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Research Paper

Investigation of productivity enhancement and biomechanical risks in greenhouse crops

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Labour is the single largest cost contributor and main limiting factor to development of the agricultural industry. Manual labour remains a major, essential factor for greenhouse-grown specialty crops. Furthermore, musculoskeletal injuries are prevalent during manual work processes performed in agricultural environments. This study aims to improve work efficiency and productivity and to identify tasks that can cause musculoskeletal injury. Working procedures were characterised using a work-study method, environmental conditions were recorded and a biomechanical analysis of the inspected task was conducted. An innovative measuring system was developed that enables synchronisation and analysis of the manufacturing, biomechanics, workload and environmental data. The study focused on the trellising and harvesting stages of pepper and tomato in greenhouses on two farms located in southwest Israel. We further conducted several experiments in which we changed the working method and assessed the effect on productivity. Another experiment was conducted to test the effect of three different trellising angles (30°, 60°, 90°) on labour and yield in tomato. The results revealed that in tomato, in comparison to current methods, picking 4 fruit per cycle will increase production rate by 17%, leaf removal from the fruit area will increase production rate by 14.4%—up to 40.2%—and the best trellising angle with respect to yield and labour will be 30°. Analysis of biomechanical risk showed that the maximum weight of lifted boxes should not exceed 12 kg, and when picking fruit growing low to the ground, the workers are exposed to medium to high risk of injury.

1. Introduction

Agricultural productivity has increased significantly over the years as a result of mechanisation and automation. However, due to task complexity, manual labour remains a major and essential part of greenhouse-growing and specialty crops. Labour is the largest single cost contributor in agriculture (Bechar & Eben-Chaime, 2014) and the main limiting factor to development of the agricultural industry in both the western world and developing countries. Shortages in the labour force impair farm revenue, yield and durability. Further, the impermanent nature of the labour force reduces production capability and quality. In an early survey performed during

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the mid-1970s, bedding-plant growers attributed about 25% of plant production costs to labour (Aldrich & Bartok, 1992). Nelson (1991) estimated the labour contribution to total production costs at 34.81%, including 5.58% depreciation and 2.5% interest. In greenhouse crops, labour is a key factor to consider, in developing and maintaining profitability and economic survivability (Manzano-Agugliaro & Garcia-Cruz, 2009). In Southern Spain, the labour cost for greenhouse crops such as tomato, lettuce, pepper, melon, watermelon, zucchini, cucumber and bean is 36–40% of the total cost (Manzano-Agugliaro & Canero-Leon, 2010; Montoya-Garcia, Callejon-Ferre, Perez-Alonso, & Sanchez-Hermosilla, 2013). Despite differences and large variability in absolute magnitudes, labour contributes about 40% of the operational costs in greenhouse crops (Bechar & Eben-Chaime, 2014). Moreover, the enormous labour force required for the various operations causes bottlenecks that downgrade productivity—reducing yield and increasing costs.

Despite recent technological developments and deployment of automation and machinery, specialty crop production in greenhouses is still labour-intensive due to task complexity. In Israel, annual labour for the harvesting and trellising stages of tomato and bell pepper for fresh produce markets is 300–600 worker-day ha^{-1} (Hadas, Gal, Litvich, & Ronen, 2010). Together, the trellising and harvesting stages account for 50% of the total number of work days invested in the product (Bechar, Yosef, Netanyahu, & Edan, 2007). This high manual labour requirement impedes cost reduction and improvements in work efficiency.

One way to improve the efficiency of work processes is to use tools and methodologies from industrial engineering, such as work studies, methods engineering and layouts by means of task allocation techniques, development and assimilation of assisting tools and machinery. In recent years, dedicated simulation tools and labour management algorithms for greenhouse environments were also developed to improve operational performance (Bechar et al., 2007; van't Ooster, Bontsema, van Henten, & Hemming, 2014; van 't Ooster, Bontsema, van Henten, & Hemming, 2015). This can increase productivity with relatively low investment in infrastructures.

In addition to the labour cost, musculoskeletal injuries have been found to be prevalent during manual work processes performed in agricultural environments (e.g. Das & Gangopadhyay, 2015; Hildebrandt, 1995; Lee, Tak, Alterman, & Calvert, 2014; McMillan et al., 2015). Moreover, a study conducted in the Netherlands on 12 agricultural crops found the highest injury rate with greenhouse specialty crops (Hildebrandt, 1995). Such injuries can reduce production rate and result in lost working days (Meyers et al., 2004). Several studies have found that the manual tasks in vegetable growing, such as planting, carrying, weeding and box lifting, call for high levels of physical effort that may cause musculoskeletal disorders (Cavaletto, Miles, Meyers, & Mehlschau, 1994; Meyers et al., 1997; Nag, 1998; Van Dieën, Jansen, & Housheer, 1997). However, most of the studies showing risks are based on self-report questionnaires (Lee et al., 2014; Palmer, 1996; Tiwari & Gite, 2002); only a few of them have characterised and evaluated biomechanical and physiological workloads in a field study of specialty-crop tasks (Cavaletto et al., 1994; Meyers et al., 2004; Tuure, 1992). Another factor that can create a physical load is environmental conditions (McArdle, Katch, & Katch, 2001), which can alter task performance (e.g., Vickroy, Shaw, & Fisher, 1982).

Work-method analysis is a commonly employed technique to improve production and operations management (Globerson, 2002). It is essential to determine standard times for greenhouse production systems and for methods such as trellising and harvesting, to enable efficient labour management (Luxhoj & Giacomelli, 1990). Luxhoj and Giacomelli (1990) compared several labour standards for application in a greenhouse tomato production system: the Maynard Operations Sequence Technique (MOST, Zandin, 2002), Element Times for Agriculture (ETA), and direct time studies. They found direct measurement to be preferable in field operations.

