Decreasing the load on the lower back with an ergonomic cutting tool for harvesting oil palm bunches

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Abstract
Harvesting palm oil crops involve different risk factors that decrease workers' safety and physical integrity. This paper compares stress on the lower back when using the conventional tool and a new cutting system for cutting bunches. The biomechanical analysis is carried out using simulations generated by JACK Siemens software. The study found a 95.97% reduction of intradiscal compression (L4/L5) when cutting bunches and showed that pressure on all joints was reduced, in certain cases, such as the back and elbow, by up to 100%. That is, when cutting using the new system, the worker maintains a neutral posture of the spine. The new design comprises a point of support on which the tool rests and means that workers only have to direct the blade. Future studies should compare both tools in terms of productivity while preserving the ergonomic characteristics.

Keys words: biomechanica; agriculture; farmer; lower back pain; human simulation; ergonomics.

Reducción de la carga en espalda baja con una herramienta de corte ergonómica para el cultivo de aceite de palma

Resumen
En los cultivos de aceite de palma se presentan diferentes factores de riesgo que disminuyen la seguridad y la integridad física de los trabajadores. Este trabajo compara el estrés de la espalda baja durante el corte de racimos, entre la herramienta convencional y un nuevo sistema de corte, a partir de un análisis biomecánico utilizando Jack Siemens. El estudio encontró una reducción del 95.97% en la compresión intradiscal (L4/L5) durante la actividad de corte. Asimismo, el estudió muestra que se disminuyó las demandas articulares, en la espalda y codo hasta en un 100%, es decir, que durante la actividad con el nuevo sistema diseñado, el agricultor mantiene una postura de espalda neutral. Este nuevo diseño consta de un punto de apoyo, en donde la herramienta descansa y por tanto, solo se debe dar dirección al corte. Los estudios futuros deberían comparar ambas herramientas en términos de productividad, pero conservando las características ergonómicas.

Palabras clave: biomecánica; agricultura; campesinos; dolor lumbar; simulación humana; ergonomía.

1. Introduction

Oil palm is a perennial tree that produces between three and four fresh fruit bunches weighing between 20 and 25 kg each harvest season, which takes place roughly three times per year during its 25 year life service. Although the tree continues to produce bunches beyond this service, the palm is cut down because its height impedes access to the fruit. The oil extracted from this palm is mainly used in the production of cleaning products, high energy fats for consumption, bio-fuels and vegetable and animal food, it is estimated that palm oil is used to make 10% of dairy based products [1]. In recent years, this plant has gained popularity among farmers because the production of oil per hectare is higher for oil palm than soy or canola, additionally oil palm needs less energy and chemicals to produce more oil than its counterparts.

Colombia is the fourth largest producer of raw palm oil, while Latin America is the world's highest producer of this substance. These types of crops necessitate a large workforce

to cover as much land as possible and to avoid excessive ripening. In 2008, the palm oil industry created 140,000 jobs, an increase of 93% from previous years; 72% of these jobs were linked to Associated Work Cooperatives (CTA) and Strategic Productive Alliances (APE) while the remaining 28% were contracts for processing and administrative activities. However, the industry depends on various different factors, and so a constant income is not guaranteed. For this reason, life insurance, tools and transport costs are usually assumed by the employee [2].

The harvesting of oil palm crops involve different risk factors that decrease workers' safety and physical integrity. Most of these factors result from the palm's physical form; features such as its height, being from two to twelve meters, and its leaves that are surrounded by crowns of thorns make it difficult to access the bunches. These circumstances force workers to adopt inappropriate postures and to make repetitive movements with their upper and lower limbs over the course of their work activities and in most of these cases this postural behavior causes pain in the lower back and neck, as well as in upper and lower limbs [3].

Harvesting and pruning are carried out using two types of tools; both of which constitute a long handle attached to a blade. The tool varies depending on the shape of the knife blade, the Malaysian knife is a sickle used for palm over 4 m in height and the Malaysian pole is a chisel used for palm of less than 4 m tall. Advances have been made in this field, but have prioritized enhancing productivity over the health of the user. Accordingly, the use of motorized tools has been proposed in order to reduce task duration, however, these machines follow the same formal principle which causes an increase in the momentum that workers' bodies have to deal with. This is due to the length of the handle on which the load (the blade) is placed, as well as the way this has to be maneuvered to cut down the bunches.

