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Design and Implementation of Hybrid Exoskeleton for Oil Palm Harvester to Reduce Muscle Strain

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ABSTRACT

When it comes to safety at the workplace, palm oil harvesters are highly exposed to body pain and muscular fatigue, which in the long term may lead to permanent spinal or shoulder damage that will undoubtedly result in different extreme societal difficulties. Meager investment in safety and long hours of manual work in awkward posture is the main challenge in ensuring safety in the palm oil field. This study aimed to develop a novel light hybrid exoskeleton exclusively built for palm oil harvesting to reduce muscular strain, maintain minimum cost, and ensure material availability in the local market. The iso-elasticity approach and DC linear motor were used for gravitational and muscular torque compensation and position control. Muscular EMG signal was taken and filtered to investigate the muscle strain reduction after implementing the developed hybrid exoskeleton. The result shows that the overall muscle strain was reduced by 16% using the passive exoskeleton and 23% using the hybrid exoskeleton compared to freehand. According to the results, it is evident that the developed exoskeleton can be implemented in palm oil harvesting, which will reduce the pain level of the workers at a significant rate.

1. Introduction

Hazards, injuries, and muscle strains associated with agricultural activities caused by manual tools, incorrect working position, inadequate rest, static holding, dynamic lifting, overloading and lack of training can be minimized by use and implementation of an exoskeleton [1-5]. The exoskeleton is a branch of robotics that uniquely deals with physical human-robot interaction (pHRI). Exoskeletons cover the human limb in one or more joints and synchronously move with the human's joints where interaction of human operators end-effort is not necessary [6]. An exoskeleton assists the workers involving static holding postures, dynamic lifting, material handling (over 30% of the

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work population in the EU), repetitive movements (63% of EU workers), awkward body postures (46% of EU workers) and workers exposed to low back pain and low shoulder pain (40% of EU workers) [7-8]. In such cases full- automation is either not possible or prohibitively expensive. Exoskeletons built with human-machine collaboration improve the use of robotics while retaining the flexibility of humans by extending human capability at the implementation level [5,9]. A passive exoskeleton is a very convenient way to reduce workload with minimum expenses as it uses materials, springs, or dampers instead of any actuator or electrical power device [10]. These materials, springs, or dampers, can store energy harvested by human motion that is later used to support a posture or a motion, increasing the performance by 30% on average with less fatigue. These exoskeletons store energy when a person bends forward; later, they use this energy to support the person to keep that position or to erect the body while lifting an object [2]. The Personal Lift Augmentation Device (PLAD), HappyBack and Bendezy erector reduce spinal muscle activity by 21-31% [11]. The arm exoskeleton proposed by [12] uses a camera stabilizing device, and the exoskeleton proposed by [13] provides mechanical support on upper limbs, which reduces the muscle activity of the Biceps Brachii and Medial Deltoid by 49% and 62%, respectively for 2kg load. The gravity compensation iso-elastic exoskeleton of [14] supports up to 7.5kg, and the industrial exoskeleton proposed in [10] are some of the most notable examples.

Though a passive exoskeleton is suitable to some extent, repetitive lifting and lowering increase energy consumption for the worker, cannot provide any support to joints which makes the joints vulnerable to injury and has restricted usage with very less flexibility. The active exoskeleton can provide solutions to the problems faced in the case of the passive exoskeleton. An active exoskeleton has one or more actuators (electric motors, hydraulic actuators, pneumatic muscles) that elevate human power and helps in actuating human joints [15]. For example, the upper limb-powered exoskeleton design in [16], has 1500 Ranges of Motion (ROM), 7 degrees of freedom and a high power-to-weight ratio but a high percentage of overshoot. A wearable power assist device was designed in [17], based on a cable-driven, curved track mechanism that could provide independent control of all five major degrees of freedom (DOF) at the shoulder complex. Active industrial exoskeleton reduces the muscle activity for the Erector Spine by 15% and Biceps Femoris by 5% for a 15 kg load [18]. The exoskeleton system for a human upper-limb motion of [19-20], has 3 DOF, sliding mode control of a 5 DOF, and the exoskeleton of [21] has high dynamic tracking performance. The development of humanoid robotics proposed by [22] can be updated in microseconds of the controller signals.