Here we integrate work-study techniques with environmental and meteorological data and physiological and biomechanics measurements to improve work efficiency and productivity, and to identify tasks that can cause musculoskeletal disorders.

2. Methods

2.1. Measuring system and tools

To enable analysis that integrates the manufacturing, biomechanics, workload and environmental data of agricultural processes, an innovative measuring system was developed (Bechar & Ronen, 2010). All system components were used simultaneously in all the experiments and it consists of four devices: i) a work-study device – an IPAQ 1930 hand-held computer (HHC) platform with dedicated software using C# developed by Bechar and Eben-Chaime (2014); ii) an environmental and meteorological device – HOBO platform capable of measuring temperature and relative humidity (RH); iii) a video recorder, and iv) a physiological measurement device intended to measure the overall work load by measuring heart rate during task performance.

The physiological workload was evaluated by measuring the workers' pulse with Polar 625 and Polar S810i pulse watches (Oulu, Finland). The watches consist of a chest belt including a transmitter and a watch that records the pulse measured by the chest belt. The sampling rate was 0.2 Hz. The worker wears the devices while performing the job. The pulse data are exported in a file to the PC station.

All devices data was synchronised and integrated into a single database using a PC. The data from the devices were synchronised with the work-study measurements based on the devices time stamps. To do so at the beginning of the experiment we ensure that the clocks of all the devices have the same time. The worker wore the pulse watch and the chest belt, the HOBO platform recorded the environmental and meteorological data and the surveyor conducted a time study of the worker performing the task or process under examination. System tests indicated that the actual system resolution is between 3 and 5 s mainly due to the time resolution of the surveyor conducting the time measurements with the work-study device (a diagram of the system is shown in Fig. 1).

A descriptive statistical analysis was performed on each work element, including number of samples, minimum, maximum, average and standard deviation of the element time, coefficient of variation value, required sample size, and the element's total time as a percentage of total working time. Based on this, the process production rate was calculated, integrated and synchronised with the Excel sheet (Table 1).

In addition, the manual force used by the workers during lifting, pushing and pulling operations was measured by a digital force meter SH-500 (Series 4 Ltd., Hampshire, UK). The palm compressive force was measured by a Takei 5001 analogue dynamometer (Niigata, Japan). In the force-measurement procedures, the workloads were characterised as the average maximal force in 10 repetitions of each operation.

2.2. Work studies

The research was conducted on bell pepper crops and three types of tomato crops: single, cluster and cherry tomatoes. The terms single, cherry and cluster tomato refers to the product type and to the way tomatoes are picked. Single tomato is usually a large tomato that picked one by one; cherry tomato is usually a small tomato that picked in clusters of usually 8–12 fruits and not one by one; cluster tomato is a middle size tomato picked in clusters of usually 4–6 fruits. Work studies were performed on trellising and harvesting processes in tomato, and on the harvesting process in pepper, in the years 2011–2013.

Work studies were performed by means of direct measurements using a hand-held computer and the dedicated application developed by Bechar and Eben-Chaime (2014). In the direct measurement method, each process was divided into work elements, and the performance time of each work element was measured. For each process and working technique, the measurements were repeated 50 to 3800 times. A total of about 55,000 measurements were obtained during the study. The measurements were performed for 4 months of each year during most of the trellising and harvesting period to characterise the differences resulting from changes in environmental conditions, such as temperature and RH, and changes in the crop. To calculate the working time, the performances of two to six workers in each working process and technique were analysed.

2.3. Data analysis

Since the variation is naturally high in agricultural processes, outlier data were included in the analyses of work-study data, because removing them would change the true distribution and impair the veracity of the measurements. In contrast, for the heart-rate data, outlier data and the first 2 min of measurements were disregarded in the analysis, because this was found to be the time needed for signal stabilisation. The work-study analysis outcomes were standard times, yield, workload and environmental conditions. In the analysis, the data from the work study, environmental conditions and heart rate were integrated to determine the influence of the work element on the worker's workload.

Evaluations of biomechanical workloads on the musculoskeletal system were performed by common methods of direct task observation. Five workload-evaluation methods were found suitable: i) OWAS – based on whole-body postures sampled during the performance of a task (Karhu, Kansi, & Kuorinka, 1977); OWAS also takes into account the frequency and forces involved in the task; ii) NIOSH – a method for quantifying the mass that can be safely lifted based on parameters describing the lift (height, mass, etc.) and on the body posture during the lift (Waters, Putzanderson, Garg, & Fine, 1993); iii) REBA – based on whole-body postures sampled during the performance of a task (Hignett & McAtamney, 2000); iv) strain index – used to estimate risk of injury to the wrists and hands, based on the applied force's frequency, repetition, posture and ratio between the total

