ADVANCES IN AGRICULTURAL AND FOOD RESEARCH JOURNAL

Original Research Article

Preliminary Assessment of Exoskeleton Suit Assistance for Fresh Fruit Bunch (FFB) Collection Task in Oil Palm Plantation

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Abstract: Exoskeletons have been widely used in rehabilitation and heavy work. The concept of exoskeleton technology showed encouraging results in helping to reduce workload and limb movements. Exoskeleton worn on the upper or lower limbs is seen to increase workers' productivity when used in agriculture. A preliminary capability evaluation on the current active exoskeleton suit (CAE) was explored and observed by implementing Fresh Fruits Bunch (FFB) collections. The CAE suit assisted significant lower-part body motions when the worker lifted the FFB, especially movements of the lower extremity, which posed a threat of hyperextension, including the knee, hip, and back. Another concern that needed attention is that the assisted lower back body could not stand independently while bearing the stress from the upper limbs. Joint motions that risk hyperflexion, such as shoulders and elbows, must be protected from injury while carrying the FFB loads. Results showed that the CAE used did not significantly support complete muscle activities when workers performed lifting of FFB. In addition, the lower back body assisted by the CAE suit could not stand on its own while continuing to bear the stress from the upper limbs, which may be harmed without any assistance and support. Hence, the exoskeleton suits must protect joint motions that pose a risk of hyperflexion, such as shoulders and elbows, while carrying the FFB loads.

Keywords: body joint motion; upper and lower body; limb movement; FFB loading; exoskeleton

Received: 31st March 2022

Received in revised form: 10th November 2022

Available Online: 30th November 2022

Published: 26th December 2022

Citation: Md Radzi, M. K. F. Preliminary assessment of exoskeleton suit assistance for Fresh Fruit Bunch (FFB) collection task in oil palm plantation. *Adv Agri Food Res J* 2022; 3(2): a0000313. https://doi.org/10.36877/aafrj.a0000313

1. Introduction`

Fresh Fruit Bunch (FFB) loading activities in oil palm plantations are one of the most hazardous agricultural tasks. In estates, traumatic injuries such as sprains (stretching or ripping of ligaments) and strains (stretching or tearing of muscles or tendons) are common accidents faced by workers. These injuries, known as musculoskeletal disorders (MSDs), are caused by ergonomic risk factors that stress the human body and lead to muscle, tendons, ligaments, and joint damage. Prolonged or repetitive bending and movements in lifting and carrying heavy objects lead MSD sufferers to a lower quality of life, reduced work productivity, and chronic disability (Bhuanantanondh *et al*., 2021).

Major labor-intensive activities in upstream palm oil production, such as Fresh Fruit Bunch (FFB) loading and lose fruit (LF) collections, need forceful exertion and involve awkward postures. Harvest collector walks from tree to tree to collect the detached FFB on the ground using a sharp metal skewer and carries them on their shoulders or loads the FFB onto a wheelbarrow. The weight of a single FFB might range from 30 kg to 50 kg, contributing to ergonomic risk factors in the work environment. Moreover, collectors performed LF collection in a crouched position to ease the sweeping and loading into a bucket or bin. Both preliminary works of FFB and LF collection exposed the workers to heavy lifting tasks, pushing and pulling in awkward postures within repetitive motions.

1.1. Exoskeleton Functional System

A novel solution to lower the aforementioned physical risk factors is the exoskeleton, which has recently attracted widespread interest for its ability to provide postural support while improving the workers' physical capabilities. An exoskeleton is a wearable structure worn by the operator and matches the shape and functions of the human body. It can improve human limbs' operations and treat weak, ineffective, or injured muscles, joints, or skeletal parts caused by disease or neurological conditions. The exoskeleton works mechanically in parallel with the human body and can be passively or actively actuated according to its power sources. The active exoskeleton comprises one or more actuators and energy devices that can help the human body move more efficiently. A passive exoskeleton utilizes gas springs or other energy-storing materials to support and help users' movement by the mechanical structure to overcome the energy loss in the exoskeleton's movement. Figure 1 illustrates the most common active and passive applications of back-support exoskeletons (lower limb) and upper limb exoskeletons designed to assist lower back pain and upper body joints, respectively (Theurel & Desbrosses, 2019).

