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STRUCTURAL DESIGN OF A PASSIVE WEARABLE EXOSKELETON TO ASSIST OIL PALM HARVESTING OPERATION

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ABSTRACT

Harvesting of oil palm fresh fruit bunches is still performed manually, involving extensive energy, awkward postures or repetitive motion, and often under strenuous conditions. Exoskeleton technologies are increasingly being explored for performance augmentation and ergonomics intervention in industrial settings. For challenging environments, like the oil palm plantation, the dynamic interactions between user, task and environment is non-trivial. Importantly, an exoskeleton should not impede a worker's movement and task performance throughout the period of wear. Intrinsically, designing an exoskeleton for oil palm harvesting entails that the dynamic interactions between the harvester, the pole, and surrounding objects is considered early in the design process. We adopted the systems approach to designing an upper limb exoskeleton to assist oil palm harvesters. The proposed design is a slimline passive exoskeleton that provides an assistive force through compression springs in the upper arm region. Structural analysis and a preliminary prototype evaluation were performed for design verification. The weakest component was the back plate. Nevertheless, permanent deformation would only occur when an equivalent of 26 kg load is applied to the exoskeleton arm. Future work includes optimising the design and elucidating its long-term effects on the harvester's efficiency and field productivity through biomechanical analysis and field tests.

Keywords: assistive technology, design, harvesting, human factors, oil palm.

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INTRODUCTION

The nature of agricultural field work is very dependent on local environmental factors, such as weather, crop type and farm or field layout. This leads to varying structures and characteristics of farm or field environments to suit the changing environmental conditions. Agricultural workers interact with and handle machines and tools of various sizes and shapes to match the characteristics of the crops and the environment. This unique characteristic of agricultural work is a challenge to comprehensive mechanisation and automation in the field (Marinoudi *et al.*, 2019; Sreeram and Nof, 2021; Vasconez *et al.*, 2019). Moreover, the dynamic interactions between the user, task and environment is especially critical for automation. Therefore, the synergistic relationship between human operators and machines will likely be a common view in the fields, especially for non-routine tasks and tasks performed by skilled workers (Marinoudi *et al.*, 2019).

In oil palm plantations, harvesting is performed by skilled workers who are adept at handling the cutting tool and manoeuvring through the

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challenging plantation environment (Preethi *et al.*, 2016). The correlations between movements carried out during oil palm harvesting, its non-ergonomic nature, musculoskeletal problems and productivity have been well documented (Mohd Nawi *et al.*, 2014; Ng *et al.*, 2013; 2014). In fact, many manual agricultural tasks are typically performed in challenging and arduous conditions such as restricted space, unpredictable terrain and environment, and high cognitive load, leading to non-ergonomic working conditions for the workers and potentially musculoskeletal pains in the long run (Benos *et al.*, 2020a; 2020c; Castaneda *et al.*, 2020; Du *et al.*, 2022; Fathallah, 2010). Amongst these manual tasks, harvesting is postulated as one of the least mechanised tasks and one of the highest contributors toward musculoskeletal disorder (MSD), and this is similarly echoed in the oil palm industry (Benos *et al.*, 2020b). Ultimately, an optimal interaction between humans, machines and the working environment is pertinent to improve the ergonomics and productivity of manual harvesting or any manual field tasks.

Occupational exoskeletons are increasingly explored in the manufacturing and heavy industries, where manual tasks are still performed. An exoskeleton is a wearable device that augments, enables, assists, or enhances physical activity (Lowe *et al.*, 2019). Immediate positive effects of using occupational exoskeletons to assist manual operators in various industries are increasingly reported, mainly in terms of lower muscle activation in the assisted joints (Alabdulkarim *et al.*, 2019; Dahmen and Constantinescu, 2020; Iranzo *et al.*, 2020). For the oil palm harvesting industry specifically, exoskeletons could be a viable immediate solution for improving the worker's productivity while a fully mechanised system is being developed. Nevertheless, the design of the exoskeletons should consider the interactions between the user, the task and the working environment to increase their overall effectiveness in the field.

An Overview of Occupational Exoskeletons

There are multiple ways to categorise exoskeleton systems. They can be categorised based on the power source, *i.e.* active, passive or semi-active system, or mechanical structure, *i.e.* rigid or soft. Active systems contain electromechanical components and require external power sources for operation, while passive systems do not require an external power source. In terms of mechanical structure, rigid exoskeletons can deliver high assistive force to the body accurately, while soft exoskeletons sacrifice this aspect to allow more flexible motion (Xiloyannis *et al.*, 2019). More recently, semi-active systems, which use low-powered actuation units to modulate the amount of assistance provided by the assistive elements, have also been introduced such as by Grazi *et al.* (2020). Exoskeletons can also be categorised into lower, upper, and full-body systems. Lower body systems typically assist the waist and limbs below the waist, upper body systems assist limbs above the waist, while full-body systems assist both lower and upper bodies. Currently, many commercially available occupational exoskeletons are passive upper limb exoskeletons including ShoulderX (SuitX Emeryville, California, USA), EksoVest (EksoBionics, California, USA), PAEXO (Ottobock, Duderstadt, Germany) and AirFrame (Levitate Technologies, California, USA). A comprehensive review of occupational exoskeletons is available in Crea *et al.* (2021), De Bock *et al.* (2022), and Vries and Looze (2019).