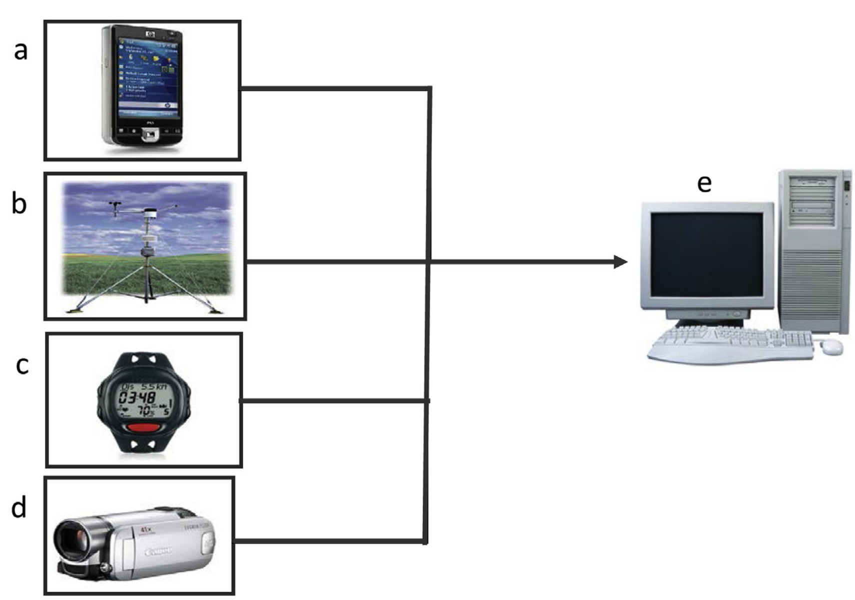

Fig. 1 – Diagram of the measurement system a) hand-held computer; b) environmental and meteorological device; c) Polar pulse watches; d) video recorder and e) synchronised to a single database using a PC.

Table 1 – An example of synchronised data from the work-study software, the pulse watch, the HOBO platform and the calculated production rate.

Time	Production rate (unit min^{-1})	Heart rate (Pulse min^{-1})	Temperature (°C)	Relative humidity (%)	Radiation (W m^{-2})
08:29	8	80.0	26.7	70.3	145.6
08:30	9	79.5	26.7	70.3	145.6
08:31	11	71.5	26.7	70.3	145.6
08:32	10	84.3	26.7	70.3	145.6
08:33	12	89.0	26.7	70.3	145.6
08:34	13	79.0	26.8	70.6	150.4
08:35	16	82.8	26.9	70.9	155.1
08:36	9	67.8	27.0	71.2	159.9
08:37	9	75.8	27.0	71.5	164.6
08:38	7	85.3	27.1	71.8	169.4
08:39	7	85.0	27.1	72.3	168.1
08:40	8	79.8	27.1	72.8	166.9
08:41	15	80.5	27.1	73.3	165.6
08:42	14	78.5	27.1	73.8	164.4
08:43	14	79.3	27.1	74.3	163.1
08:44	13	78.3	27.2	73.0	161.4
08:45	15	79.5	27.3	71.7	159.6
08:46	12	82.3	27.4	70.4	157.9
08:47	10	89.3	27.4	69.1	156.1

work time and the total duration of the specific task (Moore & Garg, 1995); v) Snook tables – the "Liberty Mutual Manual Materials Handling Tables", also known as the Snook tables, provide the percentage of females and males that are capable of performing manual material-handling tasks (lifting, pulling, pushing, lowering) without overexerting themselves (Snook, 1978; Snook & Ciriello, 1991).

In this study, the NIOSH method was used to analyse workloads caused by lifting weights. The REBA, OWAS and strain index methods were used to evaluate different exertion operations, and the Snook table method was used for lifting, lowering, pulling and pushing operations. Part of the evaluation was conducted with ErgoFellow software by FBF Sistemas Ltd. (Cruzeiro Belo Horizonte, Brazil), which combines several evaluation methods to reduce occupational risks and increase productivity.

2.4. *Farm data*

Data were collected at two locations: a research and development (R&D) facility and a modern farm in southwest Israel. The R&D facility included 3 ha of tomato and pepper greenhouses. The modern farm included 2.4 ha of tomato in two greenhouses, each divided into four plots. In both locations, the greenhouses were operated for one or two growing cycles annually.

Work studies were performed in greenhouses of 0.2–1.2 ha. The distance between tomato rows was 1.3 m, and 1.5 m for pepper rows. The spacing between plants within rows was 0.5 m for tomato and 0.35–0.4 m for pepper. The average yield for pepper and tomato was 135 and 220 t ha^{-1}, respectively.

The trellising operation, which includes trimming the plants and wrapping each plant top around the trellising rope, was performed once or twice a week. The trellising period began 2 weeks after planting and lasted 60 days in the summer and 100 days in the winter.

Harvesting was performed every 1–2 weeks for 2–6 months. The workers picked the fruit either singly or in clusters, depending on the cultivar and market demand, and placed them in plastic boxes, carried on a cart.

2.5. *Tomato growing angle experiment*

After 2 years, based on our previous findings, we performed an experiment to examine a novel tomato-growing method with angular trellising, which reduces manual labour overload and risk of injury, and increases productivity and yield. The experiment was conducted on a greenhouse tomato plot and consisted of three treatments, in which the plants were trellised at different angle (measured as elevation from horizontal): 90°—the common trellising angle (control), and 30° and 60°. Each treatment consisted of six 30-m long garden beds. The experiment was performed over one growing season, and had as dependent variables work-study data, work-element time and crop yield.

3. Results

3.1. *Work study*

3.1.1. *Pepper*

At the pepper-harvesting stage, 12 work elements were defined: 1–3) three fruit-picking elements, designated according to fruit height (low, middle and high, Fig. 2); 4) in-row movement with the cart; 5) turning from one row into another at the end of each row; 6) looking for fruit to be picked; 7) arranging the fruits in a box; 8) uploading boxes to the in-row cart; 9) downloading boxes from the in-row cart; 10) uploading boxes to the towed cart; 11) idle element; 12) null.

Table 2 presents the descriptive statistics for the work elements at the harvesting stage. The productive work (fruit-picking) elements comprise about 50% of the total working

Fig. 2 – Fruit-picking heights. (a) low; (b) middle; (c) high.

time. The average element time for picking a fruit is 4.2 s. Moving along the row takes 13.8% of the total working time, searching for fruit to be picked, 10.6%, and transporting the fruit away from the row about 7% of the total working time. A statistical analysis using least significant difference (LSD) test was conducted on elements of the three fruit-picking heights. The average time for the 'high' fruit-picking element, which requires lifting the arm above shoulder height and stretching for the fruit, was significantly ($p < 0.01$) longer, by 32%, than when the picking operation required bending of the back or knees and picking at a height between shoulder and hips ('low' and 'middle' height elements, respectively). There was no significant difference between the average times for the 'low' and 'middle' height elements. The element of searching for fruit to be picked has high variance and depends on the crop state and harvesting time. In a plant bearing many fruits, the average searching time will be low.