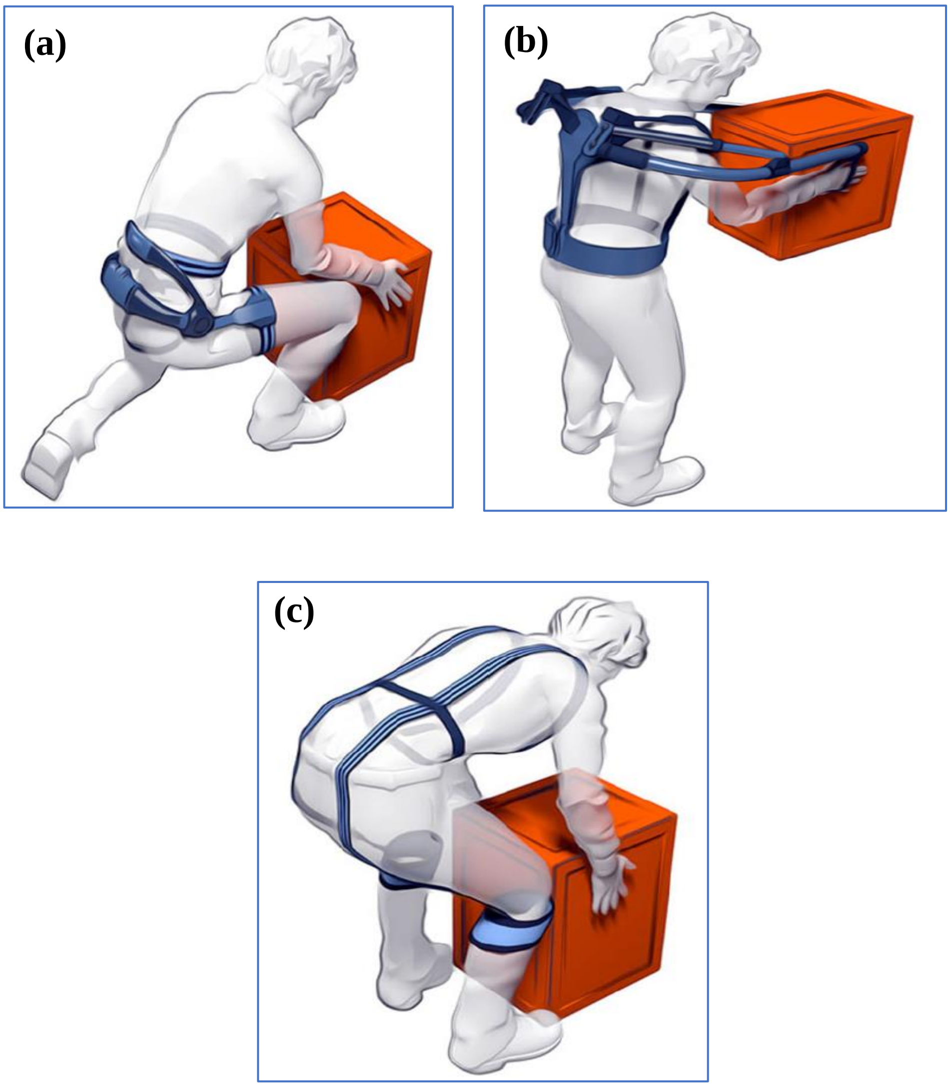

Figure 1. Illustration of the support system of (**a**) Active exoskeleton for lower limbs supports, (**b**) Active exoskeleton for upper limbs support, (**c**) Passive exoskeleton for both lower and upper body (whole body) support.