Many occupational exoskeletons aim to improve the load-bearing capability of the assisted limbs or joints, and consequently the user's ergonomic condition. For example, the Chairless Chair (Noonee, Wendlingen, Germany) enables sitting without a chair by transferring the user's body weight to links that run in parallel with the thighs. For upper body exoskeletons, the load-bearing capability could be improved by distributing load to the larger muscles in the body. Upper body exoskeletons typically aim to assist arm raising or stabilising. An example is the Raku Vest (Kubota, Japan), an active system that aims to minimise the energy spent to stabilise the arm in specific positions. Finally, full-body exoskeletons have the advantage of assisting the upper limbs and transferring the load from the upper body directly to the ground. However, a full-body attachment can be cumbersome, partly due to multiple attachment points. Furthermore, bulky exoskeleton systems will interrupt the natural physical movement of the entire body, including causing imbalance (Kim *et al.*, 2018a; 2018b).

One of the first exoskeletons developed to assist agricultural tasks is an active full-body exoskeleton (Toyama and Yamamoto, 2010). The proposed system weighs 30 kg and has 10 joints with various control modes to match the user's movement during specific tasks, including radish harvesting, cucumber harvesting, and fruit tree pruning. An initial assessment of the prototype indicated problems in matching the motion of the system and the user at the shoulder and back, potentially caused by irregular movements by the users during harvesting.

Multiple studies have reported on the evaluation of passive exoskeletons for agricultural tasks, particularly in the last five years (Dewi and Komatsuzaki, 2018; Harith *et al.*, 2021; Thamsuwan *et al.*, 2020; Ulrey and Fathallah, 2013; Wang *et al.*, 2021). These studies evaluated either commercially available or prototype-staged exoskeletons. The overall results of these studies indicated some forms of reduced demand on the assisted joints. However, many recommended observing exoskeleton usage onsite and over a longer duration, and/or modifying the designs for better user acceptance. Therefore, commercial exoskeletons may not be readily adopted in the field without further modification, particularly because many are designed for specific tasks and not for challenging environments (Mudie *et al.*, 2022). Moreover, field evaluation of exoskeletons in the agricultural field is currently too few (Thamsuwan *et al.*, 2020). A number of surveys also have highlighted the importance of aligning exoskeleton design with users, tasks and work environment for field adoption (Mudie *et al.*, 2022; Omoniyi *et al.*, 2020; Upasani *et al.*, 2019). Thus, considering the overall user's motion during usage and the working environment when designing the exoskeleton will reduce the mismatch between an exoskeleton's design and its application in the actual environment and encourage exoskeleton adoption in the industry (Mudie *et al.*, 2018).

Assistive Devices Design Considerations for Challenging Work Environment

Occupational exoskeletons are designed to improve the physical capability of the user in performing specific tasks. Interestingly, a recent study highlighted that exoskeletons designed for a specific task and not considering the operating environment prevent exoskeleton adoption in dismounted combatants (Mudie *et al.*, 2022). Agricultural operators similarly perform multiple tasks and handle different tools or machinery, typically in an unpredictable environment. In this setting, it is crucial that the exoskeleton or any assistive device is simple, easy to operate and does not restrict movement. Naturally, ease of use has been suggested as having a more important role in predicting the intention to use exoskeletons, compared to social influence and performance expectancy in a survey involving industrial workers (Elprama *et al.*, 2020). Moreover, wearing an exoskeleton will change an operator's body size, shape and inertia, and cause workers to modify their movements (Desbrosses *et al.*, 2021). Therefore, the technology should be adaptable and comfortable for the users throughout the duration of use.

In this study, we present the design of a passive upper limb exoskeleton for oil palm harvesting operators that was developed via the systems approach. For this approach, problem-solving focuses on systems taken as a whole, instead of their parts taken separately, as the interactions between parts cause dynamic changes in the system (Ackoff, 1971; Arnold and Wade, 2015; Monat and Gannon, 2018). In this study, the dynamic interactions between the user, the tasks, and the working environment was considered to establish the design criteria of the exoskeleton. The working environment is considered as the system, and the subcomponents are the harvester (and the movements performed), the pole, and surrounding objects including the uneven ground, the trees, hanging fronds, and other objects on the ground. The following sections describe the proposed design and the verification of its mechanical structure.

METHODOLOGY

The Oil Palm Plantation Environment

The dynamic interactions between the user, the device, the environment and the tasks should be considered in designing an assistive device to optimise its function in the actual operating environment (Mudie *et al.*, 2022; 2018). The oil palm plantation environment is characterised by dense canopies with hanging fronds from oil palm trees. The trees are now more commonly planted on hilly or undulating terrain. Other objects are also present on the ground, such as loose fruitlets, grass, weeds, and cut fronds. In short, a harvester must be aware of the surrounding while navigating through the plantation. *Figure 1* illustrates objects that could be present around the harvester during the operation. The presence of other objects in the harvester's surroundings and the plantation's uneven ground demand a slimline design without protruding components for ease of movement and safety. Additionally, since the pole extends below the waist and beyond the shoulder, both areas should be clear of any exoskeleton component to prevent interference with pole handling.

The Oil Palm Harvesting Tasks

Harvesting oil palm fresh fruit bunches (FFB) is a manual task that is physically demanding and ergonomically unfavourable (Nawi *et al.*, 2016; Ng *et al.*, 2013). Generally, harvesting comprises two main activities, cutting the fronds and FFB, and collecting the harvested FFB and loose fruits/ fruitlets. These tasks may be performed by one operator, but a team of two operators is also widely practised. In this study, we focused on the cutting activity. A harvesting pole with a sickle is typically used for harvesting FFB from palms more than 3 m high. The weight and length of the pole increase with tree height, and the complexity of handling the pole increases with increasing pole length. The harvester's pole handling skills, pole structure, tree height and FFB locations are a few factors affecting efficiency.