3.1.2. *Tomato*

At the trellising stage, the main work elements are trimming the side branches, wrapping the plant top around the trellising rope and moving with the in-row cart along the row, together making up about 86% of the total working time.

At the harvesting stage, the main work elements are fruit picking and placing them in a box—about 60% of the total working time. The fruit-picking operation is divided into two elements: picking from the upper part and lower part of the plant. Transporting the picked tomato boxes away from the rows to the towed cart requires 20% of the total time. Pushing the in-row cart during the movement in the row takes 8.4% of the total time. The last two are considered to be high biomechanics workloads and will be discussed and analysed further on.

Figure 3 presents the average picking times for different fruit heights of cluster, cherry and single tomatoes. In all cultivars, the tomato-picking times from the lower part of the plant were significantly longer ($p < 0.05$) than from the upper part, by 108, 11 and 27% for single, cherry and cluster tomatoes, respectively. The term 'low' represents fruit at a height of 0–30 cm above the ground for all three tomato cultivars. 'High' represents fruit at a height of 30–60 cm above the ground for cherry and cluster tomatoes and 60–120 cm above the ground for single tomato. The difference in height between single to cherry and cluster tomatoes is due to the plants' physiology and agrotechnical factors.

3.1.2.1. *Number of picked tomatoes in each cycle experiment.* During the harvesting of single tomatoes, the worker picks tomatoes and puts them in a box on the in-row cart. In each 'picking element', the worker picks several tomatoes, holds them in his/her hands and then puts them in the box. An experiment was conducted with six workers on 2700 tomatoes

Table 2 – Summary and descriptive statistics for the work elements at the pepper-harvesting stage.

	Mean [s]	Std. [s]	Min. [s]	Max. [s]	N	Total time [s]	% Total time	Production rate (fruit h^{-1})	Total yield (fruit h^{-1})
Fruit picking 'high'	5	2.9	1	24	1532	7616	16.10	724	437
Fruit picking 'low'	3.8	2.2	1	24	1145	4348	9.20	948	
Fruit picking 'middle'	3.8	2.3	1	19	3069	11,742	24.80	940	
In-row movement	6.8	7	1	59	964	6558	13.80		
Between-row movement	27.1	16.1	4	83	90	2437	5.10		
Fruit locating	6.7	3.7	1	26	752	5023	10.60		
Fruit arranging	10.8	7.8	2	57	139	1496	3.20		
In-row uploading	23.7	31.4	2	168	97	2300	4.90		
In-row downloading	19.4	14.1	2	58	54	1045	2.20		
Towed cart uploading	191.6	114.4	70	475	17	3257	6.90		
Idle	59.3	97.9	2	362	21	1246	2.60		
Null	27.9	12.1	10	56	11	307	0.60		

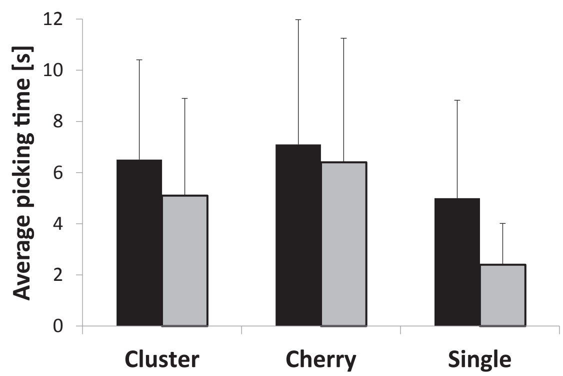

Fig. 3 – Average picking times for different fruit heights of cluster, cherry and single tomatoes. Error bars represent standard deviations. The black columns represents fruit at low height and the grey columns represents high fruit.

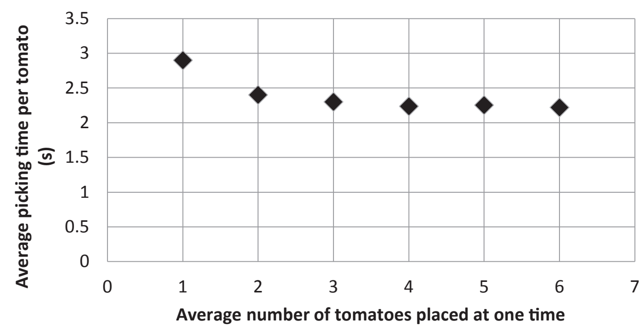

Fig. 4 – Average picking time per tomato for different numbers of tomatoes placed in the box at one time.

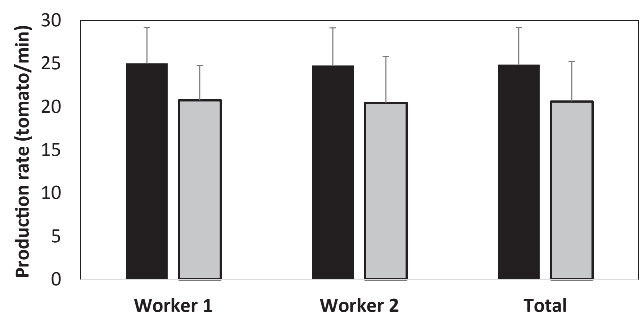

Fig. 5 – Production rate of the two examined methods. The current method (grey columns) had no restrictions or constraints; the alternative method consisted of picking exactly 4 tomatoes each time (black columns). Error bars represent standard deviation.

to examine the relationship between the number of picked tomatoes and picking time. In each 'picking element', the number of tomatoes and the time taken to pick them were measured and the production rate was calculated. On average, in each 'picking cycle', the workers put 2.24 tomatoes in the box.