Generally, exoskeletons can be classified into three broad types based on their intended use. The first category is human efficiency enhancement exoskeletons which attempt to maximize non-disabled individuals' durability, stamina, and other physical qualities. Exoskeletons that have been enhanced may assist in lifting heavy items, hauling heavy loads over long distances, or managing heavy tools. The manufacturing industry requires a support system for repetitive manual tasks such as cement laying, frame cutting, part handling, manual screw tightening, surface grinding of parts, and floor leveling. Several exoskeleton systems are used in various industries, including shipbuilding, automotive, agricultural, and aerospace manufacturing, to relieve physical workload during standing and squatting work (Hwang *et al*., 2021; Yan *et al*., 2021).

The second application of the exoskeleton is haptic interactions that include assistive devices for patients with mobility problems due to stroke, spinal cord injury, or muscle weakness. These exosuits are more likely to be found in manufacturing facilities, development sites, emergency response functions, military bases, and adventure activities. Related commercial exoskeletons have been introduced and assessed in helping patients' mobility and rehabilitation, as well as military applications that allow soldiers to carry heavy equipment while marching fast in hazardous terrain.

The third broad group is therapeutic exoskeletons, which are used for medical and rehabilitation purposes. Exoskeletons for restoration have been created for a variety of applications. They are used in either the lower or upper limbs for gait rehabilitation. Medical exoskeletons are a type of robotic medical equipment categorized in this group which is intended to assist physically impaired, injured, or weak individuals who cannot walk owing to a range of medical conditions such as spinal cord injury, neurological illnesses, catastrophic trauma such as stroke, or cerebral palsy.

1.2. Applications of Exoskeleton

Research on exoskeletons is now being adopted in various sectors, including medicine and engineering. Current active and passive commercial exoskeletons that have been explored concerning end-users for lower-body and upper-body according to applications and needs are listed in Table 1.

Table 1. Active and passive exoskeletons for the lower- and upper body.

Exoskeleton Name	**Exoskeleton type**	**Support Structural**	**Assisted Task**	**Reference**
IPAE	Passive (full-body)	Back support, elastic waist units, leg supports, hooks, shoulder straps, and waist straps	Lifting work	(Qu *et al*., 2021)
PAEXO	Passive (upper-limb)	Support structure with an expander that connected to the upper arm by an arm brace and a hip belt	Overhead work activities	(Schmalz *et al*., 2019)
ShoulderX (SuitX)	Passive (upper-limb)	The designed actuator provides a supporting torque profile that mimics the angle-dependent torque about the shoulder due to gravitational forces	Overhead work activities	(Engelhoven *et al*., 2019)
HAL	Active (lower-limb)	Exoskeletal frames and power units on bilateral hip joints	Snow shoveling	(Miura *et al*., 2018)

An exoskeleton system might be a feasible option in supporting the operation of oil palm plantations. However, report on exoskeletons used in agricultural task is limited. Therefore, the objective of this project was to evaluate the functions of commercial lower-limb exoskeleton suits in assisting lower muscles' activity of loaders during FFB collection. Observations were carried out in an oil palm plantation in Peninsular Malaysia.

2. Materials and Methods

2.1. Active Exoskeleton Suit

Current commercial active exoskeleton (CAE) for lower back support was used in this field trial. The CAE comprises exoskeletal frames and power units (battery-driven) that are fixed to the wearer’s back body and hip joints, respectively. CAE was used to test and observe the hypothesis that the exoskeleton might reduce back pain during repetitive collection movements. Figure 2 and Table 2 show the CAE device model and general specification information about the device’s functional used in this trial work, respectively.

Figure 2. Example model of current Commercial Active Exoskeleton (CAE)

Table 2. Specified information of CAE.

