during transplanting. The second will be to develop a RTK GPS controlled automatic weed knife that can remove weeds growing in the row between crop plants. Combined, these two technologies will help United States specialty crop producers become more competitive by reducing their need for manual labor and their need for herbicides by automating a large amount of the weed control effort. In addition, the technology will be applicable to both organic and conventional farming, providing organic farmers a much-needed technology for one of their most critical production problems. Another added benefit of the approach is the reduced need for herbicide application and worker exposure to emergence of soil fumigants, which has been shown to have negative environmental impact. Lastly, the project will develop a tool to replace the hoe for precision weeding around the crop plant. This is expected to further reduce the MSD and LBD risk involved in weed control, and reduce crop plant damage.

Relevance to NORA Sectors and Priority Research Topics

This study focuses on the **agriculture/forestry/fishing** sector identified in the National Occupational Research Agenda (NORA). The aims of this study address several of the 17 priority research topics identified in the Production Agriculture/Forestry/Fishing sector of NORA, including: (1) reducing the number of unintentional injuries, (2) education/outreach to increase the knowledge of effective occupational safety and health interventions for agricultural workers, and (3) intervention to reduce adverse safety and health events in migrant/seasonal farmworkers.

Manual weeding is not unique to California, for it is performed in almost every vegetable crop in the US, and hence, the implications of this study should translate to other regions that have crops requiring manual weeding. As was indicated above, hand hoeing may be estimated at 44 million man-hours annually nationwide. Furthermore, the mechanical weed control portion of the project will also be suitable for automatic thinning of direct-seeded crops that have been planted with an RTK GPS seed planter, giving additional utility to the system for those growers planting both direct-seeded and transplanted crops. This project fits well within NIOSH research to practice (r2p) initiative of transferring technologies and translating research findings into effective products, which can be adopted in the workplace. The project findings can be translated into actual modifications to existing practices, especially for farmers who are already using the GPS technology.

Studies Conducted

To achieve the study specific aims, this project conducted three main studies: 1) Development of the GPS-Based Intra-Row Weed Control System (**Specific Aim 1**), 2) Mechanical Weed Management Based on an Accurate Odometry Techniques (**Specific Aims 1 and 2**), 3) Evaluation of Operator Mental Workload in Controlling a Mechanical Weeding System (**Specific Aim 2**), and 4) Ergonomic Evaluation of Three Hoes for Close-to-Plant Weeding (**Specific Aims 3 and 4**).

Study 1. Development of the GPS-Based Intra-Row Weed Control System

Introduction

Weed control is a very important issue for Californian vegetable farmers because even low numbers of weeds can reduce marketable yield (e.g., Lanini and LeStrange, 1991) and have a detrimental impact on produce quality and economic competitiveness. The number of herbicides currently available to vegetable crop farmers is limited and they are only partially effective. As a result, Californian farmers frequently rely on hand weeding and mechanical cultivation to control weeds. Labor shortages in the USA for agricultural tasks have been reported (Wood, 2005) as border security has increased. Thus the weed control task is a major issue particularly in the organic setting (Posner et al. 2008).

In geospatial relation to the crop plants, Blackmore et al. (2007) defined three weeding zones: inter-row, intra-row and a zone that is close to crop (called a safety zone in this research). Weeds present in the inter-row zone can be controlled effectively with conventional mechanical cultivation, but leaves weeds in the other two zones. Autoguidance systems based upon machine vision (Slaughter et al., 1995; Slaughter et al., 1999; Sogaard and Olsen, 2000; Fennimore et al. 2010) or GPS (Abidine et al., 2004) can be used to cultivate or spray very close to the crop plant row (~ 5 cm) at very high ground speed (up to 11 km/h), improving the effectiveness of inter-row cultivation. However, weed control in intra-row and close to crop zones is still conducted by hand in vegetable production in the USA.

Thus there is a need for new automation technologies that can provide both efficient and cost-effective weed control for intra-row and close-to-crop weed management zones in vegetable crops. The objective of this research is to show that a significant reduction in the current reliance on hand labor in organic and conventional production systems can be achieved by RTK-GPS geospatial location technology to both map the crop and planting and then utilize the as planted GPS crop plant map to automatically control a mechanical weed knife system that kills weeds in the intra-row zone.

Materials and Methods

An automatic intra-row weeding machine was designed using a pair of intra-row mechanical weed knives setup for precision intra-row weed control using RTK-GPS based knife actuation. Knife actuation was achieved via pneumatic cylinders attached between a frame on the cultivation sled and the knife linkage arms, Figure 1. The weed knives where positioned directly behind an inter-row close cultivation implement. With the precision intra-row knives in the operating position (called the closed position in this research), all weeds in the row center were killed, Figure 3a. Moving the knives to the standby position (called the open position in this research), created a knife-free uncultivated region about each crop plant, Figure 3b. The knife control system utilized a ruggedized, real-time, embedded controller (cRIO-9004, National Instruments, Austin, TX, USA) with a low-power CPU (195 MHz Pentium, Intel, Santa Clara, CA, USA) and 512 MB of nonvolatile flash memory storage. This system was designed to control the path of the weed knives based upon the real-time GPS location of the leading edge of the knives and their geospatial relationship to the crop plants. Crop plant location was determined from a GIS crop as planted map that was loaded into the memory of the embedded controller. When the knives were in the intra-row zone, shown as position 1 in Fig. 2, they were positioned in the "closed" position with interior knife tips touching and killing all weeds along the row centerline. As the knives reached the close-to-crop safety zone, they were automatically repositioned (or "opened") away from the row centerline and into the inter-row zone, safely bypassing the crop plant, shown as position 2 in Figure 2. After passing the crop plant, the knives were automatically returned to the closed position at the end of the safety zone, resuming the task of intra-row weed control.

Figure 1. Photograph of the RTK-GPS automated transplant mapping system being used to plant tomato transplants on the UC Davis campus farm

A field test was conducted during the spring of 2011 using processing tomato transplants as the target crop. The field site was located at the Western Center for Agriculture Equipment (WCAE), on the University of California, Davis campus (Latitude: 38.53894946 N, Longitude: 121.7751468 W). In this test, sixteen rows were planted (single crop row/bed, 1.5 m bed spacing) with an improved version of the GPS mapping transplanter described by Sun et al. (2010). The transplanter was operated at a ground speed of 1.6 km/h using rows that were laid out in a predominantly East-West direction. The transplanter sled was pulled behind a tractor steered by an RTK GPS autoguidance system (model EZ-Guide 500, Trimble Navigation Ltd., Sunnyvale, CA, USA). All seedbed preparation operations were also conducted with a tractor steered by GPS autoguidance using a common set of GPS AB line coordinates for all tillage, planting operations and weed control tasks. No herbicides were used in the trial, in order to simulate weed populations common to organic production systems. The GPS crop plant map was created using the optimization method of Ehsani et al. (2004), but modified for real-time odometry sensing.

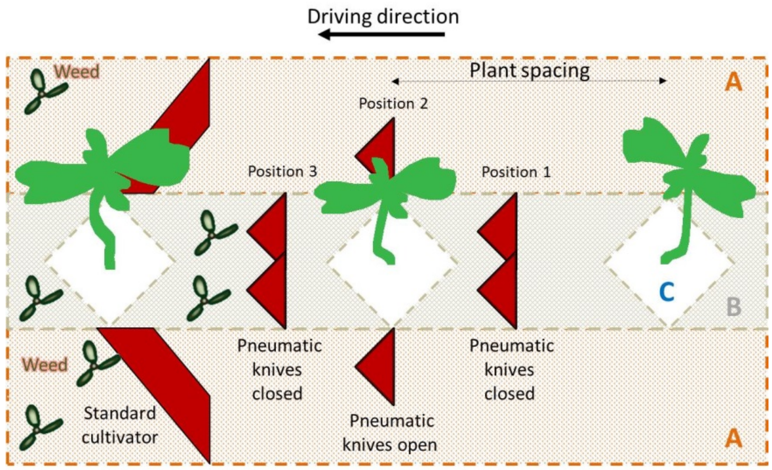

Figure 2. Diagram showing the three weeding zones: A=inter-row (orange dashes with < symbols), B=intra-row (gray dashes with small square inside), and C=safety zones and the ideal path of the weed knives

Approximately three weeks after transplanting, the automatic intra-row weed control system was evaluated. Weed densities were measured prior to precision cultivation. The automatic weed knife system was operated at a travel speed of 1 km/h. Half of the test plot (8 rows) was randomly assigned to the automatic intra-row weed control and the other half used as a control treatment for weed control using traditional manual control of intra-row weeds. Labor savings in follow-up hand weeding was documented by measuring the time required for experienced laborers to hoe remaining weeds after the automatic system had been operated and compared to the amount of time required to hand hoe the control rows using a randomized complete block design in assigning farm laborers to weeding treatments. All results were analyzed by ANOVA using the SAS PROC GLM statistical software.