Table 3 shows the descriptive statistics of each worker in the experiment and the differences between them.

Further, a relationship was found between the number of tomatoes the worker picked each time (the number of tomatoes picked in each 'picking element') and the picking time and production rate. Analysis of the time required to pick different numbers of tomatoes per picking cycle indicated that picking time per tomato decreases with increasing number of tomatoes per picking cycle up to 4 tomatoes per cycle. For numbers above 4 tomatoes, the improvement in picking time per tomato is minimal. Therefore, the practical minimum picking time per tomato was set to 4 tomatoes per picking cycle (and putting all 4 tomatoes in the box at once), and it was 11% lower than the current picking time per tomato (Fig. 4). In addition, a theoretical analysis of the influence of picking time on the entire process was performed. Reducing the picking time per tomato will reduce the total time taken to perform the transportation elements to the towed cart, and the total time to harvest will be reduced by 16.5% for a single row and by 13.15% for a work day.

To verify the theoretical analysis, a second experiment was conducted with two workers on 3618 tomatoes to compare two working methods: i) the current method with no restrictions or constraints (control), and ii) an alternative method in which the workers were instructed to pick exactly 4 tomatoes each time. A two way ANOVA with significance level of 0.01 was conducted. The results showed that the working method type is highly significant ($p < 0.001$) meaning that there is a statistical significant difference in the picking times between the two methods. The worker 'type' and the interaction of the worker*method was found to be not significant, meaning that there is no significant difference between the picking time of the two workers. It was found that in the alternative method, the worker yield was 17% higher than in the current method ($p < 0.001$). Figure 5 shows the production rates for the two workers and the two methods.

Table 3 – Results of the tomato-picking experiments. The tomato number represents the average number of tomatoes picked and placed in a box per picking cycle.

Worker	N	Average fruit number per picking cycle	S.D. of fruit number	Average picking time per fruit (s)	Yield (fruit h^{-1})
1	537	1.69	1.03	2.51	744
2	403	1.94	1.14	2.32	867
3	758	2.21	1.28	2.54	928
4	451	2.48	1.74	2.10	1064
5	262	2.79	1.29	1.98	1223
6	318	2.79	1.33	1.92	1240
Total	2729	2.24	1.36	2.23	1011

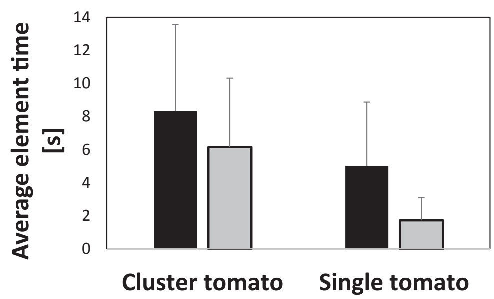

Fig. 6 – Average picking times for visible (grey columns) and non-visible (black columns) fruit of cluster and single tomatoes. Error bars represent standard deviation.

3.1.2.2. *Fruit visibility*. The influence of visually exposing fruits on picking time was examined on the picking of 'low' single and cherry tomatoes. In a prior operation, fruits were visually exposed by removing leaves from the fruit area. The analysis was conducted on 1046 units of single tomatoes and 358 clusters of cluster tomatoes. The mean time of the picking element was found to be significantly reduced ($p < 0.05$) by 26% (to 6.15 s) with single tomatoes (Fig. 6) and by 65% (to 1.73 s) with cluster tomatoes. Since this work element is dominant for both single and cluster tomatoes, the production rate increased by 14.4% and 40.2%, respectively.

3.2. *Environmental conditions*

The influence of temperature on production rate at the harvesting stage was examined for both peppers and tomatoes. Temperature had a significant and similar effect on production rate ($p < 0.01$) for pepper, single tomato and cluster tomato, albeit with low correlation coefficients of 0.25, 0.29 and 0.36, respectively. In pepper, the average production rate at 17 °C was 53% higher than at 29 °C. In cluster tomatoes, a 1 °C increase in temperature reduced production rate by an average 19 clusters, and the average production rate at 12 °C was 65% higher than at 26 °C (Fig. 7).

In single tomatoes, a 1 °C increase in temperature reduced the production rate by an average 1.22 tomato min^{-1}. The results are given in two separate graphs (Fig. 8) because measurements were performed in two seasons and on different plots with different temperature ranges.

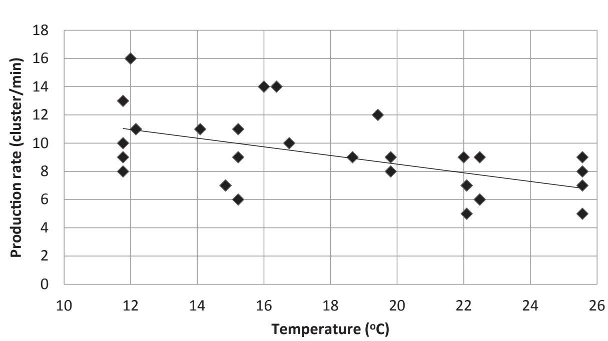

Fig. 7 – Influence of temperature on production rate in cluster tomatoes. The line represents linear regression equation with R2 = 0.29.

The influence of RH on production rate of single tomatoes at the harvesting stage was also examined. An increase in RH in the range of 58–92% caused a significant increase in the workers' yield ($p < 0.01$). A 1% increase in RH reflected, on average, an increase of 0.34 tomato min^{-1} in workers' yield. The results are given in two separate graphs because measurements were performed on two plots and in two seasons (Fig. 9).

