Semarak Current Biomedical Technology Research Journal

Journal homepage:
https://semarakilmu.my/index.php/scbtrj/index
ISSN: 3030-5616

A Case Study on the Use of a Powered Exoskeleton for Oil Palm Harvesting

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ARTICLE INFO

Article history:
Received 20 December 2024
Received in revised form 25 March 2025
Accepted 2 April 2025
Available online 30 June 2025

Keywords:
Exoskeleton; muscle activity; oil palm; harvesting; performance; productivity

ABSTRACT

A worker's performance is affected by his physical fitness, environmental conditions, interaction with work tools and work postures. It is also recognized that fatigue can be indicated by physiological signals, such as muscle activity and heart rate. When harvesting oil palm trees, a worker needs to execute his tasks in challenging environmental conditions and poor ergonomic working condition, such as handling a long harvesting tool and performing repetitive motions for an extended duration. This study investigated the immediate effect of a prototype exoskeleton on harvesting workers, which aim to assist workers in handling the harvesting tool. The changes in selected upper limb muscle activities when performing the targeted tasks while using and not using the exoskeleton prototype was observed. Results indicated the activity of all observed muscles reduced when harvesting while wearing the exoskeleton. The average RMS improvement when using the exoskeleton for harvesting motion in all four muscles is approximately 22%.A full-scale field trial is necessary to evaluate the effects of the proposed solution toward workers' and harvesting productivity.

1. Introduction

According to the International Labour Organization (ILO), almost 2 million people die at work every year due to fatal work-related diseases, including musculoskeletal disorder (MSD), a type of occupational disease that results in injuries or pain in the musculoskeletal system such as joints, ligaments, muscles, structures that support limbs, neck and back [1]. MSD affects workers across all sectors, such as manufacturing, agriculture, construction, and retail, affecting companies' productivity and resulting in an estimated loss of USD45 – 54 billions each year. In the manufacturing

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https://doi.org/10.37934/scbtrj.5.1.110

industry, many processes and tasks are too complex to be done by robots or made fully automated. Human dexterity, cognitive judgement and flexibility are still more reliable than robots and allow quicker adjustment to workflow changes. MSD are exacerbated by highly repetitive tasks, working in a repetitive or sustained awkward position, continual forceful exertion of effort, and insufficient recovery time between movements. For example, car assembly workers may have to lift their arms approximately 4,600 times a day, i.e. 92,000 times a month and palm oil harvesters' work requires eccentric posture and hence its productivity is limited by the physical fitness of the harvester. Fatigue, mainly of muscle, is a major factor that would reduce manual workers' productivity [2,3].

This study aims to present a case study on the effects of a powered upper limb exoskeleton on selected muscle activities during overhead tasks during harvesting oil palm fresh fruit bunches (FFB).

2. Background

2.1 Oil Palm Harvesting Task

Harvesting of oil palm FFB uses about 60% of the workforce and accounts for 50% of the cost when operating an oil palm plantation [4]. Manual harvesting is still widely practised as it provides a wide range of manoeuvrability during harvesting. This is important due to the location of the FFB on the trunk of the tree and the arrangement of the fronds which restricts direct access to the FFB [2,5]. Unfortunately, since manual harvesting is laborious and requires eccentric posture, its productivity is limited by the physical fitness of the labourer. Fatigue is a major factor that would reduce labourers harvesting productivity [3]. To date, there is no commercially available exoskeleton to assist harvesting of oil palm trees.

One of the factors influencing the productivity of oil palm harvesters and maintenance workers is their physical fitness. For oil palm harvesters for example, it has been reported that fatigue affects their productivity [3]. Manual harvesting is still practised in the industry for different reasons, including lower cost compared to other alternatives, impossible to replicate human skills and capability, and challenging environmental conditions such as restricted space and unpredictable environment. When cutting trees that are more than 3 m tall, a pole with chisel is used. A harvester will handle the pole throughout the shift. A typical sequence of task include walking to the oil palm tree with the pole, scout for fruit bunches to be cut, aim the pole toward fruit bunch or frond and apply repeated push-pull motion of the pole to complete cutting [2,6]. It has been postulated that the dynamic push-pull motion applied on the pole is the most energy intensive task during harvesting [4]. A number of biomechanical investigations on harvesting, particularly the push-pull motion have been reported recently [7-10]. Both biomechanical and ergonomic investigations seem to agree that the shoulder and/or the trunk have been identified as joints requiring assistance for pole harvesting.