(a) (b)

Figure 3. Photographs showing the operation of the automatic, mechanical, intra-row weed knife system. Fig 3a shows the knives in the operating or "closed" position, where weeds growing along the row centerline between crop plants are killed. Fig 3b shows the knives in the standby or "open" position, where the knives are temporarily placed in the inter-row zone to bypass the tomato plant. Note in actual operation the cutting edge of the knives are located ~2cm below the soil surface. They were positioned at the soil surface for visualization purposes in this figure.

Results and Discussion

In total, 2278 tomato transplants were automatically mapped using RTK-GPS during planting in the sixteen rows of the test plot for this study. The mean weed density in the test plot was 23.9 weeds/m^2 and no significant difference in weed load between treatments was observed (p-value=0.44). RTK-GPS Fixed quality was obtained for all GPS antenna positions recorded during transplanting and mapping performance was comparable to that observed by Sun et al., (2010).

The automatic intra-row weeding machine successfully killed intra-row weeds between tomato plants without a significant (p-value=0.57) reduction in crop plants. Video analysis of knife operation showed satisfactory dynamic performance in following the desired cutting path. A significant (α=0.01) reduction in the amount of man-hours required for follow-up hand weeding was observed in rows automatically weeded by the machine. Figure 4 shows boxplots for the distributions of the man-hours required for hand weeding in the test. In the control treatment a mean of 206.7 h ha^{-1} was required to hand weed the intra-row and close-to-crop zones. Although the boxplot for the control treatment appears asymmetric, the Shapiro-Wilks test failed to reject the assumption of a Normal distribution for either treatment (p-values > 0.1). The additional hand weeding required in region B in Fig 2. For the RTK GPS automatic weeding treatment following the automatic intra-row weed knife operation was 99.7 h ha^{-1}. This data shows that the automatic system developed can replace a significant amount of hand hoeing labor currently required to perform weed control in areas between crop plants in the row centerline.

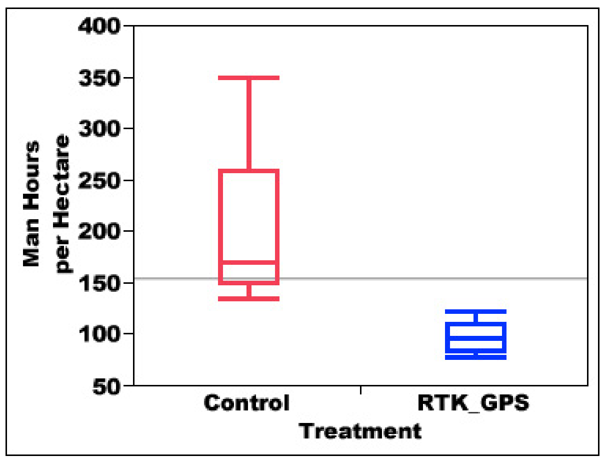

Figure 4. Comparison of intra-row hand weeding labor required for RTK GPS automated weed control vs. conventional hand hoeing.

Overall, a 52% reduction in the man-hours per hectare was obtained by using the automatic GPS-based intra-row weeding machine. Assuming hand weeding labor costs of US$10 per hour, this level of labor reduction potentially represents a significant savings in the cost of manual labor for hand hoeing. The cost savings in hand labor will need to offset the equipment cost, making the system more economically advantageous in organic production systems where weed loads tend to be highest. Utilization of RTK GPS equipment for other tasks in the crop production system can help disperse the equipment cost across many cultural practices, reducing the equipment cost penalty in the weed control operation and may make it economically viable in conventional production systems.

Conclusions

An automatic intra-row weeding machine was successfully designed and tested, using real-time automatic RTK GPS mapping of crop plants during transplanting and automatic RTK GPS based weed knife path control for mechanical removal of weeds growing between crop plants along the row centerline. The system was tested in a processing tomato field where a common set of GPS AB line coordinates was used for all operations from initial tillage and seedbed preparation until automatic intra-row weed control was conducted about one month after planting.

A pair of intra-row mechanical weed knives was successfully used for precision intra-row weed control, significantly reducing the amount of follow-up hand labor required to remove all weeds in the close-to-crop zone. Overall, a 52% reduction in the man-hours per hectare was obtained by using the automatic GPS-based plant mapping and intra-row weeding machine.

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Study 2. Mechanical Weed Management Based on an Accurate Odometry Techniques

Introduction

Recently, promising, innovative technologies have emerged to reduce the drudgery, ensure food safety and increase the productivity of agriculture operations, including organic farming in which weed control operations have received much attention. For example, the prototype robotic weeder (HortiBot) was able to move through the field autonomously with a vision system controlling a precision dosing system (Sørensen et al., 2009). This area of research is similar to others with the main goal of increasing farm performance (Van Evert et al., 2011), however the economic aspect related to production costs are often not examined in detail or even commented upon in many studies. Recent reviews of robots in agriculture typically do not mention any commercially available weeding robots (Billingsley et al., 2008; Slaughter et al., 2008).

Current technology exists for effective control of weeds present between crops rows. For example, disc cultivators (Bowman, 1997; Mohler, 2001), brush weeders (Fogelberg and Kritz, 1999), rolling cultivators (Lampkin, 1990) and rolling harrows (Peruzzi et al., 2005). The critical need for developing weed control operations is the removal of weeds between the crop plants, which is still done by hand, adversely impacting production costs.

In organic crop management the use of herbicides is prohibited so the major challenge and priority on most organic farms is weed control. While economic non-complex equipment is available to control the inter-row weeds, intra-row weed control still requires costly hand weeding (Sivesind, et al., 2009). In many crops (e.g., onions) this added labor cost can be significant (Mojzis 2002). For manual weed control the operation in many cases causes the worker to be stooped and in uncomfortable bending postures over large periods, which may cause seriously chronic health issues for workers and therefore costs to growers. In California, the labor costs for hand weeding is $232 and $261/ha in broccoli and lettuce, respectively (Smith et al., 2004; Tourte and Smith, 2001). This hand weeding operation complemented conventional application of herbicides in bands (herbicide costs of $111/ha and $118/ha, for broccoli and lettuce) and cultivation (cultivator costs of $40 and $67/ha, for broccoli and lettuce) (Haar and Fennimore, 2003). Hand weeding in these cases represented 60% in broccoli and 58% in lettuce of the total cost of weed control.

Currently, farmers may find different commercial types of machines for intra-row weeding with different costs and field capacities. Some of these are; i) the finger weeder has been shown to be capable of removing weeds in the seedline, but weeds need to be small (2nd true leaf) and the crop firmly rooted (guide price $860/row and field capacity 1ha/h) (Turner, 2000), ii) the torsion weeder has been shown to be capable of removing weeds in the seedline, but again the weeds need to be small (2nd true leaf) and the crop firmly rooted (guide price $180/row and field capacity 1ha/h) (Bowman, 1997), iii) the weed blower uses compressed air to control weeds by blowing them out of the crop row (guide price $2100/row and field capacity 1ha/h) (Lutkemeyer, 2000; Vale, 2003), iv) flame weeding can be less costly than hand-weeding in some cases, but there is a high machine cost (guide price $4700/row and low field capacity) (Ascard, 1998), and v) intelligent systems using digital cameras to view the crop and use a spinning disc to remove weeds (guide price $17000/row and speed limited at 3 km/h) (Dedousis et al., 2007). Ascard (2007) suggests that the constraints of cost, low capacity, low selectivity and time to perform all the necessary adjustments have made a number of recently developed weed control systems unattractive.