Hence, the aim of this paper is to compare the stress to the lower back when cutting bunches with the conventional tool and a new cutting tool proposed using a biomechanical analysis simulated in JACK Siemens. The jack static strength prediction calculates the moments and the lumbar static compression of the intradiscal (L5/S1), it also estimates the muscular force necessary to lift or carry loads, based on the Chaffin equation [3,4]. This equation calculates an estimation of the load on an intervertebral disk, considering factors such as weight, posture and the distance over which the load is lifted.

2. Materials and methods

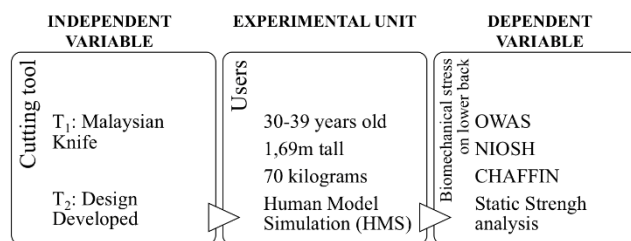Fig. 1 shows a diagram of the experiment.

Figure 1. Experiment diagram.
Source: The authors.

2.1. Independent variable

The experiment is designed as a single factor study, the single factor designated factor A "Tool". The experiment presents two treatments:

2.1.1. Malaysian knife

(Fig. 2) is a tool commonly used for pruning oil palm leaves or harvesting oil palm bunches, it is composed of a sickle-shaped knife attached to two or more rods which increase its length, and it weighs between 5 and 6 kilograms. The Malaysian knife can reach bunches and leaves from 4 to 12 m high.

2.1.2. The new proposed cutting tool (Cutting System)

Is based on the anthropometry measurements of males between 30 and 39 years old. Consequently, the tool has a height of 1.1 m which matches the distance from the elbow to the ground (A). It has two handles with a diameter of 4 cm which are separated by the bi-acromial distance (C); the first handle is placed at 25.1 cm from the body according to the length of the forearm, and is used to raise the rods. The second handle is pulled back, to make the chopping action (Fig. 3).

These treatments were analyzed on three levels. These correlate with each moment in which the measurement was taken, the first when the operator is carrying the tool, designated 0º, the second when the operator raises the tool at 70º and finally when the operator starts to pull on the tool, named 70º + force (Fig. 4).
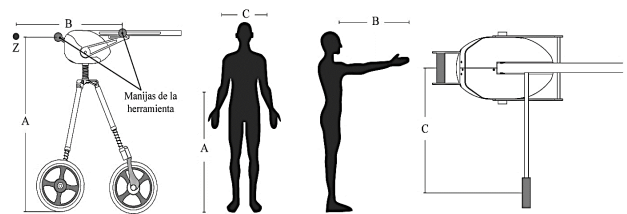

Figure 2. Malaysian knife
Source: The authors

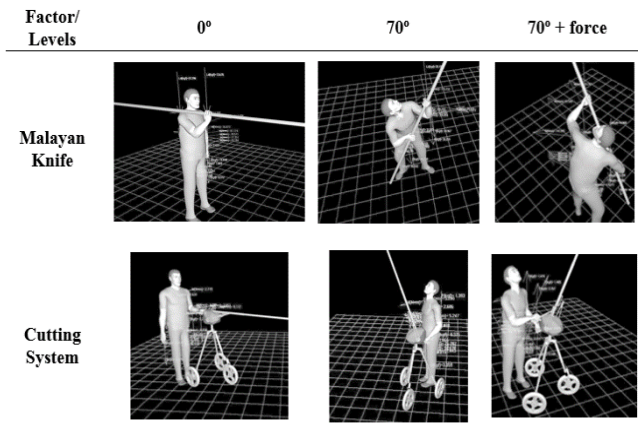Figure 3. Oil palm cutting tool.
Source: The authors.

Figure 4. Treatment levels for each measurement.
Source: The authors

2.2. Dependent variable

The dependent variable considers biomechanical stress on the lower back in terms of reaction forces (kgf) and rotational moments (Nm). These were studied with Lower Back Pain (LBP) analysis using the virtual simulation Software JACK Siemens and the Chaffin equation.

2.2.1. Description of the procedure

Biomechanical stress was measured by studying the corporal positions of the extremities while workers are using each tool. In the case of the Malaysian knife, four different videos were filmed while the worker used it to harvest oil palm bunches, the videos were then imported into the free software Kinovea (https://www.kinovea.org/), and there a measurement of the angles between limbs and corporal planes was carried out over a period of between 2 and 3 minutes, which is roughly 5 photograms per second. The static load on each hand is determined using a free body diagram of the Malaysian knife with two support points (Fig. 5).