For a harvester who performs cutting, the task involves two main movements, namely walking while handling the pole and cutting FFB and

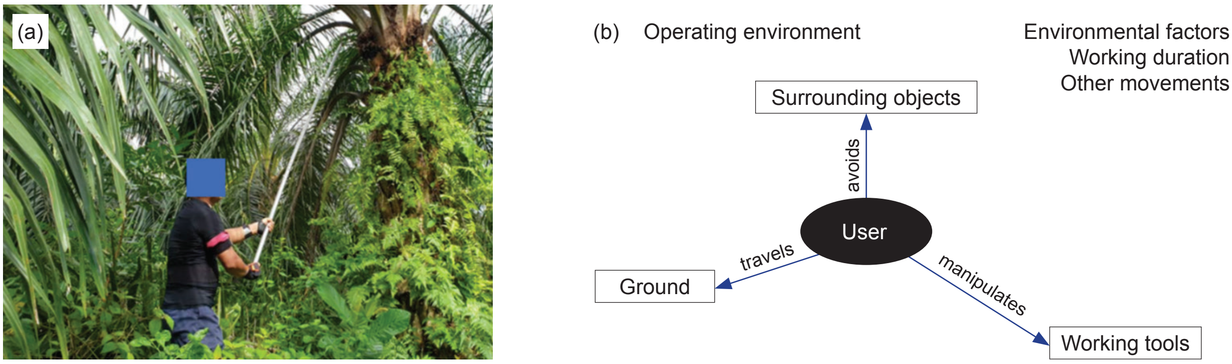

Figure 1. (a) An illustration of the work environment during oil palm harvesting. An operator is aiming the pole for the frond or bunch while hanging fronds are present in the surroundings and weeds are present on the ground and tree trunks. (b) A concept map highlighting the dynamic interactions between a harvester and multiple elements within the working environment.

fronds. The operator carries the pole most of the time throughout a shift. Walking while holding the pole mainly involves static holding with the arms positioned between the shoulder and the waist, while cutting involves frequent dynamic overhead movement. When harvesting trees that are more than 3 m high, the shoulder and the elbow move in extreme ranges of motion (Parras-Burgos *et al.*, 2020; Syuaib, 2015). The cutting movement, *i.e.* pushing and pulling of the pole has been postulated as the most fatiguing task, which has led to the development of a powered harvesting pole to reduce the intensity of pulling the pole (Jelani *et al.*, 2008). Our field observations of harvesting indicated that at least one side of the arm frequently moves in the region slightly above the shoulder and underneath the shoulder (Harith *et al.*, 2021). Similar descriptions of the cutting movement during oil palm harvesting have also been reported recently (Chan *et al.*, 2022; Tumit *et al.*, 2021). Additionally, the cutting movement, specifically pulling the pole, occurs very swiftly, *i.e.* over a fraction of a second (Chan *et al.*, 2022).

Ergonomics reports highlighted that the back, the shoulder and the neck had the most frequent complaints of pain in harvesters (Nawi *et al.*, 2016). Although harvesting is not limited to cutting tasks, biomechanical investigations on oil palm harvesting naturally focused on the cutting movement (Nawi *et al.*, 2016; Ng *et al.*, 2013). These investigations highlighted that the shoulder and/or the trunk are the main regions requiring assistance (Chan *et al.*, 2022; Harith *et al.*, 2021; Mohamaddan *et al.*, 2021; Tumit *et al.*, 2021). Nonetheless, the interpretation of these results is limited for exoskeleton design purposes because the exoskeleton will likely be worn throughout the harvesting operation during which movements are not limited to cutting. In this study, partial biomechanics analysis in terms of muscle activity for a complete harvesting operation was performed to enhance the interpretations of previous reports.

Muscle activity of selected shoulder muscles during harvesting. The human shoulder complex allows flexion/extension, internal/external rotation, and abduction/adduction of the upper limbs, and comprises four joints: Glenohumeral, acromioclavicular, sternoclavicular, and scapulothoracic joints. The elbow joint allows elbow extension and flexion. We observed the behaviour of two shoulders and two elbow muscles of three right-handed harvesters during harvesting (*Figure 2*). The muscle activity of the biceps, triceps, trapezius and deltoids was collected using electromyogram (EMG) sensors (Trigno Avanti, Delsys, MA, USA). The trapezius and deltoids were observed to mainly indicate shoulder motion, while the biceps and triceps were observed to mainly indicate elbow motion.

Figure 2. The position of four EMG sensors on four upper limb muscles based on SENIAM standards (1: Trapezius, 2: Deltoids, 3: Biceps, and 4: Triceps).

Three harvesters performed one cycle of harvesting comprising walking and holding the pole, followed by cutting one or two FFB on one tree. To detect EMG signals, dry electrodes were attached to the subjects throughout the experiment. Skin preparation was performed using alcohol wipes to reduce electrode impedance with the skin. Eight electrodes were placed parallel to the muscle and away from other muscle groups according to the Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) recommendations. The EMG data were band-pass filtered and fully rectified by the international guidance; (10-500) Hz for surface electrodes, and denoised using wavelet transform (type DB6). The EMG averaged envelope was acquired using the moving averaging window method so that EMG levels can be compared. The peak root means square (RMS) of each muscle was averaged for three subjects to identify the strength of muscle activation during the harvesting cycle.