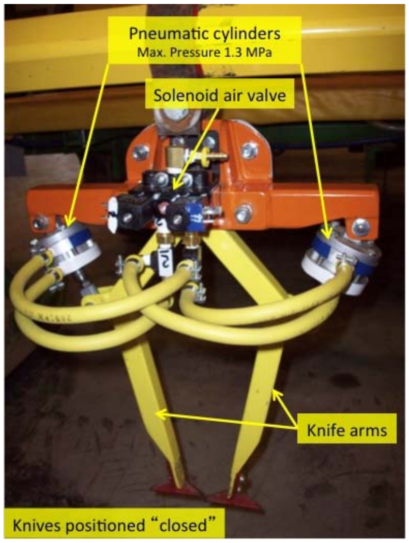
Some recent research in the field of precision agriculture has used the RTK-GPS mapping crop technology as a good alternative to real-time weed sensing for use in removing intra-row weeds (Griepentrog et al., 2003 and 2005; Slaughter et al., 2010). Plant maps generated based on GPS required high precision (~2-3 cm) and this is achieved using an RTK-GPS system during the seeding or transplanting operation. These implements needed an independent RTK GPS system located on the transplanter or seeder with a large price/performance penalty due to the high initial investment cost.

The aim of this work was to investigate the performance of a semi-automatic intra-row knife-based weeding system with automatic knife actuation based on odometry sensing. This system was developed to achieve a more cost-effective control of intra-row weeds and reduce the economic, and ergonomic problems associated with hand weeding.

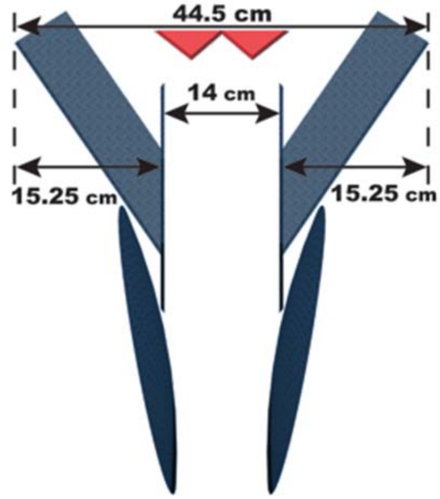
Materials and Methods

Intra-row knife weeder design

A semiautomatic intra-row weeding machine was developed using a mechanical weed knife system similar to the one used in the prototype developed by Pérez-Ruiz et al. (2012) but modified for precision intra-row weed control using odometry information. The system consisted of a pair of pneumatically actuated weed knives that could be positioned at the row centerline in a side-by-side configuration where all weeds in the central 14 cm in-row region were cut (see Figure 5). As the knives approached each crop plant, the knives were propelled at a high velocity away from the centerline, to a position that prevented damage to the crop plant. Once past the close-to-crop zone, the knives were returned to the closed position to continue intra-row weed control. A pair of pneumatic cylinders (model Speedaire 5YCL0, Dayton Electric Mfg. Co. Niles, IL, USA) powered knife actuation. Knife motion was operated by an embedded controller (cRIO-9004, National Instruments, Austin, TX, USA) connected to an air control valve (model P2LCX593EEHDDB48, Parker Hannifin Co., Cleveland Ohio, USA) that provided air pressure (0.97 MPa) to the pneumatic cylinders. The operation of this mechanical weed knife system was much simpler and had fewer moving parts than the mechanically complex cycloid hoe used by Nørremark et al. (2008), and the control algorithm required for precision intra-row weed control was also simpler than the elaborate control algorithm required by either the Nørremark et al. or Tillett et al. (2008) systems. Preliminary soil tillage tests (unpublished data) indicated that the weed knives could transition from the closed to open positions or vice versa in about 20 to 30 ms depending upon soil conditions.



(a)



(b)

Figure 5. Mechanical intra-row weed knife system. Fig. 5a shows a rear view of the knives (red) in the "closed" position, with the inner knife tips touching to kill all weeds growing within the row centerline. Fig 5b shows the inter-row disks and sweep knives (gray) with the intra-row knives (red) in the closed position.

Knife control

The semiautomatic mechanical weed control knife system was supervised by an operator seated behind the implement and above the row crop with a clear view of the knife. At the beginning of the row, the operator initiates a brief (~10 s) machine-learning step in which an embedded controller records 8 pairs of knife open and close events. A ground-wheel driven optical encoder was used to continuously monitor weed knife location (Figure 6). After initial training, the controller automatically estimates plant spacing and close-to-crop zone size. Future knife opening and closing events were then automatically controlled based upon odometry. The plant spacing and close-to-crop zone were periodically adjusted as needed by the supervisor.

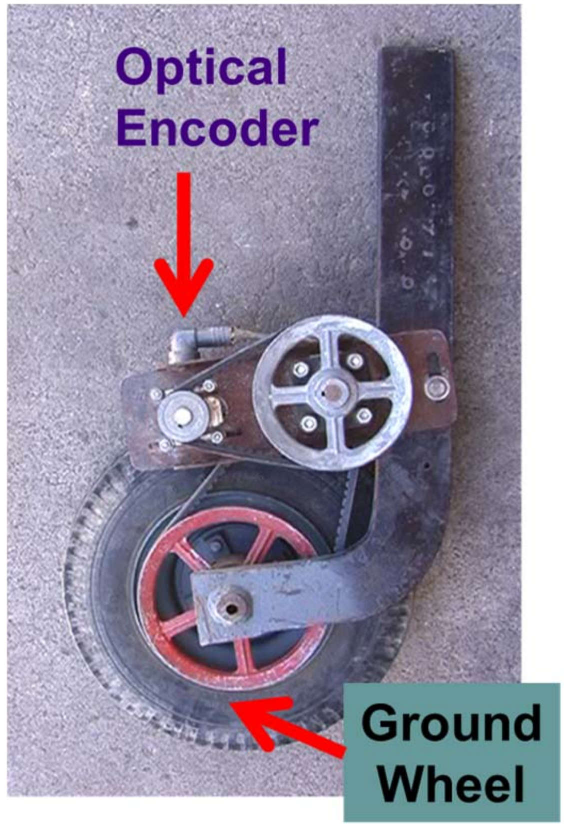


Figure 6. Ground-wheel driven optical encoder to continuously monitor weed knife location.

Field experiments

Fourteen rows were planted at the Western Center for Ag. Equipment at UC Davis using processing tomato transplants as the target row crop. Precision inter-row and intra-row cultivation was done in a single pass. Standard inter-row cultivation used an unpowered rotary cage cultivator. The experimental plot consisted two types of tests: automated intra-row weeding using the Odometry sensor and a conventional Control treatment, each with seven rows. For both treatments, precision inter-row cultivation was performed with a set of disks and cultivators set 14 cm apart as shown in Fig. 5b.

In both treatments a follow-up hand weeding operation was conducted to remove remaining weeds in the central 14 cm band along the row centerline using two volunteer workers (workers A & B). Worker A weeded 4 Control and 3 Odometry rows, and worker B weeded the remaining 3 Control and 4 Odometry rows (Figure 7). For each row, initial weed density, the worker's time spent hand weeding, and tomato plant counts along the row were measured and recorded. The method of Fennimore et al., 2010 was used to test and compensate for any differences in weed and crop plant densities between treatments as well as in worker productivity. ANOVA showed that there were no significant differences in weed density between treatments or workers A & B (p-values >0.35). This method also allowed an estimate of the potential time saving difference between the Control and Odometry treatments that would result from the semi-automated weeding operation.

Figure 7. Workers hand hoeing the Control and Odometry rows.