In the case of the Cutting System, the posture used is shown in Figs. 4 and 6. The weight of the complete tool was measured using material selection analysis followed by the ASHBY methodology [5], taking into account the indices of low weight and high strain resistance. With this information, it was possible to establish a free body diagram of the operators using this artifact, and determine the loads on workers' hands.

These results are translated into reaction forces and the rotational moments on each articulation using a Human Model Simulation (HMS). The experimental unit is a male between 30 and 39 years old, 1.69 m tall and weighing 70 kilograms, in accordance with the 50th percentile of the Colombian population [6,7]. This information was used to generate a human model using the virtual simulation Software JACK Siemens and the Chaffin equation (1). The results of both procedures are compared to determine the validity of the results. In addition, OWAS and NIOSH procedures are carried out to analyze the completed task.

Figure 5. Angles of limbs while workers use the Malaysian knife
Source: The authors

$$\sum T = (W * L_W) + (P * L_P) - (M * L_M) = 0 \qquad (1)$$

W= weight of trunk, head, neck and arms
L_W=Distance from the center of gravity of grouped trunk, head, neck and arms to vertebral unit L5/S1
P= Weight of the load
L_P= Distance from load's center of gravity to vertebral unit L5/S1
M= Force that lumbar muscles must to exert to maintain the position
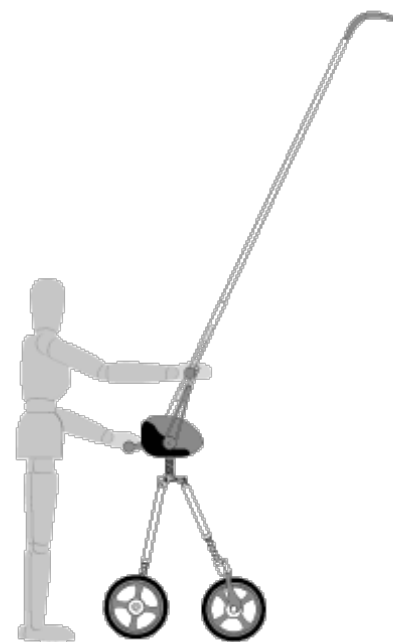L_M=Distance from insertion point of lumbar muscles to vertebral unit L5/S1.

Figure 6. Body posture while worker uses Cutting System
Source: The authors

3. Results

3.1. Postures

The results of the observational analysis of the Malaysian knife using the Kinovea software are shown in Table 1. Arm joints are specified as EA and FA, the arm represented by A, while E corresponds to the extended arm while F to the flexed arm. This distinction is important due to the fact that workers use the tool differently according to their dominant hand. Additionally, it is important to note that the last two postures (in the last two columns of Table 1) show the same quantities. This is because the only difference between them is the pulling force performed for the chopping action.

An ergonomic and biomechanical movement analysis of workers during task performance is used to determine their posture when using the Cutting System (Fig. 7). Each point represents a joint, in this sense H, C, M, and D represent Shoulder, Elbow, Wrist, and Finger distal point respectively. Angle values are shown in Table 2. In this case the suffixes EA and PA correspond to the Elevated arm (in charge of raising the cutting knife) and the Pulling Arm (in charge of performing the cutting task) respectively.

3.2. Hand loads

In the case of the Malaysian knife, the forces that affect each hand, F_{h1} and F_{h2}, were determined based on the Free Body Diagram (Fig. 8).

In Fig. 8, part A shows that FH and Fh2 correspond to the points where workers usually grip this tool while they carry it (0º position). FH is a reaction of 219,6 N generated by the shoulder where users support the tool as they transport it, while Fh2 is a force of 134.1 N performed by the hand to keep

Table 1.
Angles of joints during harvesting task using Malaysian knife.