2.2 Occupational Exoskeletons

An exoskeleton is a wearable device that can augment human's physical performance or provide additional support to the human body [11,12]. Several studies have demonstrated exoskeleton systems designed for tasks in specific environments, including rehabilitation, manufacturing and strength training. A comprehensive list of industrial exoskeletons is available in [13,14]. Many commercially available industrial exoskeletons are passive exoskeleton with rigid structure due to more effective assistive force generation and transfer. Soft exoskeletons are typically active as it requires actuators to provide the assistive force. The need for a rigid vs soft, and active vs passive exoskeleton for task assistance depends very much on the work environment setting and the task itself [13]. The modelling and control of the exoskeleton closely resembles a pendulum system such as that studied in Rani *et al.,* [15]. Based on the oil palm plantation environment and laborious nature of harvesting, particularly the overhead task during pole handling, a powered upper limb exoskeleton was developed to assist the overhead task by reducing the load on the shoulder. The main objective of this project was to perform an initial investigation on the effects of a powered upper limb exoskeleton prototype on harvesters. More specifically, we would like to describe the difference in selected upper limb muscle activity when using and not using the prototype exoskeleton during harvesting.

3. Methodology

3.1 Research Design

A worker's performance is affected by his physical fitness, environmental conditions, interaction with work tools and work postures. It is postulated that fatigue could be indicated by numerous physiological signals, such as muscle activity and heart rate. Nevertheless, there are many factors contributing toward fatigue. In this study we aimed to look at the immediate effects of using the prototype exoskeleton by investigating the changes in certain muscle activity in users due to exoskeleton usage. Two sets of experiments were performed, lab and field trials. Muscle activity data and users' feedback were collected in both trials. The tasks undertaken by the participants in this study have been approved by the Ethics Committee for Research Involving Human Subjects Universiti Putra Malaysia (JKEUPM).

3.1.1 Study location and participant

The harvesting tasks experiment was performed at the Motion Analysis Lab, School of Biomedical Engineering and Health Sciences UTM Johor Bahru, and at an oil palm plantation estate belonging to Sime Darby Plantation in Kulai, Johor. Three physically healthy male participants (no stated muscle injuries or disorders in the last 12 months) participated in this study.

3.1.2 Exoskeleton design

The prototype, weighing approximately 3 kg, has been designed with the following criteria: (1) it supports a total of 12 kg external load, and (2) it does not interfere with the motion of the users. The maximum external load on the prototype that will cause its structure to deform permanently is 20 kg. The exoskeleton can be fully deactivated or put in a rest state when it is not in used by fully extending the arm downward. The design was analyzed using an engineering design software to ensure that the structure can withstand the loads and motions involved when carrying out the tasks. The exoskeleton was designed to accommodate users with 41 cm to 47 cm shoulder width and 48 cm to 54 cm shoulder width separately. The conceptual design and the CAD model of the upper limb exoskeleton are shown in Figure 1 to 3, and the prototype is shown in Figure 4. The system weighs about 4 kg and is made mainly of rattan, plastics and metal. The exoskeleton is a hybrid system, which combines both passive support (gravitational compensation through springs) and active actuation (through DC motor).

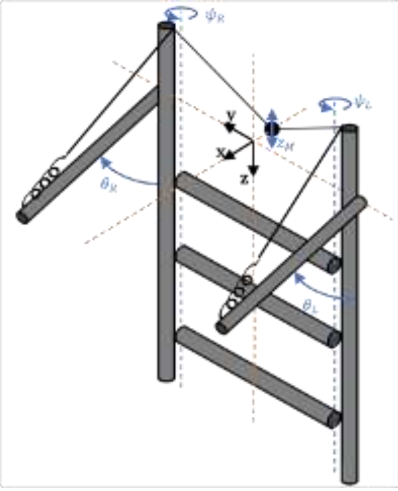

Fig. 1. Conceptual design of the proposed exoskeleton. Its range of motion is indicated by blue arrows and symbols

Fig. 2. The CAD model (solid) of the proposed exoskeleton. All electronic components are placed at the back plate (in green)