Results and Discussion

A low cost, semiautomatic intra-row weeding cultivator, which utilized ground wheel odometry in real-time to determine the open and close events of weed knives to eliminate the intra-row weeds was successfully developed and operated.

Figure 8 shows a diagram of the knife's operation to control weeds. Three regions are differentiated; region A is the inter-row zone, region B is the intra-row zone, and region C is the safety zone. In this design, a pair of weed knives was used to control most weeds in the intra-row zone and a standard cultivator was used to control inter-row zone weeds.

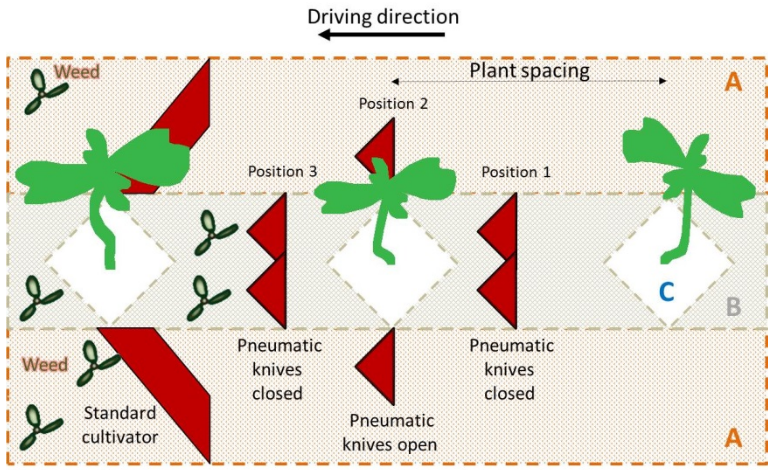


Figure 8. Diagram showing the three weeding zones: A=inter-row (orange dashes with < symbols), B=intra-row (gray dashes with small square inside), and C=safety zones and the ideal path of the weed knives

Pneumatic knives in position 1 are shown in the “closed” state with the two knives side-by-side in the intra-row zone. As the knives approach the tomato plant in the center they separate, following the grey dashed lines in the ideal case; position 2. This leaves the safety zone C unweeded. As the knives pass the tomato plant, they again follow the grey dashed lines, in the ideal case until they meet in the center of the row; position 3. This process is ideally repeated for each tomato plant.

The pneumatic knives based on odometry real-time data were operated in seven rows and the remaining seven rows were established as control rows. Within this study, a total of 1119 tomato plants were used for the semiautomatic intra-row cultivation with the pneumatic knives and 1191 tomato plants for the control treatment. At the time of intra-row weeding operation, weeds were mostly in the cotyledon through 2nd true leaf stages. According to various researchers, mechanical tools to remove weeds are most efficient when the weeds are in the white thread or cotyledon development stage (Bellinder, 1997).

There was a significant difference between hand hoeing hours per hectare required for the two treatments (p-value <0.0001). Figure 9 shows boxplots for the distributions of the hand weeding required of the treatments. In the control treatment a mean of 240 h ha-1 was required to hand weed region B. Although the boxplot for the control treatment appears asymmetric, the Shapiro-Wilk test failed to reject the assumption of a Normal distribution for either treatment (p-values > 0.4). The additional hand weeding required in region B in the Odometry treatment following the automatic intra-row weed knife operation was 102 h ha-1. This data shows that the system developed replaced a significant amount of hand hoeing labor for weed control in areas close to the crop plant. The workers had to work approximately 57.5 % less area. Focusing upon the economic aspect the data, assuming hand weeding labor costs of US$10 per hour, a saving cost in weed control of US$1,380/ha was achieved.

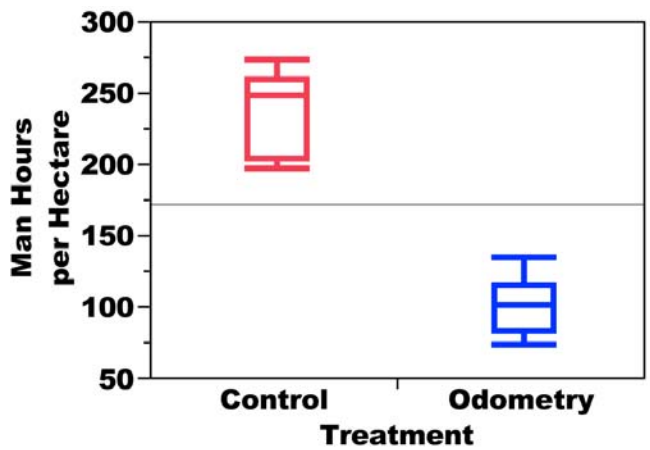


Figure 9. Frequency distribution of operator hour per hectare of the fourteen rows (control vs. odometry). Bars (or whiskers) represent the dispersion of the values below or above the lower quartile and the upper quartile, respectively

This does not imply that all the challenges are completely solved. This study has not monitored and therefore evaluated the long-term health impacts on workers, but it is reasonable to conclude that a reduction in the time spend hand weeding would result in a decreased risk of injuries and Musculoskeletal disorders (MSDs) for farm workers.

Conclusion

A semiautomatic intra-row non-chemical weeding machine was developed and operated using a mechanical weed knife system and odometry information in real-time to determine the open and close events of the weed knives to control the knife path to circumvent the crop and eliminated the intra-row weeds. The following conclusions were drawn based upon the results of this research:

- A system that uses odometry technology for real-time knife path planning, in comparison with more costly alternatives such as RTK-GPS mapping crop technology, is a viable technique for precision intra-row weed control. By eliminating the need for an RTK-GPS system located on the transplanter or seeder, it has both reduced equipment costs and makes farm management simpler by decoupling the planting and weeding tasks. The reduced equipment cost of the system makes the technology better suited for small farms that are unable to afford costly RTK-GPS equipment.

- The average worker's hour per hectare required to hand weed the intra-row region was 240 h ha^{-1} in the control treatment and 102 hours ha^{-1} in the Odometry treatment. This is an indication that the system developed can replace a significant amount of traditional hand hoeing with precision weed control in areas close to the crop plant.

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Study 3. Evaluation of Operator Mental Workload in Controlling a Mechanical Weeding System

Introduction

As discussed in the previous two studies weed control is a very important issue for farmers, particularly for those producing vegetable crops and is crucial for organic vegetable crops farmers. One of the goals of this project is to develop the cutting system in such a way as to allow manual activation for use by small farmers and/or farmers who do not own a GPS system. A worker interface box [WIB) was developed to facilitate the manual activation of the weeding cutter. The objective of this study is present the WIB and a preliminary evaluation of operator mental workload when controlling this new weeding system, which consists of a semi-automatic intra-row knife-based weeding system with automatic knife actuation based on odometry sensing [Study 3).

Methods

The WIB system includes a toggle switch for manual Reset [up)/Learning and an "Auto" mode [down); a momentary button, learning mode [Figure 10): Knifes open [up)/Knifes closed [down); a plant spacing tweak thumb wheel; a plant range tweak thumb wheel and status LED's. The connection to the National Instruments cRIO controller is currently being developed.

Using National Instruments LabVIEW programming and interface capabilities, a field-programmable gate array [FPGA) and compact Realtime Industrial Controller [cRIO) were developed and controlled [Figure 11). The FPGA was programmed to correctly read switches, buttons, and wheels, and to write to LED's. The cRIO programming is currently undergoing and is designed to read knife open and close events; events counting; calculate average plant spacing and range from knife events; change cRIO state from Learning [green) to Auto mode [yellow); provide plant spacing and range adjustment with tweak wheels; as well as manual reset forces knife open.