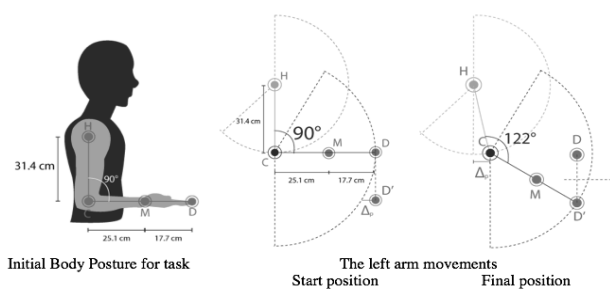| Joints	0°	70°	70°+Force
Neck	0°	33.25°	33.25°
Back	0°	15.75°	15.75°
Shoulder (EA)	56.68°	135°	135°
Shoulder (FA)	0°	89.5°	89.5°
Elbow (EA)	101.6°	20.75°	20.75°
Elbow (FA)	0°	101.75°	101.75°

Source: The authors

Figure 7. Biomechanical Movement Synthesis. Harvesting task using the Cutting System with the Elevated Arm.
Source: The authors

Table 2.
Joint angles during the harvesting task using Cutting System

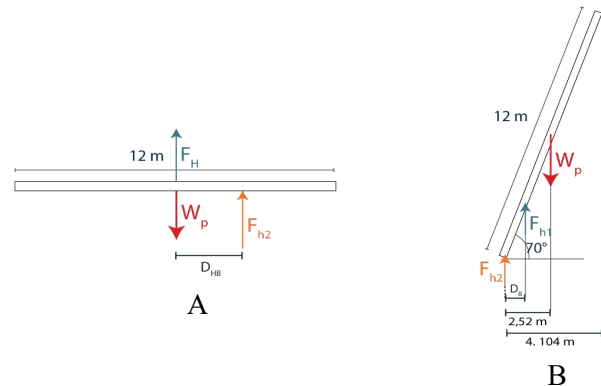| Joints	0°	70°	70°+Force
Neck	0°	30°	30°
Back	0°	0°	0°
Shoulder (EA)	0°	90°	90°
Shoulder (FA)	0°	11.34°	11.34°
Elbow (EA)	0°	0°	0°
Elbow (FA)	90°	122°	122°

Source: The authors

Figure 8. Free Body Diagram while Malaysian Knife is used
Source: The authors

the tool in position. The DHB is a distance of 45.9 cm measured from shoulder to the hand in this position, this dimension is calculated based on limb length and limb angles (Fig. 8). Part B shows the moment when users raise the Malaysian knife up to a 70º angle, like in part A, F_{h1} of 440 N corresponds to the force of the hand which is placed further up the handle, while F_{h2} of 345 N is the reaction generated on the hand nearer to the operator's body.

In the case of the Cutting System, the complete weight of the tool was determined using the ASHBY methodology, and as a result, aluminum 5083 H16 was chosen as the material for the structural parts of the tool with an estimated weight of 20 kg. However, as the design is not going to be supported by the body, that is, the workers just have to push the handles for the system to move freely, in this analysis only two forces were considered. The first force elevates the rods and the second force pulls and generates the chopping motion. Taking this into account, these forces were determined according to the minimum value for repetitive work; 3 kg for the hand that performs the elevation and 18.04 N [8] for the hand that executes the pulling action, these figures are outlined in the AFNOR NF X 35 – 106 guidelines developed in France.

3.3. Biomechanical simulation

The biomechanical analysis developed using the JACK Siemens determined the reaction on each joint while the worker uses each tool across the three different moments. The important values in the study are those which give information about the behavior of the spine, precisely, from vertebra L1 to L5. This information is presented in Table 3 for the Malaysian Knife and Table 4 for the Cutting System; both compression forces and rotational moments are shown.

Table 3.
Reactions and Moments of joints during the use of the Malaysian knife

Malaysian knife			
Joint	0°	70°	70° + Force
	F (kgf)	F (kgf)	F (kgf)
Vertebra L5L4	72,2097	116,1854	114,5916
Vertebra L4L3	70,4452	114,4209	112,8272
Vertebra L3L2	67,7187	111,6945	110,1008
Vertebra L2L1	65,7888	109,7646	108,1710
Left shoulder	3,4312	38,6114	48,2987
Right shoulder	17,1071	48,2987	37,0250
Right Elbow	15,3408	46,5324	35,2593
Right wrist	14,0477	45,2393	45,2393
Left Elbow	1,6649	36,8451	46,5324
Left Wrist	0,3718	35,5520	33,9667

Source: The authors

Table 4.
Reactions and moments of joints during the use of the Cutting System

Cutting System			
Joint	0°	70°	70° + Force
	F(Kgf)	F(Kgf)	F(Kgf)
Vertebra L3L2	29.1530	26.2869	26.3521
Vertebra L2L1	27.1373	28.1719	24.4676
Left shoulder	1.6525	0.375	0.294
Right shoulder	2.8632	3.4342	1.7828
Right Elbow	1.4446	1.6662	0.5747
Right wrist	0.3496	0.3734	1.4851
Left Elbow	1.9913	1.3929	1.474
Left Wrist	2.7596	2.6858	2.7669

Source: The authors

Additionally, the Chaffin equation was used to verify the values obtained from the Virtual simulation. The biomechanical model was developed based on the 0º posture (Fig. 9), calculated with equation 1 (the Chaffin equation). The compression force on vertebra L4/L5 is 3.486 kgf which could be consider similar to the results obtained with JACK's simulation where this value is 72.2097 kgf.