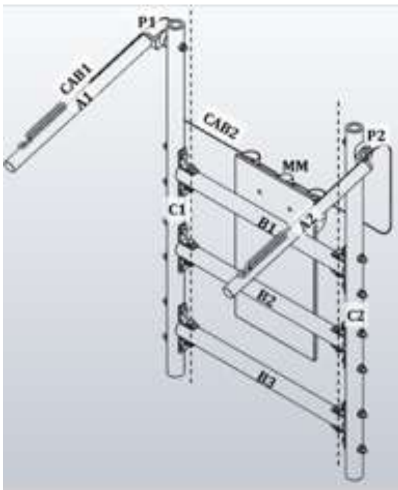

Fig. 3. The CAD model (wireframe) of the proposed exoskeleton

Fig. 4. The exoskeleton prototype used in this study

Table 1 details the components of the exoskeleton based on Figure 3. The exoskeleton has two lever arms, a DC linear motor, a cable connecting the motor and the lever arms, springs, and pulleys. The right and left lever arms support the harvester's arms, the DC linear motor actuates both lever arms, and the cable is connected to the DC motor moving part and each lever arm's tip. The springs provide passive gravitational compensation, and the pulleys hold and guide the cable and provide enough angle to generate lifting power. All electronic components are placed on the back plate. With the motor configuration demonstrated in the gold circle in Figure 4, the DC linear motor will either 'pull' or 'release' the cable, which in turn, will bring the lever arms either 'upward' or 'downward', respectively.

Table 1
Exoskeleton components list based on Figure 3

No.	Component types	Abbreviations
1	Moving motor part	Mot (motor) M (moving part)
2	Lever arms R and L	A1 (right) A2 (left)
3	Horizontal bars TOP, MID, and BTM	B1 (top) B2 (middle) B3 (bottom)
4	Vertical columns R and L	C1 (right) C2 (left)
5	Cable segments 1 and 2	CAB1 (arm side) CAB2 (motor side)
6	Pulleys R and L	P1 (right) P2 (left)

The single linear DC motor provides a linear motor force via a moving motor part (MM) that travels only in a single, vertical axis. Here, the moving part is considered as a point mass that is also connected to two cable segments that go all the way through their associated pulley to the tip of a lever arm on the right and left sides of the exoskeleton. This cable connection transfers the linear motor force into the tip of the right and left lever arms via cable tension, T. Depending on the value of the tension, the tips will be lifted or released. The motor body is positioned at the top side of the exoskeleton in such a way that the cable is ‘pushed’ downward via MM to lift the lever arms. To model the exoskeleton design, the cable configuration comprises cable segments, the pulleys, and the springs, and they are considered massless. The cable is considered as inextensible. Hence, the total cable length is fixed and is divided equally into the right and left cable sides. Each cable side has two further cable segments: the lever arm and motor segments. They are denoted as CAB1 and CAB2, respectively. For consistency, the length of the cable is selected in such a way that when the motor moving part is in its zero position, the lever arms are already inclined by 30 degrees.

3.1.3 Experimental setup

The experiments were performed as follows; upon arrival, participants completed three forms, namely demographic information, informed consent and health declaration forms. Then, participants were briefed on the functionality of the prototype exoskeleton and were allowed to practice donning (putting on) and doffing (taking off) the prototype until comfortable. Next, anthropometrical measurement was performed, and the prototype was adjusted to fit each participant. Then participants proceeded to perform the specified tasks. Two types of trials were carried out in this study, lab and field trials. The description of each trial is detailed in section 3.1.4. One participant participated in the lab trial, while three participants participated in the field trial. Participants were allowed to rest between tasks and repetitions.

The electromyography (EMG) signals of selected muscles were recorded throughout the trials. To detect EMG signals, dry electrodes were attached on the subject’s skin. Skin preparation was performed using alcohol wipes to reduce electrode impedance with the skin. Eightsurface Electromyography (sEMG) system (Delsys Inc., Natick, MA,USA) were placed parallel to the muscle fibres (both left and right biceps brachii, triceps brachii, trapezius and anterior deltoid) and away from other muscle groups according to Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) standards. The exoskeleton body straps were adjusted with comfortable looseness to allow the sensor to function. The EMG data were band-pass filtered and fully rectified in accordance with the international guidance; (10-500) Hz for surface electrodes, and denoised using wavelet transform (type DB6). The EMG averaged envelope were acquired using the moving averaging window method so that EMG levels can be compared.