However, an active exoskeleton has a very complex design with high maintenance and heavy weight for using actuators, motors, and batteries. As a result, it is not suitable for partial body design with very low robustness. To achieve both advantages of the passive and active exoskeleton, a hybrid exoskeleton was proposed. Hybrid exoskeletons are defined as exoskeletons that use an electrically controlled actuator (e.g., electric motor, pneumatics, hydraulics) in combination with Functional Electrical Stimulation (FES) to provide active assistance/resistance to the user [23]. Like in the studies carried out [24-25], it is stated that among available pure active and passive interventions, several technical limitations are preventing satisfactory gait compensation following Spinal Cord Injury (SCI). Another example of combining technologies is reviewed in [26], where a pneumatic force-feedback system consisting of a double-acting cylinder and a set of high-speed on-off valves is controlled by a fuzzy controller.

Currently, there are no commercially available upper-limb hybrid exoskeletons, so predicted prices for these exoskeletons having a long-term view of commercialization are not expected to be cheap [27]. Besides, none of these are suitable to support the posture and movement of palm oil harvesting.

In this project, a light weighted hybrid exoskeleton was developed to reduce muscle strain in oil palm harvesting. This hybrid exoskeleton uses a passive mechanism for gravity compensation and support and an active actuator for torque compensation. EMG signal was used to check muscle strain due to harvesting work, filtered by low pass filter using MATLAB DSP tools. The overall muscle strain was reduced by 16% using the passive exoskeleton and 23% using the hybrid exoskeleton. According to the results, it is evident that the developed exoskeleton can be implemented in palm oil harvesting, which will reduce the pain level of the workers at a significant rate.

The sections of this paper are organized as follows: Section 2 presents the process and methods to design and develop the exoskeleton. Section 3 introduces the data acquisition process, setup as well as the noise cancellation process. Section 4 describes the main results of functional testing in a laboratory environment and a further result discussion. Finally, the paper ends with the conclusion and future work in Section 6.

2. Methodology

2.1 Passive Exoskeleton Using Iso-Elasticity

The purpose of this project was to build and analyze the passive and hybrid exoskeleton to reduce muscle strain and fatigue during palm oil harvesting. The exoskeleton was designed to have 4 degrees of freedom (DOF) so that it would not restrain the movement of the shoulder joint to aid specific postures required for palm oil harvesting [28]. According to a recent study, solder joint reliability greatly depends on the microstructure of the solder matrix and the morphology of intermetallic compounds (IMCs) in the joints [29]. Figure 1. is the pictorial view of the passive exoskeleton design. The base structure consists of a square wooden frame to distribute all the loads of exoskeleton and the pole on upper back along the backbone. The frame was then connected to vertical wooden poles using a screw to provide a front and back degree of freedom. These poles were joined with an arm-supporting structure using a screw to provide up and down movement, which ensured two more degrees of freedom.

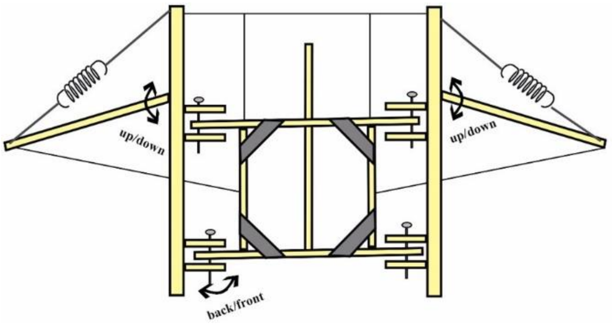


Fig. 1. Structural design of the passive exoskeleton

These 4 DOF support the chisel movement while reaping the palm fruit. The free edge of this structure was connected to two springs to provide gravitational compensation. AB wire was attached to connect both springs to transfer power for static holding and carrying. The torque acquired by the spring holds the CD arms at an upright position shown in Figure 1. Torque/position control is achieved manually shown in Figure 2.

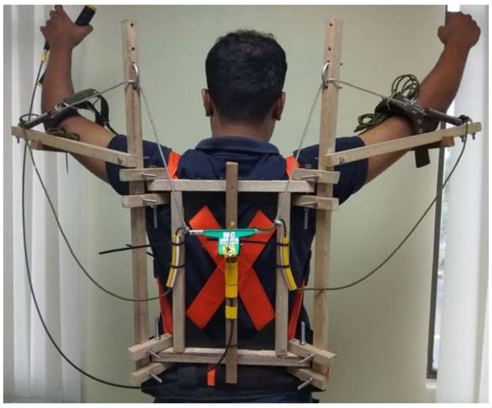


Fig. 2. Developed passive exoskeleton for oil palm harvesting

This exoskeleton is developed for FFBs cutter which is a 5kg pole with chisel. So, the downward force caused by gravitation and weight of this cutter need to be opposed to provide gravitational compensation. The downward force caused by this cutter is, $F = F_g = mg = 5(kg) * 9.8(ms^{-2}) = 49(N)$. Thus, an extension type spring which can withstand and provide a force opposing the weight of the load is used. From the equation of iso-elasticity, for Figure 3 we can write