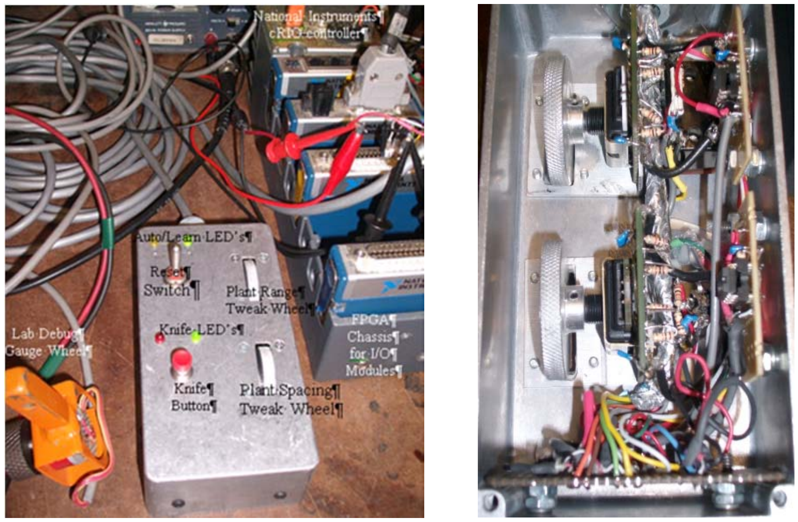

Figure 10. Worker interface box overview [left), and inside [right)

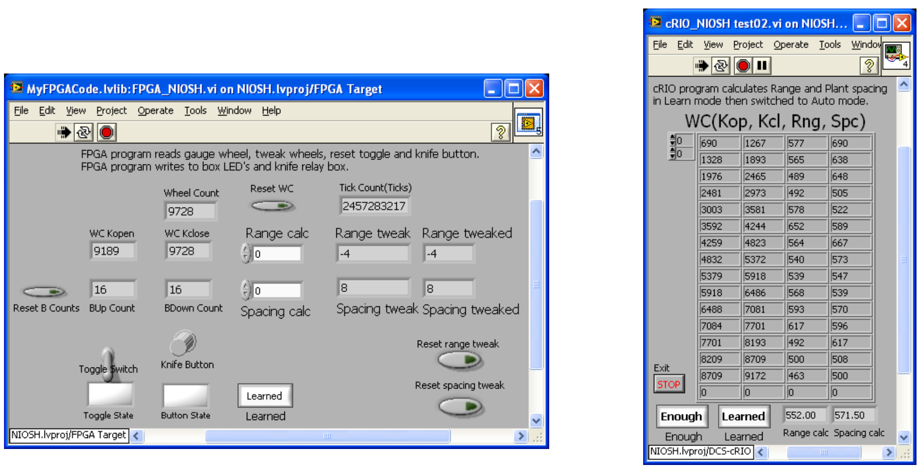

Figure 11. The FPGA [left) and cRIO [right) interfaces in LabVIEW.

Placement and design of the worker seat on the implement were two issues that were also evaluated. Issues that were evaluated include tractor versus car seat; seat paint color; position and placement of seat; and connection to the implement. The decision was made to use a tractor seat [Figure 12) on the outside of the tractor connected to the implement [Figure 13).

Figure 12. Worker seat selected: Tractor seat.

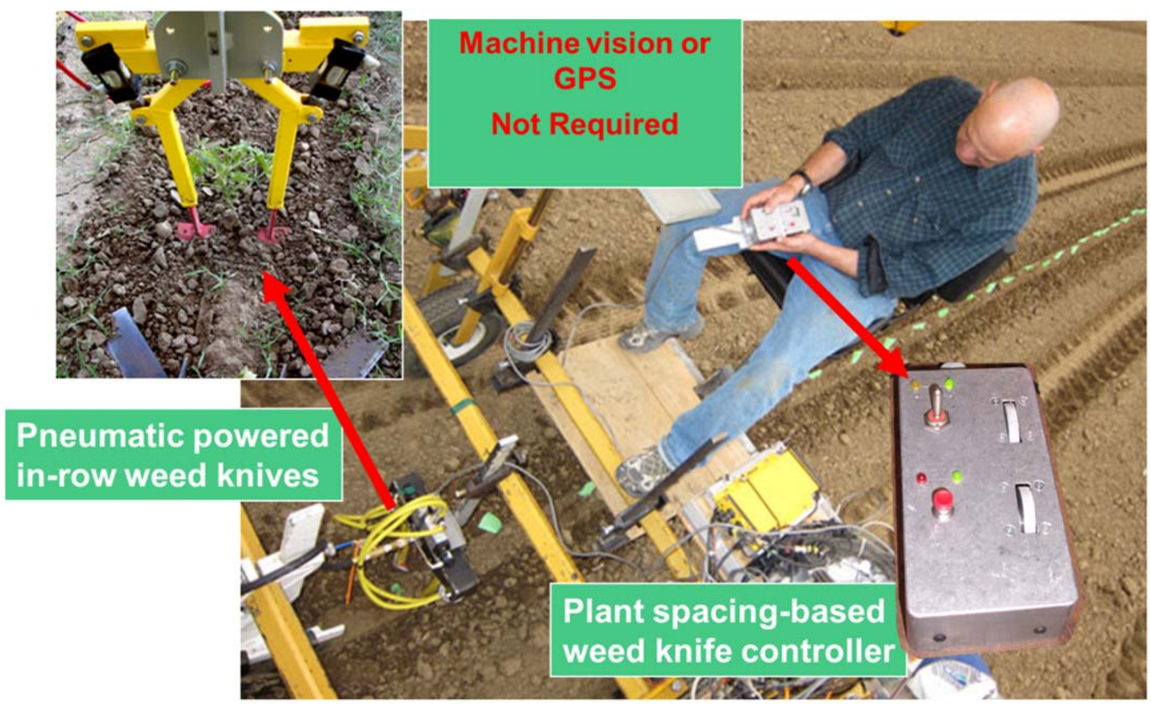

Figure 13. Weeding system workstation. Worker adjusts knives system opening and closing using the WIB based on pre-configured plant spacing data.

The entire system that is implemented to an agricultural tractor is shown in Figure 14.

Figure 14. The controlled knives system and operator workstation implemented on an agricultural tractor.

Four subjects [three males, one female; average age/standard deviation 20/2.3 years) volunteered to participate in this study. The participants were briefed about the purpose of the study and signed an approved IRB consent form.

The subjects were trained on the use of the WIB in a controlled environment using a motorized belt system that allowed equally-spaced plastic straws [to simulate plant location) to continuously rotate in front of the subject [Figure 15). The subject task was to adjust the WBI in order to make the system knives to open when they reach a straw [i.e., plant).

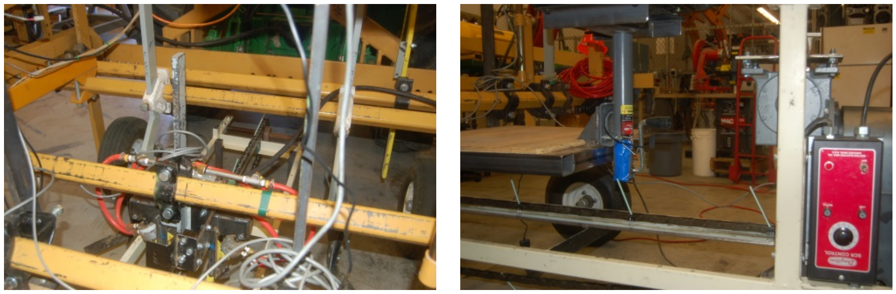

Figure 15. Controlled simulation of spaced-plants using a motorized continuous belt and colored plastic straws.

In the field trials, subjects were asked to control the system at 1, 1.5, and 2 miles per hour tractor speed. Equally spaced straws were planted in the field to simulate the plants [Figure 16).

Figure 16. Field trails example. The worker controls watches the straws [plants) and adjusts the WBI as the knives open and close between straws.

In order to assess the potential for excessive mental and/or physical workload by the system operator, task mental and physical workload [i.e., fatigue) was captured using an adapted version of the validated and widely used NASA Task Load Index [NASA TLX) (Hart, 2006; Hart & Staveland, 1988) [Figure 17). The revised multidimensional weighted workload index considers three dimensions related to the demands imposed on the subject [Mental, Physical. and Temporal Demands) and three related to the interaction of the subject with the task [Effort, Frustration, and Performance).