Since RH is influenced by temperature (usually when the temperature increases the RH decreases and vice versa), an analysis of the influence of the heat load index, which combines temperature, RH was performed for single tomatoes. True heat index calculation is complex and take in to account many parameters such as dimensions of a human, activity, clothing resistance to heat transfer and more (Steadman, 1979).

However in order to use a more conventional parameter, Rothfusz (1990) develop a regression equation for heat index based on the temperate and the RH which are commonly used today in heat index tables and heat load calculators.

The temperature, RH data comprising the heat load index were measured by the HOBO meteorological station and the heat load index was calculated using the 'heat load calculator' at the National Weather Service website. Figure 10 shows the correlation between production rate and heat load index consisting of data from four measurement days in two seasons and five workers. Heat load index had a significant effect on workers' yield ($p < 0.05$) for the two ranges (two seasons). An increase in heat load index resulted in a reduction in production rate.

3.3. *Biomechanics and workload analyses*

Biomechanics and workload analyses were performed on several working tasks using NIOSH, REBA, OWAS, strain index and Snook table methods.

3.3.1. *Harvesting methods in peppers*

Two methods were examined for harvesting of 'middle' and 'high' pepper fruit: i) the workers picked a fruit using pruning shears; ii) the workers picked the fruit using bare hands. In the second method, the fruit-picking element was significantly ($p < 0.05$) shorter (by 18%) and the production rate was 16% higher (non-significant) than in the first method for fruits located in the middle and upper parts of the plant (Fig. 11).

Next, the biomechanical loads on the workers using both methods were investigated. In the first pepper-harvesting method, the workload was examined with new (sharp blade) and used pruning shears (they are replaced once every few months). The workload was calculated with the strain index method. The maximum force applied by the worker on the pruning-shear handles was recorded with the force meter. The experiment, conducted on three workers, consisted of three treatments: i) picking fruit with new pruning shears; ii) picking fruit with used pruning shears; iii) picking fruit by hand. In each treatment, each worker picked 10 fruits. The required force to pick a fruit was similar when using new or old pruning shears and both were 17% lower than when using bare hands (Table 4). However, the strain index score for using shears was 1.125 and for picking fruit by hand, 3.375, both of which are considered low risk for injury to the

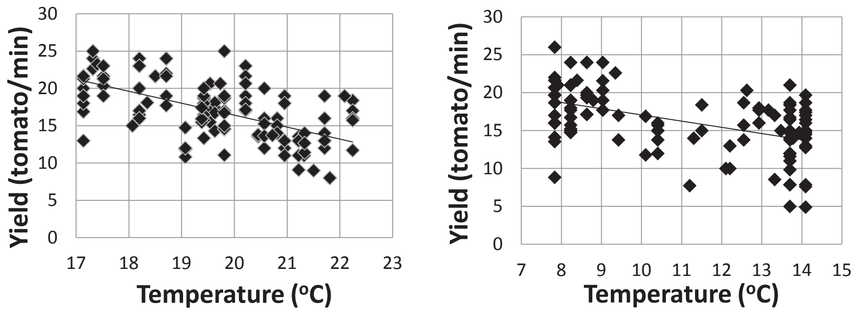

Fig. 8 – Influence of temperature on workers' yield from harvesting single tomatoes. The lines represents linear regression equation with R2 of 0.36 (left) and 0.25 (right).

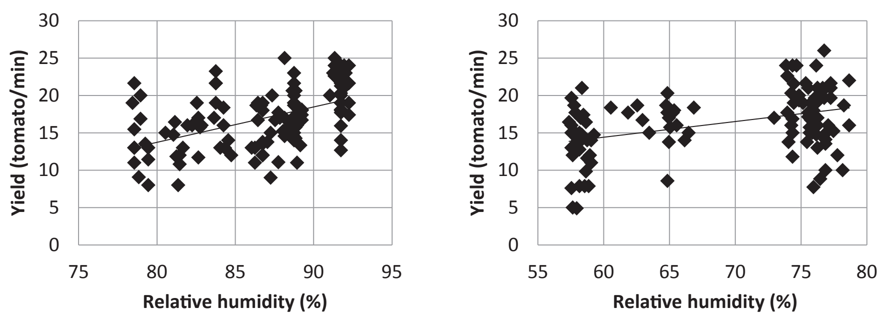

Fig. 9 – Influence of relative humidity on workers' yield from harvesting single tomatoes. The lines represents linear regression equation with R2 of 0.25 (left) and 0.17 (right).

musculoskeletal system. Although the average picking time was better with bare hands, pruning shears are preferred due to longer shelf life and for agronomic reasons.

3.3.2. *The loading process*

In tomatoes, the pace for loading boxes from the in-row cart onto the towed cart is 6–7 lifts per minute. In each lift, one or two boxes are lifted. The worker lifts the box to a height of 40 cm above the starting point, thus limiting, based on NIOSH, the maximum lift weight to 8.88 kg. Therefore, it is recommended to lift one box at a time and to limit the box size to 9 kg.