3.4. NIOSH analysis

The NIOSH method [9] establishes three limits for back compression: the first is below 3400 N and work in this category is considered safe; the second limit is between 3400
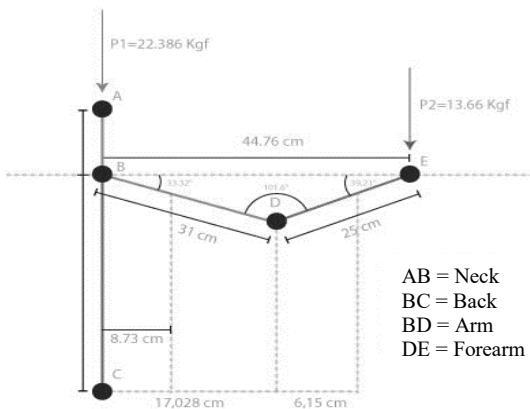

Figure 9. 0° Posture to establish Chaffin's equation
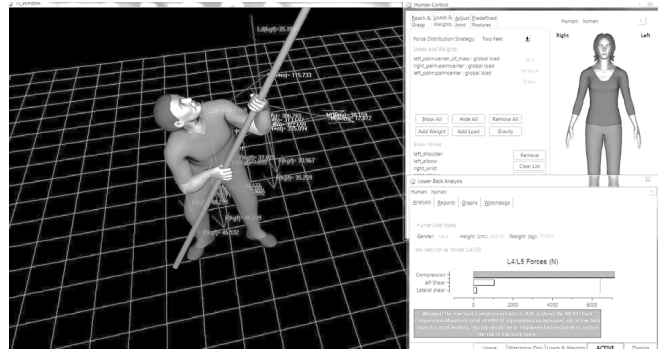Source: The authors

Figure 10. NIOSH analysis for 70° posture
Source: The authors

N and 6400 N and is characterized as a medium risk activity; any activity above this upper limit presents a greater risk of developing musculoskeletal disorders.

This analysis showed that using the Malaysian Knife generates more compression for postures at 70º (Fig. 10) and at 70º + force; its values are 7685 N and 8385 N respectively, however, the 0º posture generates 2443 N for back compression. On the other hand, the analysis of the Cutting System showed that each posture generated forces of below 3400 N, in this sense, the 0º, 70º and 70º + force postures present back compressions of 409 N, 440 N and 338 N respectively.

3.5. OWAS analysis

Ovako Working Analysis System (OWAS) [10] showed an increase in risk for workers when using a Malaysian Knife to perform pruning or harvesting tasks (Fig. 11). The 70º and 70º + force postures were categorized as medium and high risk tasks, this means that the activity requires intervention and a corrective method as these postures overload the musculoskeletal system.
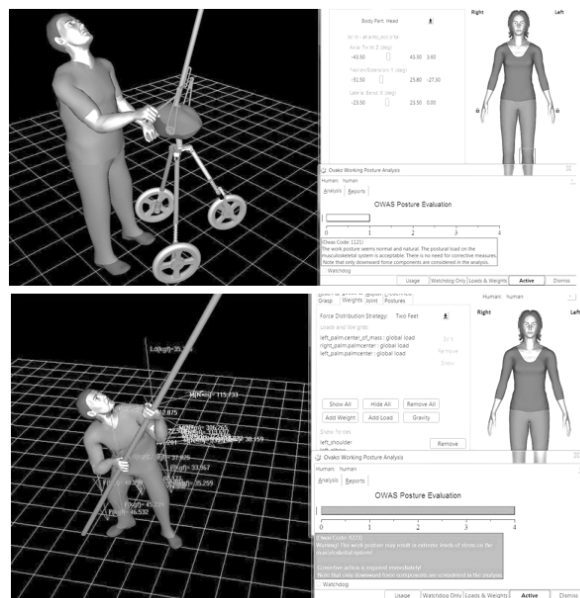

Figure 11. OWAS analysis Malaysian Knife case study
Source: The authors

However, the 0º posture does not present risk for operators and is placed within first category; the work posture seems natural and there is no need to take corrective measures.