$$F_Q/_Q = F_b/_b = F_d/_d \tag{1}$$

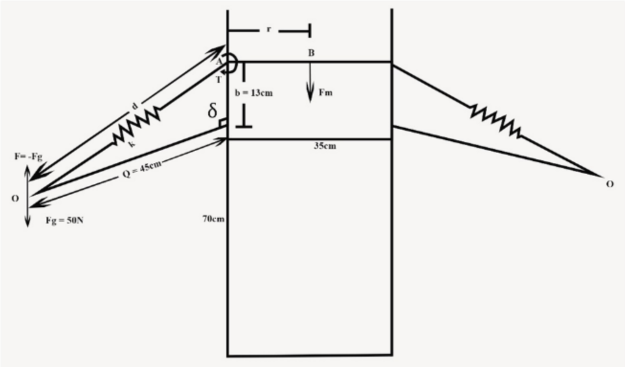
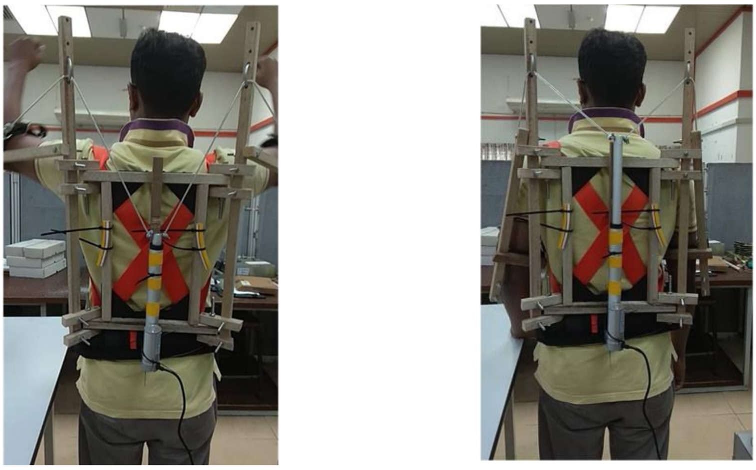


Fig. 3. Schematic design of the passive exoskeleton

where, F_Q, F_b, and F_d are the forces along Q, b, and d respectively. Let consider, $F = -F_g = F_b$ as F is applied in same direction as F_b and both depend on the length of b, and $F_d = k * d$ from where, we get k=0.377 N/mm. Due to unavailability of spring having this exact spring constant, the closest available one is used in this design. The used a spring with 74N tension and spring rate of 0.46N/mm. Initial force is an internal force that holds the coils of a spring tightly together i.e., this is the maximum force that can be withhold by a spring. So, this chosen spring can easily give gravitational support to a 5-kg load.

2.2 Hybrid Exoskeleton

The passive exoskeleton cannot assist lifting load and exact torque/position control. An actuator and controller are required to give force while lifting the load upwards and control the positioning of the hands. A linear DC motor was used to ensure linear movement and lightweight. The specification of the dc motor depends on the required force of torque compensation and position. Torque T was decided to be given at joint A for lifting a 5kg load shown in Figure 1. Motor drive is used to run and control the torque provided by the motor. Position control was done manually by keypad mounted on the palm of the user. The developed exoskeleton is shown in Figure 4. The overall weight of this hybrid exoskeleton is 3kg which is very light compared to the exoskeleton of [26-27].



(a) Hands up position (skeleton version) (b) Hands down position (skeleton version)

(c) Side view (covered version) (d) Front view (covered version)

Fig. 4. The Developed Hybrid exoskeleton

3. Data Acquisition

Data were acquired by checking muscle strain, which was done in the lab by mimicking the harvesting work on an oil palm plantation. A healthy right-handed male volunteer having the strength and quality of a standard palm oil worker, participated in this study as a test case. Later, This was validated in the oil palm field. Every experiment was done on the same participant, ensuring he was well rested where necessary.