3.1.4 Experimental tasks

As mentioned earlier, two sets of trials were carried out for this study, lab trial and field trial. The lab trial involved two sets of experiments, the control experiment and harvesting simulation experiment. Both experiments were performed with and without the exoskeleton.

For the control experiment, the Functional Impairment Test-Hand, Neck, Shoulder and Arm (FIT-HaNSA) protocol was modified to suit the activity of lifting and lowering of the harvesting pole. The FIT-HaNSA test as described by (MacDermid, 2007) was performed in the lab to assess the basic function of the upper-limb and to observe the practicality and general effectiveness of the exoskeleton. Only one participant was involved in this trial as this was only a preliminary study. The participant lifted a 5-kg weight from the waist height shelf to an eye level height shelf and back to down to the lower shelf. These tasks were repeated five times, each with and without wearing the exoskeleton. Next, the participant performed harvesting simulation in the following sequence; lift the pole, walk 8 meters with the pole, tug the pole by pulling a load amounting to 15 kg five (5) times, and rest the pole on the ground. This simulation was also repeated five (5) times, each with and without wearing the exoskeleton.

For the field trial, three participants performed the actual harvesting task, involving cutting or pruning five (5) oil palm trees continuously (a maximum of two minutes per tree), followed by resting the pole on the ground. This sequence was repeated five (5) times, each with and without wearing the exoskeleton.

3.1.5 Data analysis

For the lab trial, the average peak root mean square (RMS) over the five repetitions for each muscle was evaluated to identify the strength of muscle activation for each experiment i.e. control and harvesting simulation.

For the field trial, the power spectrum density (PSD) analysis was used to analyse the overall firing rate of the motor unit during the actual harvesting activity of five oil palm trees. Maximal power of the PSD indicates an increase of muscle contraction level. All analyses were performed in EMGWorks (Delsys, MA, USA) software.

4. Results and Discussion

4.1 Muscle Activation during Laboratory Trials

Figure 5 shows an example of the EMG signal for one repetition of the lab harvesting simulation. In general, the exoskeleton has significant effect on the biceps and triceps for both the left and right arms. However, less effect is observed for the deltoid and the trapezius muscles. This is possibly because the deltoid and trapezius are not heavily used during the harvesting process. For the control experiment, the peak RMS changes were minimal when performing tasks with exoskeleton as shown in Figure 6. The largest change during control motion was observed in left biceps and right trapezius, where the peak RMS increased with exoskeleton. For harvesting simulation, minimal change was observed as shown in Figure 7. These results indicate that the range of assistance provided by the exoskeleton may not be suitable for the targeted tasks and/or the user. Nevertheless, these results were not conclusive as they were obtained from one participant.