The data were analysed for two settings: (i) harvesting and walking, and (ii) harvesting only (excluding walking with a pole). This was done to observe the differences in muscle activity between a complete harvesting cycle (harvesting and walking) and cutting alone. All analyses were performed in EMGWorks (Delsys, MA, USA) software.

Design Criteria for an Oil Palm Harvesting Exoskeleton

Based on the description of the plantation environment and the dynamic interactions between the harvester, pole, task and environment, the proposed design criteria for the upper limb exoskeleton to assist harvesting are as follows:

i. A passive upper limb system
ii. Low-profile or slimline frame/structure
iii. Wearable standalone unit
iv. Minimal restriction on shoulder movements

A passive system was selected because an external power source may not be readily available outdoors. The dependency on power may increase the load carried by the user such as battery packs or chargers or may include complex components such as power sources and cables that may affect the user's safety. A rigid structure was selected for efficient force delivery and transfer. Nonetheless, the exoskeleton's frame should be slimline or low profile and light since the operators work on uneven ground, in restricted space and in an environment with hanging objects. The exoskeleton shall be worn like a backpack, attached to the body via harnesses. The assistive force is expected to be delivered in the upper arm region via compressive springs to assist the shoulder and elbow joints. To ensure ease of movement, kinematic misalignment at the shoulder shall be minimised and the assistive mechanism shall be easily turned on and off to free the harvester's arm when not handling the pole.

Minimal restriction on shoulder movements. A perfect match between the exoskeleton and a shoulder movement is difficult as the shoulder rotates and translates in multiple planes. We included three ways to minimise interruptions toward shoulder movements. They minimise kinematic misalignment, freeing the spaces beyond the shoulder joint and below the waist and lastly, include an on-body deactivation mechanism.

Kinematic misalignments between humans and the exoskeleton reduce the effectiveness of the system (Delgado *et al.*, 2020; Schiele and Van Der Helm, 2006). The techniques that have been used to reduce kinematic misalignment include: (1) increasing the number of joints on the exoskeleton, and (2) bypassing the user's shoulder joint altogether. Ekso Evo (Ekso Bionics, Richmond, USA) uses multiple joints that extend from the user's back and slightly below the shoulder to the upper arm, while ShoulderX (SuitX, Emeryville, USA) uses multiple rotational joints at the shoulder. These designs enable a more fluid shoulder motion compared to rigid links. However, increasing the number of joints may reduce load-transfer efficiency, increase the number of potential failure points, and lead to bulky design. Alternatively, Armor-man2 (Tilta, Burbank, USA) adopts a design that bypasses the shoulder joint altogether. Instead, the arm linkage directly connects the torso to the hand. However, this results in a high-profile design and extends further away from the body. This is unfavourable for the oil palm plantation environment because protruding parts are hazardous due to the presence of other objects in the surroundings and they will interrupt the harvester's movements. Therefore, both techniques to reduce kinematic alignment at the shoulder were adapted in the proposed design to produce a mechanism that allows uninterrupted shoulder movement.

It is also important that no component is placed above the shoulder and below the waist as the pole frequents both regions during the cutting movements. Since the pole is long, the presence of exoskeleton components may cause unnecessary worries for the harvester when manoeuvring the pole.

Agricultural workers commonly perform multiple tasks or handle various tools or machines (Upasani *et al.*, 2019). Harvesters work over long hours and will need to perform tasks other than harvesting. Therefore, an exoskeleton that could be turned on (assistance provided) and off (assistance not provided) without being taken off is very convenient and will potentially improve ease of use. For example, Armor-man2 (Tilta, Burbank, USA) and ExhaussWorker (Exhauss, France) allow users to release their hands in the middle of a task to rest or perform other tasks and resume by securing their hands to the exoskeleton again. It is important to ensure that the arm is stowed securely as the unstowed linkage is hazardous and may interrupt movements in restricted space. Therefore, a mechanism to easily deactivate and securely stow the exoskeleton arms when users need to release their arms is included in the proposed design.

3D Model of the Proposed Design

The proposed design of the exoskeleton was built and analysed in CAD software, Autodesk® Inventor® 2018 (Autodesk, Inc., CA, USA). The overall dimensions of the exoskeleton frame followed the anthropometric data of Malaysian workers (Hassan *et al.*, 2015). Conceptually, the assist mechanism would be placed below the user's arm and above the waistline, and the assistive force would be provided through a compression spring. The on-body deactivation mechanism was incorporated into the design of the arm linkage and the assist mechanism.

Determining the spring specification. Next, the dynamic simulation environment in Inventor 2018 was utilised to determine the appropriate compression spring specifications to assist arm raising during pole handling. The stiffness of a spring varies with the spring wire diameter, the number of active coils and the mean coil diameter based on the selected material. The dynamic simulation was performed in multiple iterations to obtain four spring specifications, with a spring load between 4 to 15 kg (the expected weight of the pole is at least 7 kg). During the simulation, the spring's outer diameter, length and number of active coils were kept constant based on the size of the exoskeleton's arm dimensions, while only the wire diameter was varied.