Exoskeleton Name	Support Structural
Applicable range of wearer’s height	140 cm – 180 cm
Applicable range of wearer’s weight	40 kg – 80 kg
External dimension	Length (depth) 292 mm x width 450 mm x height 522 mm
Weight	3.0 kg (including a battery)
Power source	custom battery
Drive time	4.5 hours
Charging time	2 hours
Operating environment	40℃

2.2. Participant and Demographic Background

In this study, a worker who had experience in palm plantation and was regularly assigned to Fresh Fruit Bunch (FFB) collection activity will be observed. This activity was carried out at an oil palm plantation located in Teluk Intan, Perak, Malaysia. Table 3 shows the details about the field demographic and worker background involved.

Table 3. Worker and demographic characteristics

Worker background	
Age (years old)	30
Gender	Male
Body weight (kg)	66
Height (cm)	171
Field demographic	
Plot area involved	Ten hectors
Palm age (years)	15
Palm count	1200
FFB weight	10-12 kg

2.3. Examination of Posture and Body Position

In this fieldwork, workers performed their regular tasks in the early morning with and without wearing the exoskeleton suit. The collector would start by walking from each palm tree to collect the detached FFB on the ground using a sharp metal skewer. Then, the FFB will be carried on the shoulder and loaded onto a wheelbarrow trailer. **S**ignificant primary muscle and joint motions were determined through posture and body position identification. Assuming the worker was energetic in the early morning, the collector would begin the task without wearing the suit.

2.4. Metabolic Parameters Analysis

The Smartwatch data logger is worn on the wrist and functions as a detector to record the heart rate profile of workers during FFB collection with and without the exoskeleton. The worker was allowed 30 minutes of the break for recovery before starting a new task to stabilize the heart rate. Then, the heartbeat data with time intervals were downloaded for analysis. One-way analysis of variance (ANOVA) was used to determine the significant differences between the average heart rate responses with and without using the exoskeleton suit. The value of the degree of freedom (DOF), F-statistic, and P-value were calculated. To determine the significant responses, the importance of the F-statistic must be higher than F-critical in the distribution table, which is 3.55 at a 95% confidence interval. The F-critical value can be defined by referring to the *f* distribution table at a 95% of confidence level, i.e., $F_{0.05}(f_1,f_2)$. The numerator, f_1, is the degree of freedom for a response, and the denominator, f_2, is the deviation of the DOF. The F-statistic can be calculated using equation 1:

$$\boldsymbol{F_{statistic}} = \frac{\boldsymbol{Mean\ square, MS\ (between\ respons)}}{\boldsymbol{Mean\ square, MS\ (within\ respons)}} \quad (1)$$

3. Results and Discussions

3.1 Significant Parts and Joints Affected

Figure 3 shows the posture and position of the worker’s body during the lifting task. This part of the evaluation included manual visual observation of the FFB collection video recordings. Based on the statement, four main posture steps support the body limb when attempting to lift heavy bunches. Firstly, lifting the FFB using a metal skewer from the ground with a hand required the comfortable position of the legs (Posture 1). The strong legs will set the stable hands' posture angle to hook the FFB (Posture 2). The collector can be seen flexing his back, slightly bending his knee into a squat stance, and maintaining this posture to lift FFB from the ground and hold it for a second before unloading it into the wheelbarrow (Posture 3). These significant primary motions are categorized into lower limbs part, which involves movements of knees, hip flexion, lumbar back bending, and rotation. In this scenario, the CAE exosuit slightly assisted some of the lower part's body motions when the worker lifted FFB.

The CAE exosuit did not significantly support upper limb muscles that make movements during unloading. Joints that pose stress risks, such as neck, shoulders, and elbows (Posture 4), must be protected from injury. This observation was reported by Tewtow *et al*. (2019) in their surveys, where 71.2% of harvesters complained about discomfort in the lower back body, followed by neck (63.5%), shoulders (59.6%), elbows (40.4%), and hands (40.4%). Additionally, shoulders and elbows risk hyperflexion, as excessive movement could injure opposing ligaments, tendons, and muscles (Syuaib, 2015).