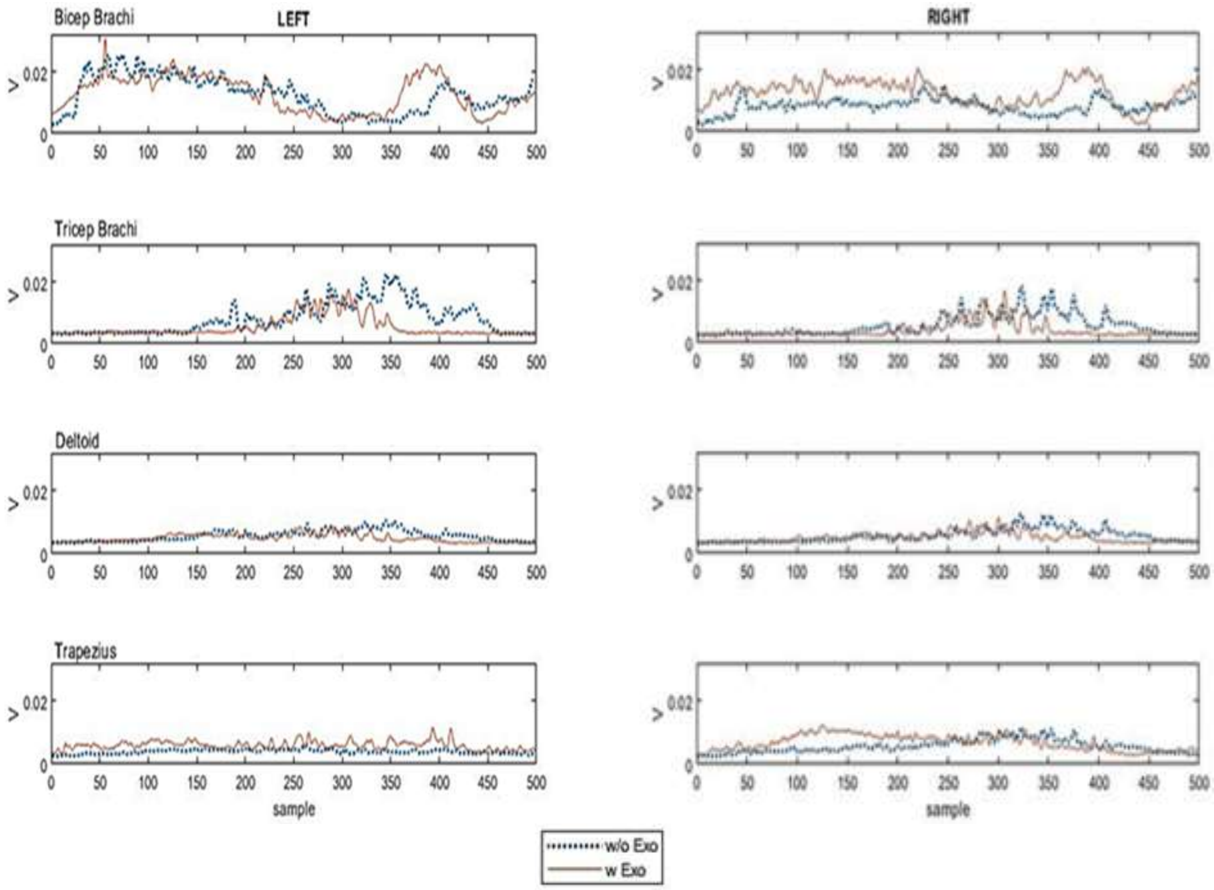

Fig. 5. An example of harvesting muscle activation pattern

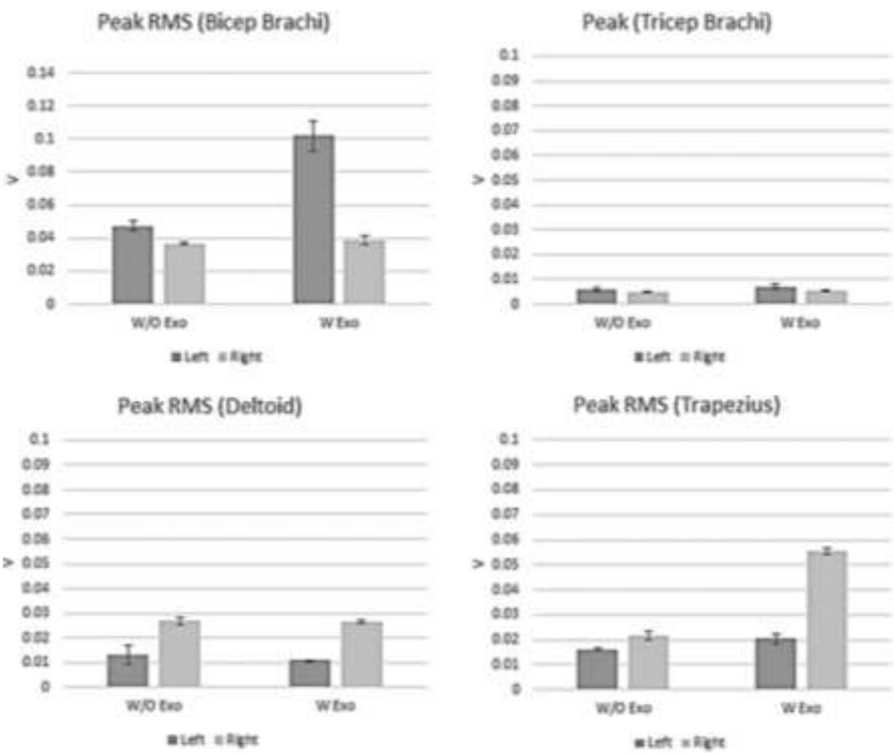

Fig. 6. Muscle activation pattern for lab trial (control motion)