The loading processes for pepper and tomato are performed similarly. The load on the workers during box loading was examined by the NIOSH method. Worker movement during this process is minimal since the worker is positioned close to the towed cart and lifts the boxes onto it. On the towed cart, the boxes are arranged one on top of the other in formation of four boxes (4 boxes are arranged one on top of the other). The boxes are loaded from two types of in-row carts: i) 12-box cart, where the boxes are in a 3 × 4 (row × height) arrangement; ii) 8-box cart in a 2 × 4 arrangement. The towed cart platform is at a height of 0.89 m above the ground. Average and maximum box weights are 8 and 10.5 kg, respectively. Box dimensions are: 0.18 × 0.54 × 0.32 m (H × L × W). In each cycle, the worker loads between 1 and 3 boxes onto the towed cart. Four cases were studied using the NIOSH method: i) loading 1 box at a time from a 12-box cart to the towed cart; ii) loading 1 box at a time from an 8-box cart to the towed cart; iii) loading 2 boxes

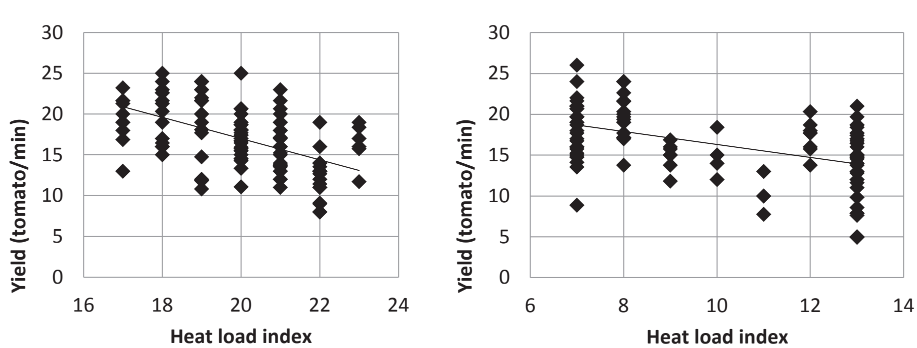

Fig. 10 – Influence of heat load index on workers' yield from harvesting single tomatoes. The lines represents linear regression equation with R2 of 0.28 (left) and 0.25 (right).

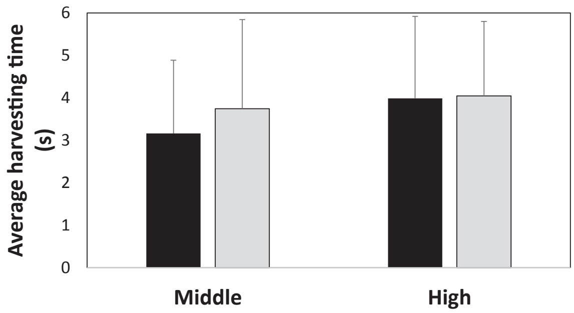

Fig. 11 – Average picking times of peppers located in the middle and high parts of the plant by two picking methods: by hand (black columns) and with pruning shears (grey columns). Error bars represents standard deviations.

at a time from the 12-box cart to the towed cart; iv) loading 2 boxes at a time from the 8-box cart to the towed cart. The composite lifting index (CLI) values of the NIOSH method for the four cases were 1.22, 1.26, 1.79 and 1.74, respectively. In all cases, the worker's physical effort was higher than recommended and in cases iii and iv, the physical effort might put the worker at risk of injury. A NIOSH CLI lower than 1 is designed to provide a safe working environment for 75% of the female and 99% of the male work force. In our case, all of the workers were males under the age of 40, therefore the four cases were also examined by Snook analysis (Snook & Ciriello, 1991). In this test, the permissible weight for 75% of the male population was 12 kg. Based on the two analyses, it is not recommended to lift more than one box at a time with a maximum weight of 12 kg. In addition, based on the Snook analysis, it was found that once the boxes have been loaded onto the towing cart, the worker should not push more than 3 boxes at a time.

3.3.3. *Pushing in-row cart for tomatoes*

Pushing in-row carts is a common procedure at the tomato-harvesting stage. For an in-row cart with 1 and 6 boxes, the required pushing force is 4.5 and 13 kg, respectively. The weight of 1 box averages12.5 kg. Snook table and strain index tests showed that in these cases, the worker is not at risk. However, according to the OWAS method, the posture of the worker while pushing the cart calls for immediate correction.

3.3.4. *Worker posture during the tomato-trellising process*

During the trellising stage, the worker stands on the ground or on a cart at a height of 65 cm above the ground. His or her

Table 4 – Workloads of fruit-picking action.

	Required force (N)	Required force from maximum (%)	Level	Score
New pruning shears	35.3	8.8	Light	1
Old pruning shears	35.4	8.8	Light	1
Bare hands	42.2	10.6	Somewhat hard	3

shoulders are at 90° or more about 75% of the time and in some cases, the upper body is bent at up to 60°;toward the plant (Fig. 12). Using REBA and strain index tests, it was found that working under these conditions involves medium risk.

3.3.5. *Worker posture during tomato-harvesting process*

The harvesting process was divided into two heights, each causing the worker to use different movement strategies for harvesting.

When the fruit were at low heights (Fig. 13), the worker used two techniques and body postures for this task: the first was bending his back, the second a kneeling posture. Using the REBA method, it was found that the back technique exposes the user to high risk of injury and the kneeling technique to medium risk (to the back in the first and to the knees in the second). These findings were also aligned with Jin, McCulloch, and Mirka (2009), who studied bush crop biomechanics. Considering the time required for picking, it was found that the kneeling technique was slower (5 s) than the back-bending technique (2.4 s).

Analysis of the working techniques and body postures used while picking tomatoes located in the 'high' parts of the plant using REBA revealed low risk of injury (Fig. 13c).

3.4. *Growing angle experiment*

Work-study measurements were conducted for the trellising, plant-lowering and leaf-removal processes for the three growing angles (Table 5). Plant lowering operation is performed when the plant reaches a certain height (a lowering height).

In the trellising process, the stages of plant-wrapping (on a rope hanging from above) and stem-removal work elements were analysed. The trellising angle had no significant effect on the wrapping-element time. However, a significant influence was found for the trellising angle on the stem-removal element ($p < 0.05$). This element time was 20% shorter with the 30° trellising than with the 60° and 90° trellising.