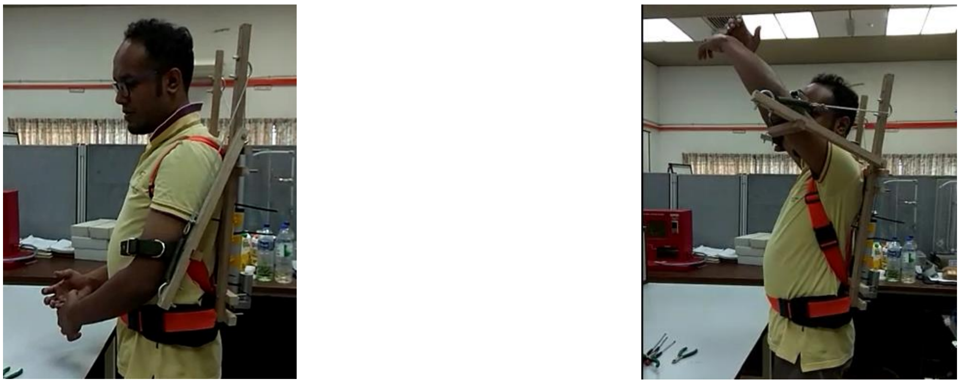
3.1 Experimental Setup and Procedure

An EMG circuit with an AD8232 chip was used to measure the muscle strain. The sensor has a common-mode rejection ratio of 80dB (dc to 60Hz), reducing power line interferences. Its compact size and customizable leads make it easy to mount on the body during testing. The EMG signal was measured for Bicep as this is the joint muscle used in every step considered. The electrode position was placed using the standard recommendation developed by the Surface ElectroMyoGraphy (EMG) for the Non-Invasive Assessment of Muscles (SENIAM) [30].

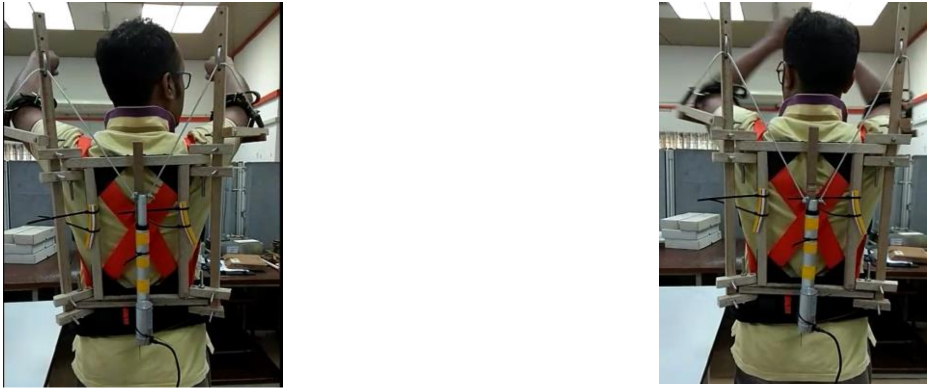
For this study, the experimental cycle was divided into 4 steps. These steps were derived by observing oil palm harvesting work. These steps are given in Table 1.

Table 1
Steps of the experimental procedure

Sl. no	Steps	Description
01	Lifting up	In this step, the load was lifted up from ground.
02	Holding Pole up & Walk	In this step, the participant walked some steps, carrying the load to represent the task moving from one tree to another.
03	Elbow extension- flexion movement	In this step, hands were extended and flexed to mimic the task of adjusting the chisel on FFBs.
04	Lifting up – down the pole:	Here, the pole was lifted-up and down at least 3 times as workers has to cut leaf branch below FFBs to get hold of them.



(a) Lifting up (b) Holding pole up & walk



(c) Elbow extension (d) Elbow flexion

(e) Lifting up – down the pole

Fig. 5. Illustrations of Steps of the experimental procedure

3.2 Noise Cancellation Procedure

The electromyographic signals are distorted from the expected result due to the interference of various noises. EMG signals are colored by the interference of Ambient noise, Inherent noise in electronic equipment, Motion Artifact and Cross Talk, Transducer and Cable noise. There are a few techniques that can cancel out these noises and come up with a pure presentable EMG signal. Some measures were taken to ensure a less noise-prone setup by following some simple steps. DC power supply was an excellent option to avoid ambient noise. Since a high-frequency power supply causes ambient noise, the DC source is not prone to this noise. Motion artefact noise was nullified by applying a conductive gel layer in the skin-electrode junction. Cross talk noise and motion artefact noise were reduced significantly by ensuring the proper spot of the electrode. The sensor used embedded circuitry to get rid of Inherent noise, cable and transducer noise. This embedded circuitry converts the unstable noisy signal into a smooth and presentable signal. The conversion steps are well explained in the Myoware muscle sensor (at-04-001) datasheet [31].