NASA-TLX Mental Workload Rating Scale

Please place an "X" along each scale at the point that best indicates your experience with the display configuration.

Mental Demand: How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc)? Was the mission easy or demanding, simple or complex, exacting or forgiving?

Low High

Physical Demand: How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the mission easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

Low High

Temporal Demand: How much time pressure did you feel due to the rate or pace at which the mission occurred? Was the pace slow and leisurely or rapid and frantic?

Low High

Performance: How successful do you think you were in accomplishing the goals of the mission? How satisfied were you with your performance in accomplishing these goals?

Low High

Effort: How hard did you have to work (mentally and physically) to accomplish your level of performance?

Low High

Frustration: How discouraged, stressed, irritated, and annoyed versus gratified, relaxed, content, and complacent did you feel during your mission?

Low High

Figure 17. Modified NASA TLX form administered to participants.

Results and Conclusions

The results of the modified NASA TLX are shown in Figure 18. As demonstrated in Study 3 above, the system shows good promise as a weed control alternative. Mental workload was moderate especially at higher speeds. This may be due to slippage in the observed in the system, and lack of sufficient training. To eliminate slippage observed in this study, the system driving mechanism was replaced with a timing-chain instead of a belt-driven system. Note that the task's physical demand was perceived as very low. From observing the subjects and from their response, the workstation needs improvement to improve the operator's relative position with respect to the plants as well as foot-placement.

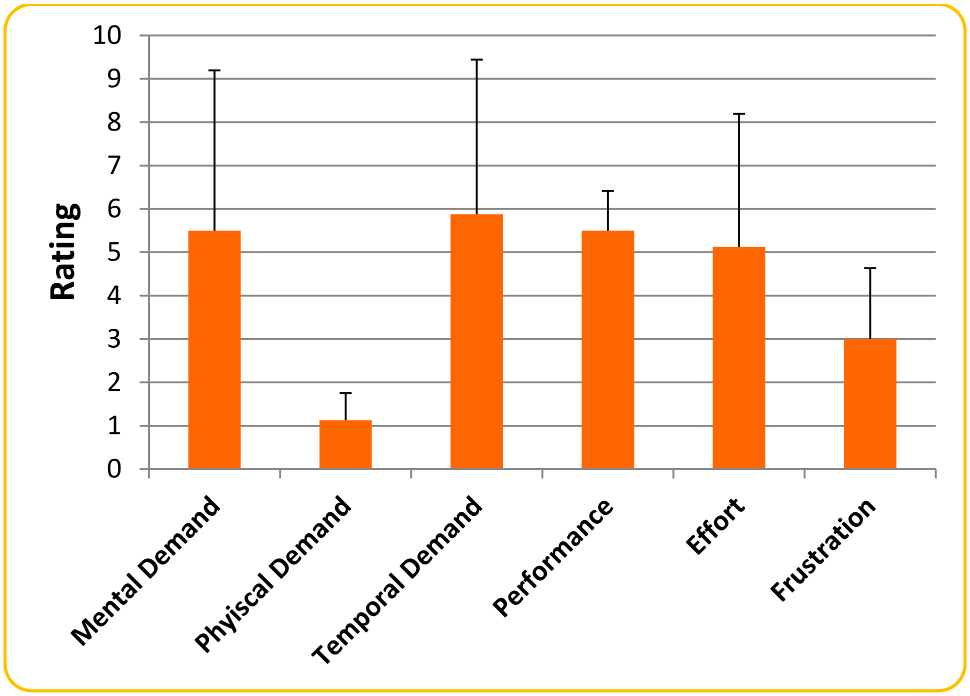

Figure 18. Results of the modified NASA TLX mental workload assessment.

Study 4. Ergonomic Evaluation of Three Hoes for Close-to-Plant Weeding

Introduction

There have been limited alternatives to traditional long-handled hoe in controlling close-to-plants weeds and reducing risk of musculoskeletal disorders [MSDs). Our group has been interested in finding alternative means for hand weeding and traditional weeding with a hoe [or hoeing). In one undergraduate student project, we have developed a potential weeding tool and compared it to the traditional hoe. The new weeding tool is a modified "E-Z Reacher," a commercially available tool commonly used by the physically disabled and custodial workers for reaching and picking objects from very low or very high places [Figure 19-Top). The modified E-Z Reacher included a reinforced spring system, and a pair of metal digging blades for uprooting the weeds [Figure 19-Bottom). Six subjects were recruited for this evaluation. Trunk kinematics were captured while the subject was weeding designated plots [Figure 20).

Figure 19. The E-Z Reacher [Top) and the modified weeding blades

The biomechanical evaluation showed that, compared to traditional hoeing, the modified E-Z Reacher significantly reduced key LBD trunk kinematics risk factors [sagittal flexion, trunk lateral and twisting velocities) (Marras et al., 1993), and was more accurate than the traditional hoe. However, as expected, the subjects completed the standardized weeded plots faster with the hoe. From the subjective evaluation, the results showed that subjects complained from excessive force application when manually triggering the device during weeding. This led to the exploration of a motorized solution for this problem [described in the next section).

Figure 20. The E-Z Reacher [Top) and the modified weeding blades Figure 6. A subject weeding using the modified device.

We recently completed a study of agricultural weeding tools and introduced an engineering approach that holds promise in reducing LBD risks during weeding [Ramahi and Fathallah, 2006). The purpose of the study was to investigate current and new methods of manual weeding. Nine agricultural workers [7 males and 2 females) participated in this study. Trunk 3-D kinematics were monitored while workers performed four weeding tasks using different methods; long- and short-handled weeding [hoe and weed "Puller"), hand weeding, and a newly developed device; the "Eater" [Figure 21). The Eater consists of two conveyor belts working simultaneously in an intermesh design to simulate the pulling and grabbing action of the hands, with handles and pads that promote its use in near-upright and neutral posture [Figure 22).

Figure 21. The Eater weeding tool.

Figure 22. A farm worker using the Eater.

Hoe weeding is considered a less hazardous alternative to hand weeding with regards to back injuries; however, consistent with our earlier evaluation, the results showed otherwise. The worker's sagittal position with the hoe weeding was not significantly different from the short-handled tool. Also, workers weeding with the hoe displayed the highest trunk velocities. On the other hand, the Eater showed promising results by significantly reducing biomechanical risk factors [sagittal flexion, lateral and twisting velocities; Marras et al., 1993). However, productivity results were not as promising due the device specifications [pulling power and speed, and battery life).

For this project we have re-evaluated the potential to use these two systems for close-to-plant weeding; however, after careful consideration and workers' lack of interest in these approaches due to their perceived inferiority, in terms of productivity, to the traditional hoe, we decided to test two alternative hoes that resemble the traditional how but may provide better accuracy and potentially reduced risk of MSDs. Therefore the objective of this study of the project is conduct an ergonomic comparison of three types of weeding hoes in a field that has been weed-controlled by the developed automatic system [Studies 1-3).

Methods

In this study we had twelve subjects [ten male, two female) [age Avg/std dev. 36.5/8.8 years) with substantial experience in manual weeding [7.2/8.6 years) participated in the study. The subjects signed an IRB approved consent form. The Lumbar Motion Monitor [LMM; Chattecx corp., Hixon, TN) was used to capture three-dimensional kinematics of the spine during this experiment. The device accuracy and validation has been shown previously (Marras, Fathallah, Miller, Davis, & Mirka, 1992).

In this study three types of hoes were tested: 1) traditional hoe, 2) Diamond/Clipper, and 3) Oscillating/Hula Hoe [Figure 23).

Figure 23. The three hoes tested in this study.

The dependent variables included key lumbar kinematic variables related to MSDs, namely: Sagittal position, lateral velocity, twisting velocity [Marras et al., 1993); weeding time; and subjective ranking/response.

Workers were asked to manually remove the between-plant weeds of 240-foot long rows of tomato plants using one of the randomly assigned hoes [Figure 24). Each row was divided into 80-feet sections, and the subject was given a short training time to acquaint with the new hoes.