Structural analysis of the proposed design. Once the spring specifications were obtained, structural analysis of the exoskeleton was performed using the stress analysis environment in the same software. The objective of this analysis was to ensure that the physical prototype is reasonably safe for testing using human participants. For this analysis, a 10 kg load was applied to the exoskeleton arm cuff, which was well beyond the targeted load (7 kg), and the best spring determined through the dynamic simulation was used for this analysis. The stresses, deformation and strain for each component were investigated. A safety factor of 5 was chosen as the minimum acceptable value. The definition of the safety factor adopted was based on the ratio of the maximum allowable stress to the equivalent stress (von-Mises), where a value larger than 1 indicates no permanent deformation on the structure. The frame of the proposed exoskeleton was modelled as a rigid frame with aluminium material properties. The shoulder and waist harnesses were modelled with nylon material properties. The boundary conditions were defined based on the range of motion designed for the exoskeleton.

Verification of the Assist Mechanism Design

Next, a set of four springs were fabricated based on the outcomes of the dynamic analyses for the design verification experiment. The experiment was carried out to determine the range of the assist/non-assist region as the physical prototype of the arm assembly rotates, and consequently, the most optimal spring to assist harvesting. The most suitable spring is one that can handle at least 6 kg of external load and an assist region between the waist and the shoulder. The arm was secured to a benchtop, and a digital force scale attached to the free end of the arm was pulled vertically downward (*Figure 3a* and *3b*). The displayed force at every 10° angle was recorded manually. The experiment was repeated three times.

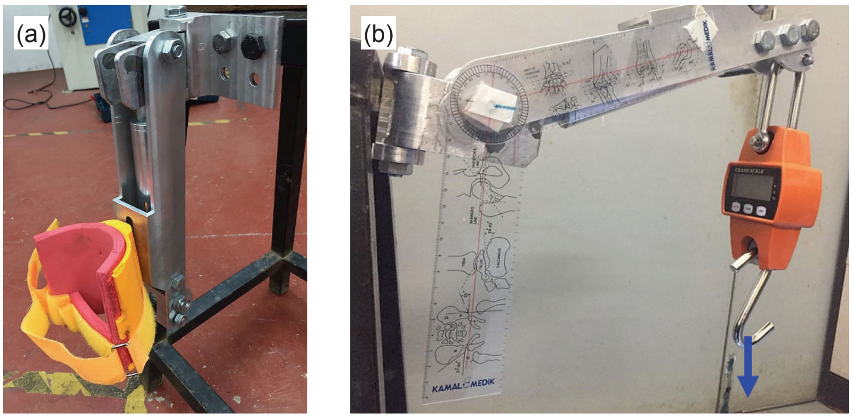

Figure 3. (a) The to-scale prototype of the arm linkage in stowed position secured to a benchtop. (b) The experimental setup to evaluate the range of motion of the arm linkage. The digital scale was pulled vertically downward as indicated by the blue arrow.

RESULTS AND DISCUSSION

The results are presented according to the order of the methods presented in the previous section, followed by a general discussion.

Muscle Activity for Selected Shoulder and Elbow Muscles During Harvesting

Harvesting the FFB involves two main movements, walking while handling the pole and cutting the frond and FFB. The average peak RMS of muscle activation for the observed muscles (deltoids and trapezius for the shoulder; triceps and biceps for the elbow) are shown in *Figure 4*. The average peak RMS pattern when comparing the left and right sides of each muscle is similar for harvesting and walking and harvesting alone, except for the trapezius. The trapezius is mainly used for scapular motion. For harvesting and walking, the peak RMS was highest in the left triceps, while for harvesting without walking, the peak RMS was highest in left deltoids and triceps. The level of activation was consistent for deltoids in both settings. Although triceps activation was high during walking and harvesting, its activation was almost halved during harvesting alone. Therefore, the assistive force was determined to be supplied from underneath the upper arm to benefit both the shoulder and elbow joints. We later learned that the immediate muscle activity in anterior deltoids and biceps indicated significant reduction when assisted by this exoskeleton during simulated pole raising and tugging (Harith *et al*., 2021). Biceps brachii is responsible for elbow flexion, while anterior deltoids are responsible for shoulder flexion. Nevertheless, participants highlighted that the design should be optimised for better usability and acceptance.

CAD Model of the Proposed Exoskeleton

The conceptual design, the CAD model and the proof-of-concept prototype of the exoskeleton are shown in *Figure 5*. The proposed exoskeleton is designed to assist oil palm harvesting, without its structure and movement interrupting the user's movement during harvesting. An assistive force is supplied in the upper arm region through compressive springs. The exoskeleton has a slimline design, and its main components are the back plate, the shoulder and waist harnesses, the arm coupling links and the assist mechanism in the arm assembly (*Figure 5b*). The exoskeleton is designed to rotate in three axes and perform a one-dimensional relative translation to follow the shoulder's range of motion as close as possible.

For anthropometric fit, the width of the exoskeleton frame is set at 30 cm and adjustable by ± 10 cm in accordance with the biacromial breadth measurement. The exoskeleton frame length was determined by subtracting the hip height from the shoulder height, both measured from the ground. Based on this calculation, the frame length is set at 50 cm and adjustable by ± 10 cm. The length of the support mechanism is 40 cm from the arm linkage joint, following the elbow span. The arm cuff is pinned in a slot on the arm linkage with screws and bearings so that the cuff can translate and rotate (component 5 in *Figure 5b*).

Arm assembly. The arm assembly (component 4 in *Figure 5b*) moves with the user's arm and supplies assistive force through compression springs during movement. It houses the assist mechanism (illustrated in detail in *Figure 6a*). The arm assembly and the arm cuff are designed to work together in following the shoulder's motion and providing uninterrupted motion of the shoulder. To do so, the frame link (component 3 in *Figure 5b*) enables the assembly's rotation about the longitudinal/vertical and frontal axes. Additionally, the arm cuff is designed to rotate as it translates along a slot on the arm assembly, partly to minimise arm sliding within the cuff during motion. This movement configuration also aims to compensate for the length difference between the user's arm and the arm linkage, enabling smooth and comfortable movement.