4. Discussion

The aim of this article was to compare the Malaysian knife and a newly designed Cutting System in terms of biomechanical stress to the lower back. The preliminary analysis established that harvesting of palm bunches is one of the principal causes of musculoskeletal disorder in workers. The mass center of the complete system (composed of the worker and tool) is outside of the operator's body and the lower back becomes the support point for both user and tool. At the same time, the dimensions of the tool increase the lower back rotational moment due to its length. One of the main factors associated with lower lumbar pain is the horizontal distance between the joint center (in this case L5/S1) and the load being lifted or carried [9,11]. The biomechanical models show that in vertebral discs the moment is directly proportional to distance, this means that if the horizontal distance increases, the moment increases.

For the Cutting System, the three postures taken for its use (Fig. 11) were placed within the first category, and thus there is no overload of the musculoskeletal system due to the natural stance of the postures.

Most of the tools developed in this industry have been focused mainly on improving productivity, intending for operators to reap more bunches in less time. However, this developmental approach does not guarantee the user's safety, while the scientific literature shows that the upper limbs and lower back are the principal body parts affected by the harvesting or pruning tasks in oil palm mills [12-14].

Although the causes of lower back pain can be multifactorial, different authors have shown that there is an association between lower back pain and the biomechanical load, when the load imposed on tissue exceeds the tissue tolerance [15] Therefore, activities such as manual lifting tasks [16,17] and heavy physical load [18,19], have been identified as risky. Based on this, here the research shows that the load on the worker's body is decreased when using the new cutting tool proposed. This mechanical design has a new support point on which the tool rests, and so users only have direct the cutting tool.

When examining the intradiscal load, a difference was found between the conventional tool and the cutting system. The study found a 95.97% reduction of intradiscal compression (L4/L5) when farmers cut off bunches (corresponding to the posture 70° + force), similarly, in the same postural condition, a reduction was observed in all reactions of each joint. Thus, NIOSH analysis showed that workers using the Malaysian knife are exposed to a higher risk factor for developing musculoskeletal disorders than if they were to use the Cutting System. These results are consistent with previous studies that suggest a high prevalence of musculoskeletal pain, and other factors associated with it, from agricultural activities [20-22], due to a high workload. These findings included harvesting tasks on oil palm plantations [3,23].

Furthermore, poor posture of the trunk is also associated with lower back pain, due to the flexion applying more load on the spine than in a neutral posture [24,25]. OWAS analysis shows that posture plays an important role during harvesting and pruning tasks. The category of postural risk fell within level 1 when the worker used the new cutting system designed for the task of cutting off bunches (at posture 70° + force). Similarly, the study shows that all body joint angles were reduced, in certain cases, such as for the back and elbow, by up to 100%. This is due to the fact that when the worker cut off bunches with the new system, their back posture was neutral. These results and the OWAS analysis confirm that the posture adopted during the use of the Malaysian knife is high risk for developing musculoskeletal disorders and there is an urgent need for intervention. Furthermore, the same analysis for the Cutting System did not show risks and the postures were qualified as normal and natural. Therefore, when the worker used the new Cutting System, the intradiscal load was low and the worker maintained a neutral posture, this explains the results found in this study.

Finally, according to [3], the traditional method increases the possibility of developing musculoskeletal disorders mostly in the upper part of the body due to inappropriate postures adopted during harvesting, in this way the aches and pains suffered by workers reduces their productivity during the workday. While the conventional system continues to operate, injuries to the lower back will not disappear because the workers' posture is a factor that influences the development of these disorders.

5. Conclusions

This study proposes a new cutting system for harvesting tasks at oil palm plantations. This Cutting Tool allows workers to complete the task without the risk of developing musculoskeletal disorders, because the weight of the tool is supported by an external structure. At the same time, it offers workers a complete transportation system which makes it easy to maneuver the tool inside of oil palm mills and it presents a wider range of cutting motions from a specific position.

Workers' welfare plays an important role in productive development, for this reason future research should focus on the design of tools with ergonomic characteristics and user centered research. Likewise, future studies should compare both tools in terms of their productivity, that is, the number of bunches harvested per hour.

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