Figure 24. A subject weeding one of the 240-long rows of tomato plants using the traditional hoe. Note that subject is wearing the LMM.

Results

The time comparison between the three hoes is shown in Figure 25. The risk of MSDs to the lower back is characterized by the three main kinematic risk factors of sagittal flexion, lateral velocity, and twisting velocity are shown in Figures 26 through 28, respectively. The subjective ranking of the three hoes is shown in Figure 29.

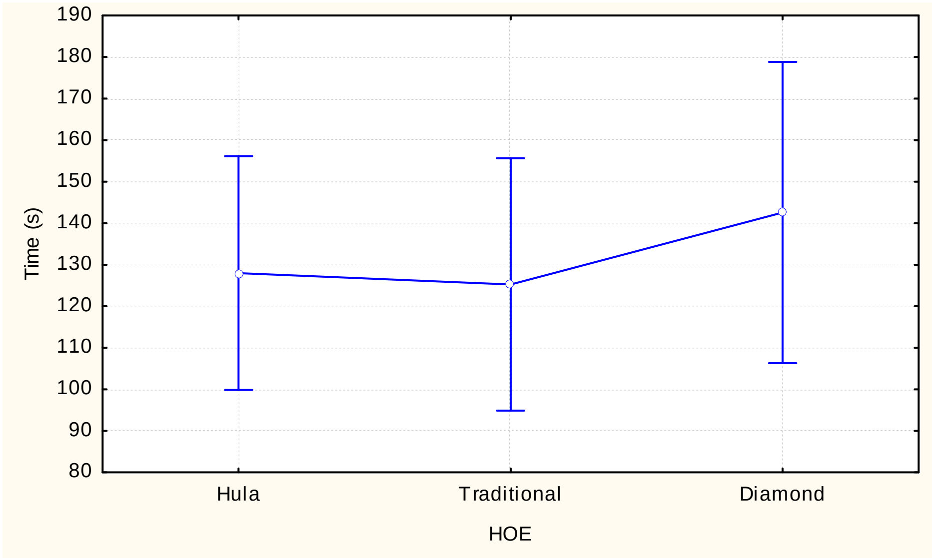

Figure 25. Average time to complete 80-foot sections of the 240-foot row for each of the tested hoes.

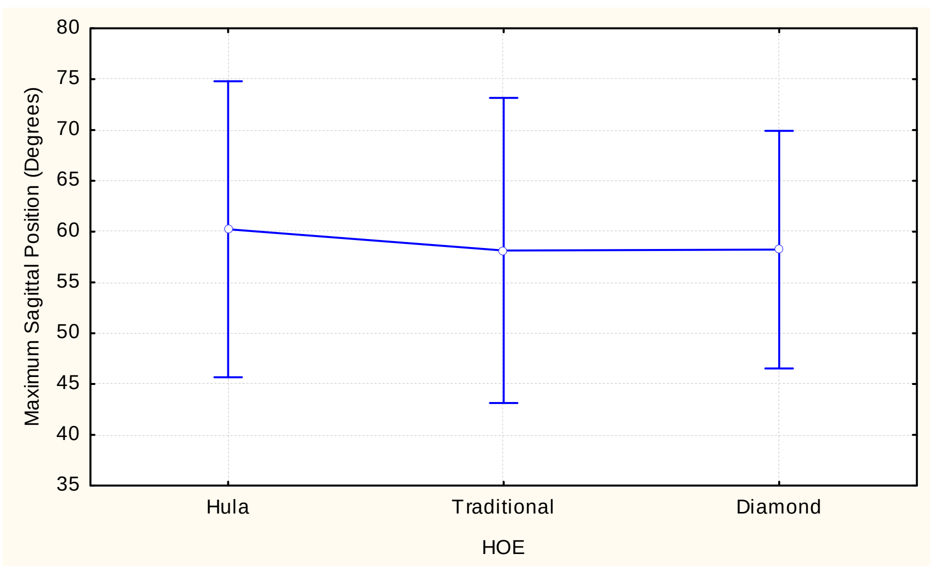

Figure 26. Maximum sagittal flexion for each of the three hoes.

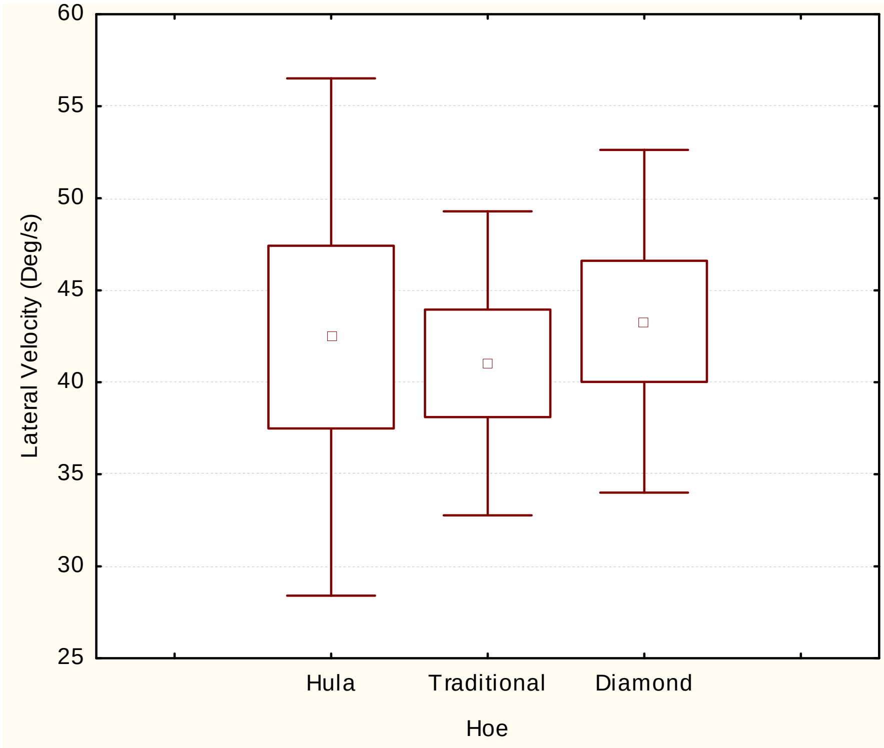

Figure 27. Lateral velocity for each of the three hoes.

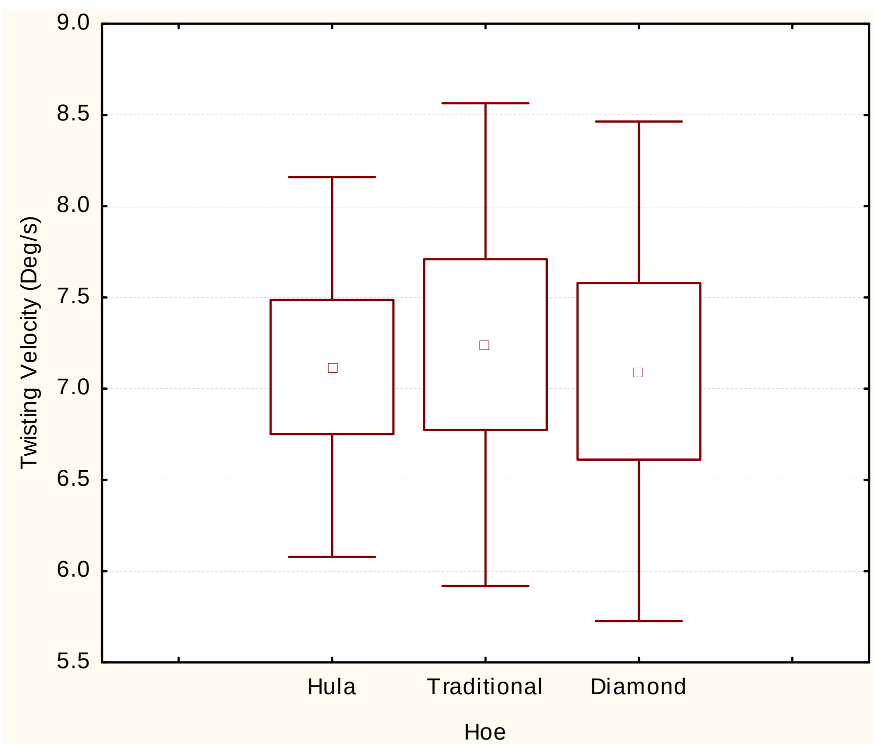

Figure 28. Twisting velocity for each of the three hoes.