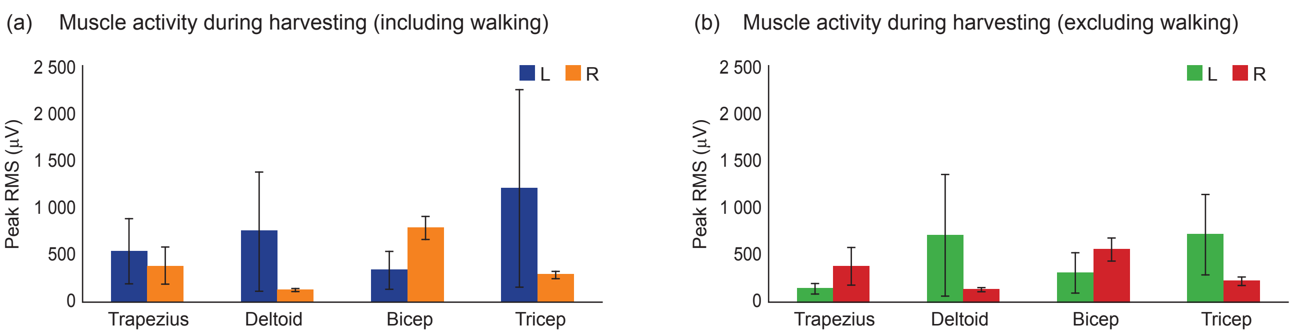

Figure 4. *Average peak RMS of the EMG signal for all observed muscles during harvesting one oil palm tree (top: walking and harvesting, bottom: harvesting only). The results for harvesting only highlight the outcomes during the pushing and pulling of the pole for cutting.*

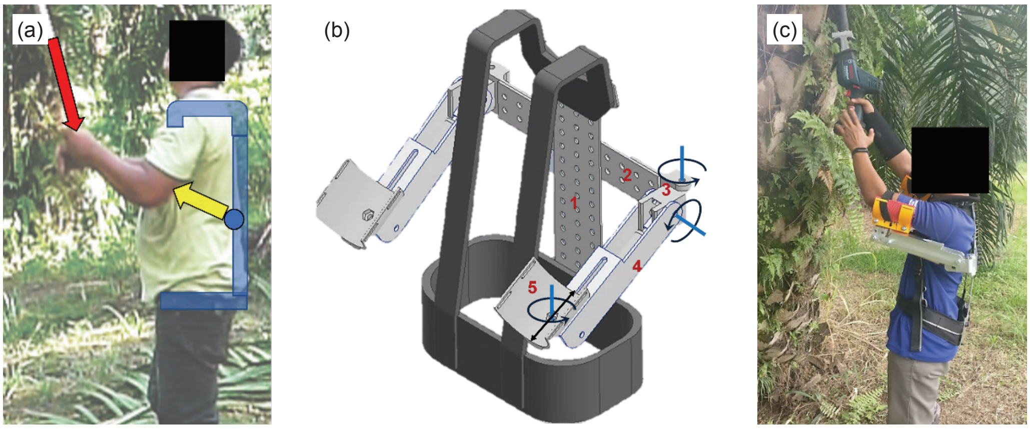

Figure 5. (a) The concept design of the exoskeleton. Thick blue lines represent the exoskeleton frame, which extends from the shoulder to the waist. The yellow arrow indicates the direction of the assistive force. The red arrow indicates the force from the pole. (b) Isometric view of the CAD model of the proposed design. The blue arrow is the axis of rotation at the joint and the black arrow is the type and the direction of movement of the component. The numbered components are [1] back plate, [2] top horizontal bar, [3] frame link, [4] arm assembly, and [5] arm cuff. (c) The physical proof-of-concept prototype is worn by a user.

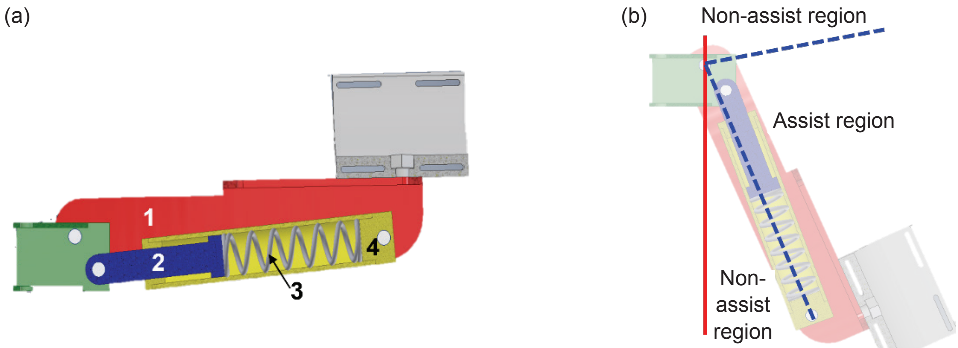

Figure 6. (a) A cross-sectional view of the arm assembly. The assist mechanism consists of [1] assembly frame, [2] guide shaft, [3] compression spring and [4] spring casing to prevent the shaft and spring from buckling. (b) The range of motion of the assembly (indicated by the red line) is limited by the shape of the frame link (green) and the configuration of the holes. The assembly moves between assist and two non-assist regions during motion.