Although pre-processing and noise reduction circuitry reduced the noise significantly, the achieved signal required fine-tuning using DSP tools. In the case of static work, achieved data is not too random or unstable, whereas a working cycle consisting of a series of individual tasks is exceptionally random, unstable, and noise prone. While imitating the working process of a palm fruit worker, each cycle was defined with a series of individual tasks, resulting in a significantly fluctuating and noisy EMG signal, which could not be presented or analyzed without applying post-processing DSP filters. The first step of DSP filtering is to identify the noise spectrum. According to the lecture on electromyography at MIT [32], since all types of noises were mixed in this signal, the interrupting noise can be called Additive White Gaussian Noise (AWGN). In order to identify the frequency spectrum of the actual signal, the achieved data must be represented in the frequency domain. In the time domain, the frequency spectrum is not visible. Two data sets achieved at the same condition (i.e., without exoskeleton and with hybrid exoskeleton) were taken to the frequency domain. Afterward, similar frequencies were considered actual signals, whereas the rest were identified as noise [33-36].

4. Results and Discussion

In this study, a passive and hybrid exoskeleton dedicated to palm oil harvesting was built and analyzed, which is cheap and lightweight compared to previous works [10,12-14,26].

Figure 6 shows the clear difference between the original and refined muscle signals without the exoskeleton. The blue line shows the original data, and the red line shows the filtered data. Filtered data is more meaningful and presentable. The exact process was applied to the dataset obtained with the passive exoskeleton and the hybrid exoskeleton. These filtered datasets are easier to analyse and more accessible to draw a conclusive decision on the project.

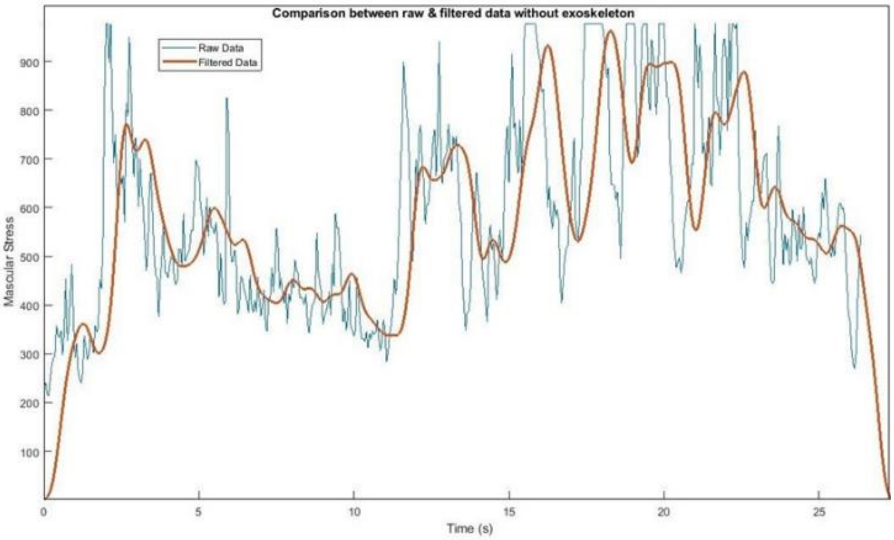
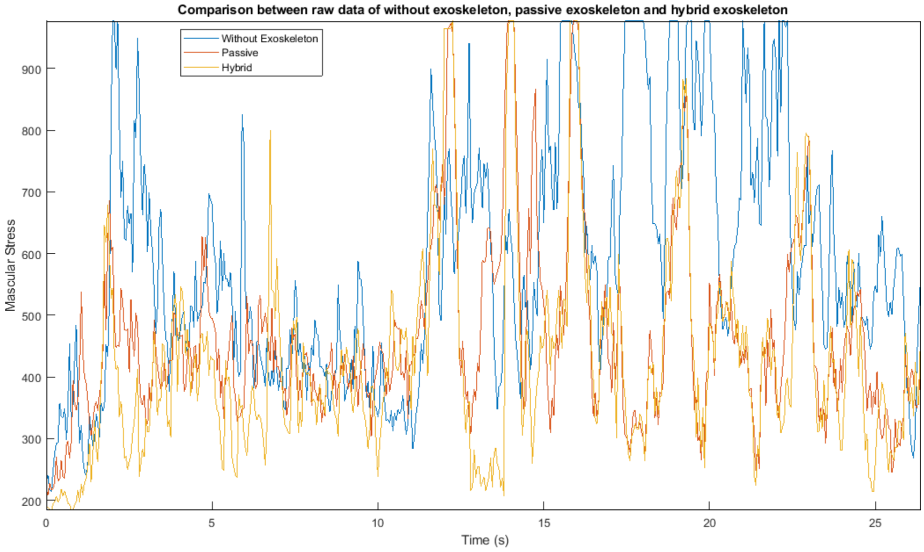