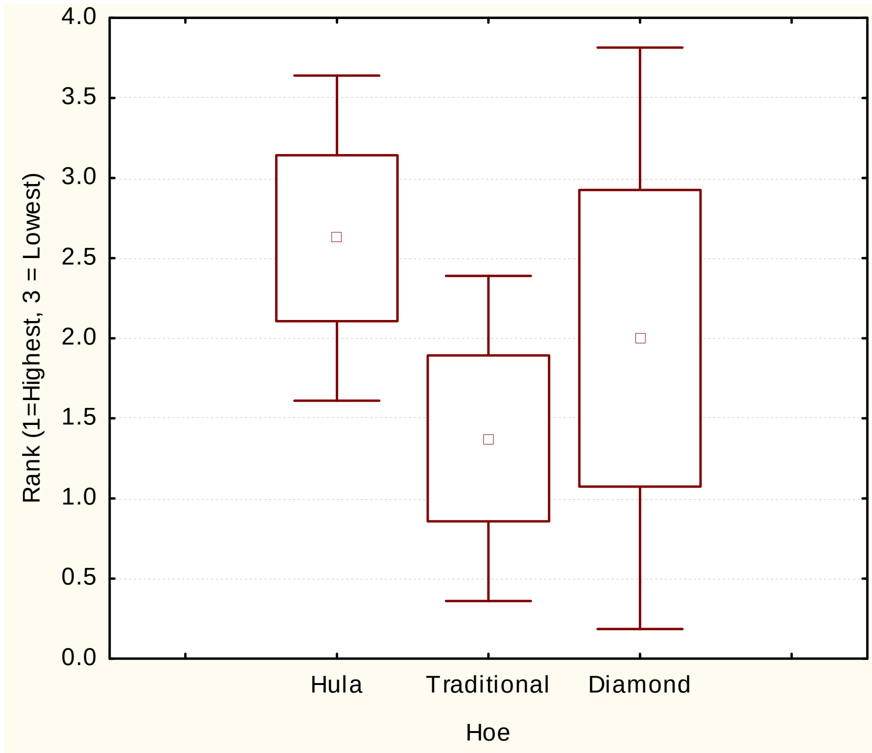

Figure 29. Subjective ranking of the three hoes.

Discussion and Conclusions

From the results of this study, it was clear that manual weeding exhibits high level of risk to the lower back (all three types of hoes). This is consistent with other studies conducted by our group. However, the Hula hoe may be a good alternative for smaller weeds due to its lighter weight (lightest hoe), as several subjects commented on its good potential to be used on smaller weeds. Note that the mechanical weeding performed on the field reduced the total required manual weeding time (Study 3). This is expected to substantially reduce the exposure time to MSD risk factors and reduce the cumulative effect of this exposure. Lastly, compared to the traditional hoe, subjects were not familiar with two alternative hoes and hence, with more training these alternative hoes may prove effective and beneficial for close-to-plant weeding compared to the traditional hoe.

STUDY OUTPUT

1. Limitations and future work

This project has focused mainly on development of automatic/semi-automatic weeding system in a single row at a time. However, to make the system more economically feasible, a multiple-row system would be more attractive to farmers. Our group has developed and currently testing a three-row knives-control weeding system to address this shortcoming (Figure 30). As in the case of the one-row system, this three-row system is expected to substantially reduce exposure to manual weeding (at least 50%) by agricultural workers and reduce their risk of musculoskeletal disorders.

Figure 30. Three-row semi-automatic weeding system.

2. Presentations

This is a list of scientific up-to-date presentations related to this project presented by the project investigators at National and International meetings:

- Slaughter, D.C., Perez-Ruiz, M., Fathallah, F.A., Upadhyaya, S.K., Gliever, C.J., and Miller, B.J. GPS-Based Intra-Row Weed Control System: Performance and Labor Savings. Presented at the International Conference of Agricultural Engineering, Valencia, Spain, July 8-12, 2012.
- Perez-Ruiz, M., Slaughter, D.C., Fathallah, F.A., Upadhyaya, S.K., Gliever, C.J., and Miller, B.J. Mechanical Weed Management Based on an Accurate Odometry Techniques. Presented at the International Conference of Agricultural Engineering, Valencia, Spain, July 8-12, 2012.
- Fathallah, F.A., Slaughter, D.C., Miller, B.J., Gliever, C.J., and Perez-Ruiz, M. Ergonomics Evaluation of Three Hoes for Close-to-Plant Weeding. Presented at the American Society of Agricultural and Biological Engineers [ASABE) Annual International Meeting. Dallas, TX, July 29-Auguts 1, 2012.
- Fathallah, F.A., Slaughter, D.C., Miller, B.J., Gliever, C.J., and Perez-Ruiz, M. Evaluation of Operator Mental Workload in Controlling a Mechanical Weeding System. Presented at the American Society of Agricultural and Biological Engineers [ASABE) Annual International Meeting. Dallas, TX, July 29-Auguts 1, 2012.

3. Publications

3-1. Thesis

- Sun, H. 2012. Automatic GPS-Based Intra-Row Weed Control System for Transplanted Row Crops. MS Thesis. University of California, Davis.

3-2. Conference Proceedings

- Slaughter, D.C., Perez-Ruiz, M., Fathallah, F.A., Upadhyaya, S.K., Gliever, C.J., and Miller, B.J. GPS-Based Intra-Row Weed Control System: Performance and Labor Savings. In Proceedings of the International Conference of Agricultural Engineering, paper #C0194.

- Perez-Ruiz, M., Slaughter, D.C., Fathallah, F.A., Upadhyaya, S.K., Gliever, C.J., and Miller, B.J. Mechanical Weed Management Based on an Accurate Odometry Techniques [2012). In Proceedings of the International Conference of Agricultural Engineering; paper #C1178.

4. Inclusion of Gender and Minority Subjects:

Table 1 shows the inclusion enrollment report for this project.

Table 1. Inclusion enrollment report.

Study Title: Development and Evaluation of a GPS-Based Weeding System for Reducing the Risk of Musculoskeletal Disorders among Agricultural Workers

Total Enrollment: 18 **Protocol Number:** 200917369-1

Grant Number: R21-OH009519

PART A. TOTAL ENROLLMENT REPORT: Number of Subjects Enrolled to Date (Cumulative) by Ethnicity and Race				
Ethnic Category	**Females**	**Males**	**Sex/Gender Unknown or Not Reported**	**Total**
Hispanic or Latino	3	14		17 **
Not Hispanic or Latino	1	3		4
Unknown (individuals not reporting ethnicity)				
Ethnic Category: Total of All Subjects*	4	17		21 *
Racial Categories				
American Indian/Alaska Native				
Asian	1	1		2
Native Hawaiian or Other Pacific Islander				
Black or African American				
White		2		2
More Than One Race				
Unknown or Not Reported	3	14		17
Racial Categories: Total of All Subjects*	4	17		21 *

PART B. HISPANIC ENROLLMENT REPORT: Number of Hispanics or Latinos Enrolled to Date (Cumulative)				
Racial Categories	**Females**	**Males**	**Sex/Gender Unknown or Not Reported**	**Total**
American Indian or Alaska Native				
Asian				
Native Hawaiian or Other Pacific Islander				
Black or African American				
White				
More Than One Race				
Unknown or Not Reported	3	14		17
Racial Categories: Total of Hispanics or Latinos**	3	14		17 **

* These totals must agree.
** These totals must agree.

5. Inclusion of Children:

There were no children included in this study.

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