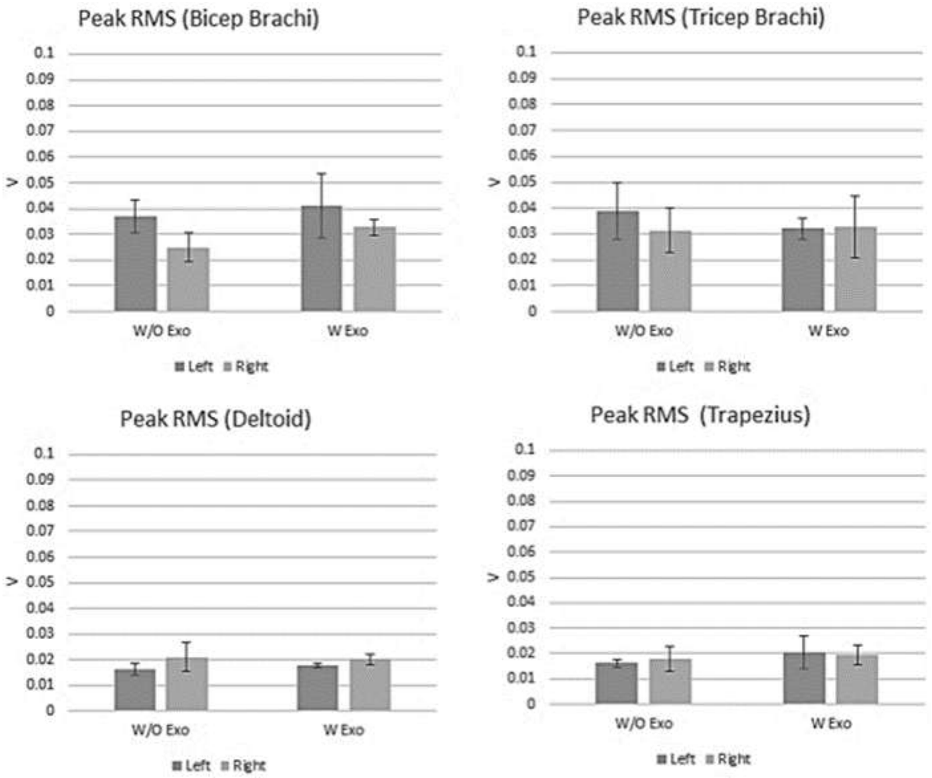

Fig. 7. Muscle activation pattern for lab trial (harvesting motion)

4.2 Muscle Activation during Field Trial

To verify the effects of exoskeleton assistance during field harvesting, 15 minutes of recorded muscle activities of harvesting actual oil palm trees were analysed. The maximal power of the PSD indicates an increase in muscle contraction level. Based on Figure 8, it was observed that muscle contraction level reduced in general when harvesting was assisted with exoskeleton, except for the right triceps brachii muscle and right deltoid. Reduced activity in biceps brachii and deltoids have been observed in assisted push-pull overhead task [8]. The lack of change in triceps brachii is likely because no assistance was provided during shoulder extension when the pole is pulled downward.

This result indicates that the proposed exoskeleton has the potential to reduce muscle activity during harvesting because the differences was observed when the data were analysed over 15 minutes of simulation. Optimization to the exoskeleton design and assistive mechanism is needed to further reduce the load at the shoulder joint. Analysis of muscle activity on the trunk muscles will also be useful for including assistance of the back. Although a manual pole was used for the simulation, it is expected that using a powered pole will result in better assistance due to the less intensive and frequent dynamic push-pull motion. Having function such as vibration-stabilizing or -absorbance may enhance assistance provided by the exoskeleton when used with powered harvesting pole.

It can be observed from Figure 7 that the average RMS improvement when using the exoskeleton for harvesting motion in all four muscles is approximately 22%.