Posture 1: Comfort position Posture 2: Hands posture angle

Posture 3: Squat position Posture 4: Shoulder and elbow suspension

Figure 3. Posture and position of worker's body during FFB collection

3.2 Exoskeleton Support Analysis

Figure 4 shows the heart rate profile of the worker during the FFB collection. There is no significant difference in the heart rate pattern with or without wearing the exoskeleton suit. The heart rate continued to increase even with the exoskeleton suit. This could be due to several factors that affect the heartbeat, such as a hot sunny day. The lower back body, assisted by the CAE suit, could not stand independently while continuing to bear the stress from the upper limbs, which otherwise may be harmed without assistance and support.

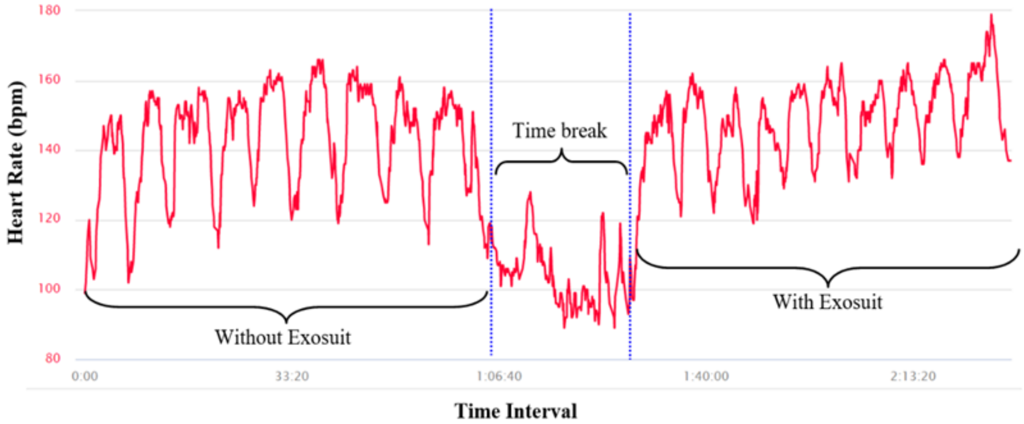

Figure 4. Heart rate profile of workers with and without exoskeleton suits during FFB collection.

Analysis of variance (ANOVA) verified that the exoskeleton used did not statistically support muscle activity when workers performed lifting tasks through calculated heart beats means value (Table 4 and Figure 4). The f-statistic value for the heartbeats responses is lower than F-critical, whereas P-value obtained was more significant than α = 0.05. The results concluded no significant difference in the mean value of heartbeats responses for both tasks.

Table 4. One-way ANOVA analysis of both responses with and without the exoskeleton suit.

Responses	Count	Sum	Average	Variance
Heart Rate without Exo	10	1528	152.8	375.0667
Heart Rate with Exo	10	1625	162.5	46.5

Source of Variation	SS	df	MS	F-statistic	P-value	F-critical
Between Responses	470.45	1	470.45	**2.231913**	0.15251	**4.413873**
Within Responses	3794.1	18	210.7833			
Total	4264.55	19				

*F-statistic < F-critical = no significant difference

4. Conclusions

Upper and lower back limbs were diagnosed as the major affected body parts due to repeated activities, twisting motion, poor posture, and overuse of muscles involved in the heavy task of oil palm plantation. Carrying and throwing tasks are common factors contributing to back pain and might cause injuries during heavy loads. The current active exoskeleton suit (CAE) used in this study did not significantly support full muscle activities when workers performed lifting of fresh fruit bunch (FFB). In addition, the lower back body assisted by the CAE suit could not stand on its own while continuing to bear the stress from the upper limbs, which may be harmed without any assistance and support. Hence, joint motions that pose a risk of hyperflexion such as shoulders and elbows need to be protected by the exoskeleton suits while carrying the FFB loads.

Acknowledgments: The authors express their sincere thanks and appreciation to the Director-General of the Malaysian Palm Oil Board (MPOB) for permission to publish this paper.

Conflicts of Interest: The authors declare no conflict of interest, and the funders had no role in the study's design, collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

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