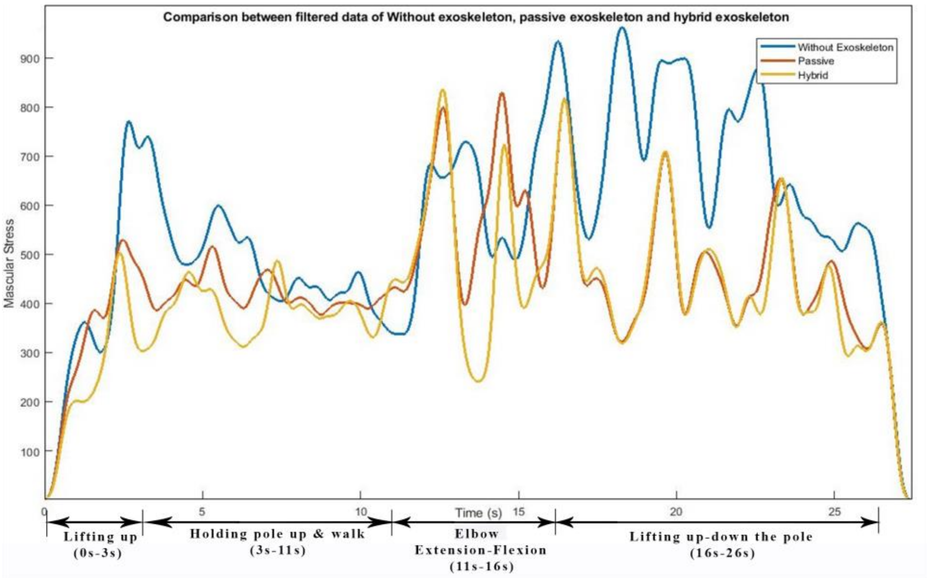
Fig. 6. Comparison between raw data and refined data (no exoskeleton)

In Figure 7, raw and filtered datasets of muscle strain without using the exoskeleton, with the passive exoskeleton and the hybrid exoskeleton, are plotted in one place, where the X axis represents muscular stress, and the Y axis represents time and steps. This data was obtained from an EMG signal accumulated by an Arduino-based EMG signal extractor and filtered using MATLAB DSP tools. According to the figure, it is evident that the muscle strain was reduced significantly after using the passive exoskeleton compared to the muscle strain obtained in free-hand work. The average muscle strain reduction value is about 16%. The passive exoskeleton was converted into a hybrid exoskeleton to achieve further less muscular strain. The result of adding an actuator is quite evident from the figure. In this experiment, it is calculated that, by converting into the hybrid exoskeleton, the overall muscle strain is reduced significantly compared to the strain while not using the exoskeleton. However, during Step 4 (Table 1), both passive and hybrid exoskeleton shows the same muscular stress because the actuator does not affect this stage.

Nevertheless, the overall muscular stress is reduced by 23% compared to the stress without using the exoskeleton. Besides, the weight of the exoskeleton is only about 3kg, which is much lower compared to the experiment conducted by [26,27].



(a) Raw Data



(b) Filtered Data

Fig. 7. Comparison between dataset of without exoskeleton, passive exoskeleton, and hybrid exoskeleton

5. Conclusions

In this study, a passive exoskeleton is built and experimented to reduce muscle strain of oil palm harvesters. Later, a hybrid exoskeleton is developed using actuator and controller to enrich its usefulness further. We found that the passive and hybrid exoskeletons reduce 16% and 23% muscle strain at an average (respectively) while mimicking the activities during palm oil harvesting. This work focuses on cheap, flexible, light weighted, and compatible palm oil harvesting where only a 5kg load supporting structure is good enough. This is the first study in our knowledge to build and investigate a hybrid exoskeleton supporting the movement and posture described in Table 1, which mimics the movements and posture of a palm oil harvester. The challenge for future improvement of this exoskeleton is to make it adjustable and develop a controller by reading intentions.

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