Analysis of the plant-lowering process showed a significant effect ($p < 0.05$) of trellising angle on lowering time. For plant lowering, the shortest time was achieved at a 90° (7.04 s on average) and the longest time with 60° (29.8 s in average). However, since the number of times that this operation is performed during the growing period is smaller at 30° than at 90° (at 30° trellising, the plant takes longer to reach the lowering height than at 90° trellising), the difference was not significant.

Performance of the stem-removal element during the trellising process showed findings similar to those of the plant-lowering element during this process. The element time was 30% and 26% shorter with 30° trellising than with the 60° and 90° trellising, respectively. In the leaf-removal process, no significant difference was found in operation time for the three trellising angles.

Since the trellising process is performed on a weekly basis and constitutes the major work and the most time-consuming process in the greenhouse, weighing all work study findings showed a comprehensive advantage for the 30° trellising method.

Fig. 12 – Worker posture in trellising operation.

The yield mass was measured from a 2.28-m^2 plot for each of the three angle treatments during 16 harvesting days (from first to last) throughout the entire season. The yield level of the 90° trellising treatment (common trellising angle, control) was 35 kg, significantly lower than the yields of the 30° and 60° treatments (56 and 66 kg, respectively). Although the highest yield level was obtained with the 60° treatment, the difference from the 30° treatment yield level was not significant.

4. Conclusions

In planning and designing an agricultural workplace and process, it is important to achieve the highest production rate while maintaining the health of the workers. In agriculture, many work processes are not planned and executed in terms of optimal production rate and the worker's health. This paper presents an innovative analysis to improve work efficiency and productivity and to identify tasks that can cause musculoskeletal disorders and is a first step in the integration of the three influencing dimensions: work methods, environment and biomechanics on the productivity of agricultural processes.

The analysis consists of integrating work-study techniques, environmental and meteorological data, and physiological and biomechanics measurements. An innovative measuring system was developed, enabled synchronisation and analysis of the manufacturing, biomechanics, workload and environmental data of an agricultural process involving manual labour. Our study proves the applicability of advanced industrial engineering and biomechanics techniques for improvement of greenhouse pepper and tomato production. In addition, an experiment was conducted on greenhouse tomatoes during an entire growing season to determine the best trellising angle with respect to yield mass and the above-mentioned aspects. The time for the stem-removal element was found to be shorter with the 30° trellising angle. Plant-lowering time was shortest with the 90° trellising. However, since the number of applications in a season is higher at the latter trellising angle, there was no difference in total time during the season. Weighing all work-study findings showed a comprehensive advantage for the 30° trellising method. The yield weight at 30° and 60° trellising was higher than with the 90° trellising treatment.

At the harvesting stage for peppers and tomatoes, the productive work elements comprised about 50% and 60% of the total working time, respectively. At the trellising stage for tomatoes, the productive work elements comprised about 86% of the total working time. The temperature and heat load index had a significant effect on the production rate in pepper and tomato in the temperature range of 8–26 °C and heat index range of 7–23. The production rate decreased with increasing temperature and heat load index. Although we assumed that the heat index will predict better, this is not the case in this study as both the temperature and the heat index

Fig. 13 – Two body postures for the harvesting operation at low height (a and b) and body posture during high height operation (c).

Table 5 – Summary of process times for the three growing angles. The percentages represent the cumulative time of the element out of the total time of the process.

Process		Trellising				Plant lowering				Leaf removal	
Work element		Stem removal		Plant wrapping		Lowering		Stem removal		Leaf removal	
		t [s]	%	t [s]	%	t [s]	%	t [s]	%	t [s]	%
Angle	30	3.79	23	5.58	63	21.6	66	10.1	18	31.99	78
	60	4.74	37	5.53	49	29.8	70	14.5	20	32.18	97
	90	4.69	34	5.5	52	7	32	13.6	59	29.43	80
Application per season		25		25		1–4		1–4		2–3	
Recommended angle		30		–		90		30		–	

achieve similar results regarding the correlation coefficient R^2. Biomechanics and workload analyses were performed on several working tasks using NIOSH, REBA, OWAS, strain index and Snook table methods.

In light of these analyses, we recommend the following practices for greenhouse tomato- and pepper-growing processes:

- For single tomatoes, workers should pick 4 fruits per picking cycle. This will increase the production rate by 17% compared to the current tomato-picking method.
- For tomatoes, leaves from the fruit area should be removed to increase fruit visibility for the picker. This will reduce the picking-element time by 26% and 65% for single and cluster tomatoes, respectively, and increase the production rate by 14.4% and 40.2%, respectively.
- Peppers should be harvested using pruning shears. Although the picking work element with bare hands is significantly shorter (by 18%), pruning shears are preferred due to longer shelf life and for agronomic reasons.
- The maximum lifting weight of picked-fruit boxes should not exceed 12 kg, or 1 box at a time with current tomato and pepper methods.
- For trellising, it is recommended that the worker be elevated to change his or her posture and to reduce risk of injury. In the current method, the worker's shoulders are at 90° or more about 75% of the time and in some cases, the upper body is bent at up to 60° toward the plant. Working under these conditions causes medium injury risk.
- The best trellising angle with respect to yield mass and work-study findings is 30°.
- For tomato picking at low heights, the workers used two techniques—squatting and stooping, each putting a load on different body parts. While from a productivity point of view, stooping was found to be much faster, from a biomechanics point of view, it might be useful for the workers to alternate between the two techniques, thereby reducing risk of injury (Jin et al., 2009).

Future research will focus on combining the three dimensions or influencing measures into one methodology or tool to design an optimal agricultural workplace and process. It will combines both production and biomechanics performance measures using an optimization of the work environment and process to maximize the production rate while minimizing the biomechanical loads.

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