The assist mechanism comprises an assembly frame, a guide shaft, a compression spring and a spring casing (*Figure 6a*). The assist mechanism is designed to move seamlessly between the assist and non-assist. Referring to (*Figure 6b*), when the assembly is loaded and begins to rotate downward, the guide shaft will push against the compression spring, shortening it and increasing its tension. When the maximum compression is reached, the spring returns to its original length and the assembly is now effectively in the non-assist region. This design allows uninterrupted arm movement when pushing/pulling the pole. On the other hand, if the assembly rotates upward from its unloaded/neutral position, the compression spring is already at its maximum length. Therefore, it does not provide any assistive force.

For on-body deactivation and safe stowing of the arm assembly, the assembly shall be lowered until it is in the non-assist region, where the spring returns to its original length and is unloaded. The absence of an assistive force that pushes up the arm assembly in this region allows it to be stowed safely for the user to free the arms for other tasks. The assist mechanism can be reactivated when the user raises the assembly into the assist region. The design on the exoskeleton also allows the unloaded/neutral position to be varied according to the user's anthropometry or preference, such as by changing the location of the arm assembly further up or down along the backplate, and spring specification by changing the spring (Tumit *et al*., 2021).

Spring specification. Four spring specifications were selected based on the outcomes of the iterative dynamic analyses (*Table 1*). Only the wire diameter was varied in the simulations. Considering the design aim of this exoskeleton, Spring 3 is potentially the most optimal spring as it has a spring load of 6.0 kg (or a total of 12.0 kg for both sides). A verification experiment was performed to confirm this hypothesis.

Harvesting is a non-symmetric motion as the shape and dimension of the pole necessitate that one arm is positioned above the other when handling the pole. Therefore, the amount of assistance required

TABLE 1. THE SPECIFICATION OF FOUR COMPRESSION SPRINGS

Spring parameter	Spring 1	Spring 2	Spring 3	Spring 4
Outer diameter (mm)	26.0	26.0	26.0	26.0
Number of active coils	13.0	13.0	13.0	13.0
Wire diameter (mm)	3.5	4.0	4.5	5.0
Spring constant, k (N/mm)	10.0	18.3	31.4	51.4
Maximum spring load (kg)	3.7	5.8	6.7	13.6

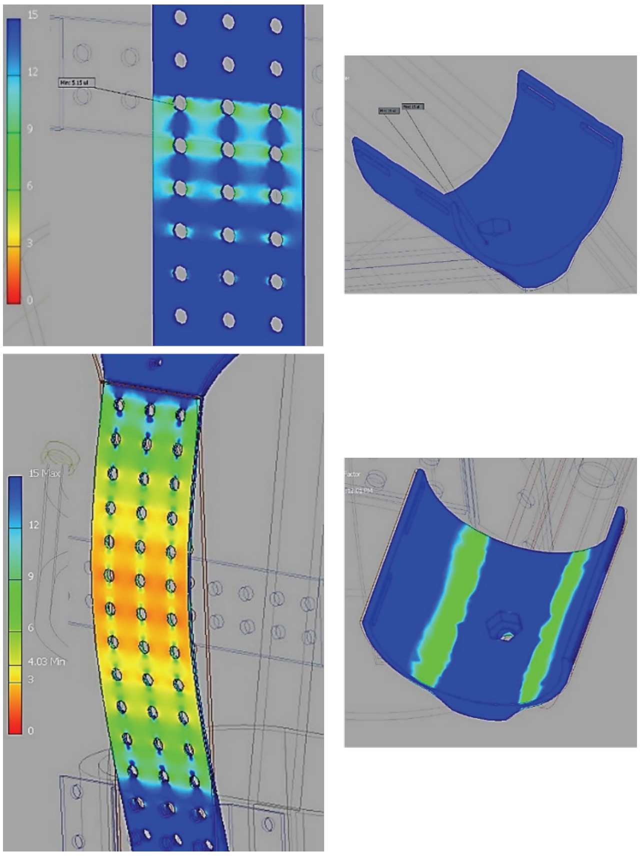

Figure 7. Two of the main exoskeleton components (left to right: back plate, arm cuff). Both were loaded with a 10.0 kg load (top row) and a 26.0 kg load (bottom row) on the arm support assembly. Legend indicates the safety factor (15, blue to 0, red). When loaded with 10 kg, the lowest safety factor (5.15) was found on the backplate in the green/aqua region. When loaded with a 26.0 kg load, permanent yield first occurred on the backplate in the red/orange region.

on each arm is likely different. Ideally, the spring specification should be customised according to the needs of each arm. This is also evident through the muscle activation results in *Figure 4*, which shows that the peak RMS for the left and right sides of each muscle were different.

Structural Analysis of the Proposed Design

Based on a safety factor of 5, the stress analysis results indicate that permanent deformation is not expected on the main components of the exoskeleton. The structural design verification of the exoskeleton is important prior to testing on human participants. Further optimisation of the design and usability is expected in future design iterations. Based on the structural analysis results, the back plate appears to be the weakest link in the design as it has the lowest safety factor, 5.15 [*Figure 7* (top row, left)] when the arm is loaded with 10.0 kg load, and it would be the first to deform permanently when a minimum of 26.0 kg load is applied on the arm [*Figure 7* (bottom row, left)]. A field analysis involving harvesters using the physical exoskeleton is required to verify if a load equivalent to 26.0 kg will be reached during its period of usage.