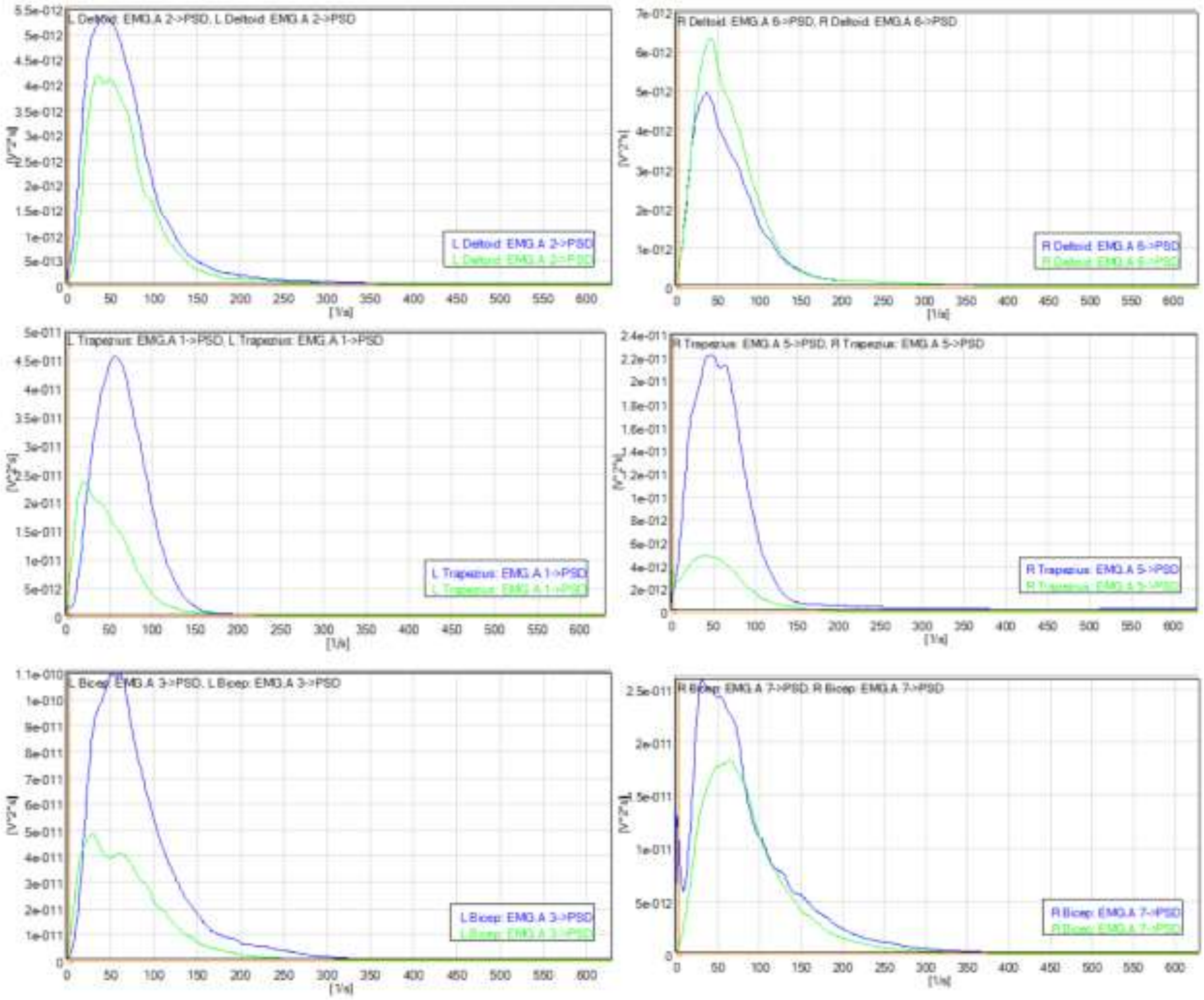

Fig. 8. Power spectrum density for field harvesting simulation – without exoskeleton (blue line) and with exoskeleton (green line)

5. Conclusions

This study demonstrates the potential of using exoskeleton as an assistive device for oil palm harvesters during pole handling based on the observed reduced activity in the shoulder and/or elbow muscles, in general, when during harvesting. The average RMS improvement when using the exoskeleton for harvesting motion in all four muscles is approximately 22%. An effective assistive device is aimed to increase harvesters' productivity and harvesting productivity. Further investigation to address the limitations of this study, including increasing the number of participants, obtaining usability feedback from participants, and performing detailed biomechanical investigation to elucidate the human-exoskeleton interactions and effects on the user, exoskeleton, tasks, and working environment, are part of on-going and future work.

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