Verification of the Assist Mechanism Prototype

The profiles for Spring 1, Spring 2 and Spring 3 based on the design verification experiments are illustrated in *Figure 8a*. Spring 4 was excluded from this experiment as it was found to be extremely stiff and unrealistic for actual usage. As seen from the profiles, the springs had slightly different unloaded/neutral positions, indicated by the largest angle for each curve. Generally, the neutral positions range between 20° to 40° from the horizontal axis. The peak assistive force and the range of assistive region also vary between springs. Spring 3 could handle the highest externally applied force (~61 N) and the widest assist region (~120°). Its assist region also lies between the waist and slightly above the shoulder. The peak force for Spring 3 is quite comparable to the spring load produced by the dynamic simulation (5.8 kg in *Table 1*). Therefore, it is postulated that Spring 3 is most suitable to assist harvesters.

As indicated in *Figure 8a*, for the current design, the spring specification influences the range of the assist region. This means that the spring can be changed to suit individual users and/or tree height. The expected weight of an aluminium pole to harvest trees less than 4.5 m high is 7.0 kg (3.2 m) for which Spring 2 or Spring 3 may be used (Jelani *et al.*, 2008). It is also highly likely that different springs can be used on each side as the range of motion and muscle activity of the joints differ between the dominant and supporting arm when aiming and cutting, which is also illustrated in *Figure 3* (Chan *et al.*, 2022; Harith *et al.*, 2021; Tumit *et al.*, 2021).

The variation in the assistive region between the springs can be attributed to the spring specifications and the design of the assist mechanism. The spring specification is represented by the value of the spring constant, *k* N/mm. Additionally, in the current design, the assist mechanism can be considered a three-link mechanism [*Figure 8(b)*]. The lengths of all links are constant. For this configuration, as the arm assembly rotates, the vertical force balance analysis occurs between the weight of the arm assembly, the downward force applied on the arm, and the vertical component of the spring force because the spring is always at an angle with respect to the assembly frame. The vertical component of the spring force can be calculated as $k*\Delta X*\cos\theta$, where k is the spring stiffness, ΔX is the change in spring length and θ is the angle between the assembly frame and the vertical axis. The value of k differs between springs and dictates the rate of shortening or lengthening of the spring according to an applied load. The compression spring will shorten when an external load is applied. Theoretically, softer springs need smaller force to start compressing in comparison to stiffer springs.

In this study, all springs had different k but the same unstretched length, and the length of all three links are constant (*Figure 8b*). Accordingly, given the same amount of external load, the ΔX and θ will vary between springs. This partly explains the variation in the neutral/unloaded position of the arm assembly illustrated in *Figure 8a*, which entails force balance between the weight of the arm assembly arm and the spring force. The neutral/unloaded position of Spring 1 (k = 10 N/mm) is closer to the body trunk as it is the softest spring (Spring 2, k = 18.3 N/mm and Spring 3, k = 31.4 N/mm). Next, when the arm assembly is pulled down, the force balance occurs between the weight of the arm assembly, the spring force and the downward pulling force. In this case, the pulling force, the spring constant, k and ΔX vary between springs and contributes toward the variation in the assist region illustrated in *Figure 8a*.

Design Limitations and Future Work

The exoskeleton design process commonly begins with considering the bodily area or joint requiring assistance when performing a task,

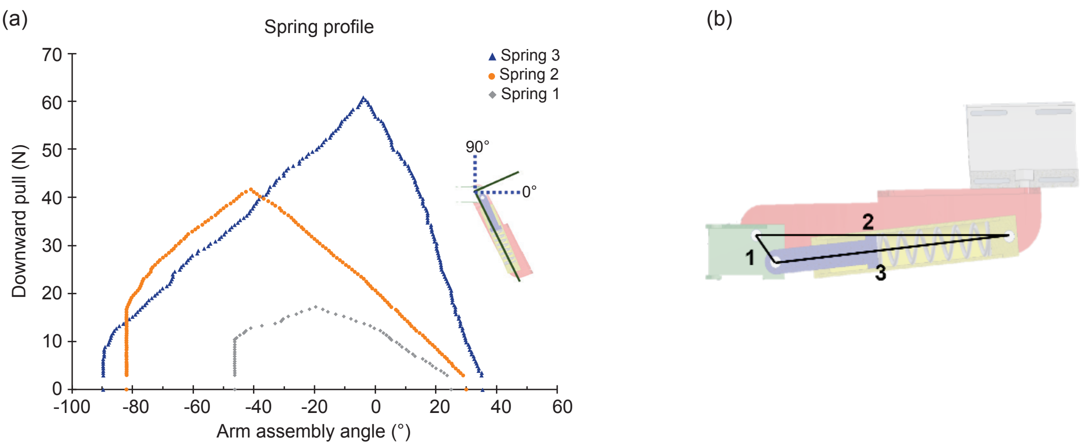

Figure 8. (a) The variation in the applied vertical force with the angle of the assistive arm assembly. Each curve corresponds to the three tested springs. The range of the assist region (between the two solid lines in the figure insert) is between the minimum and the maximum angle for each curve. 0° aligns with the horizontal axis and 90° aligns with the vertical axis. Spring 3 has the highest stiffness value and Spring 1 has the lowest stiffness value. (b) An illustration of the three links (numbered) for the assistive mechanism, which connects all of the components within the arm assembly.

followed by determining a potential assistive mechanism and then designing the mechanism and structure. This approach has not yet resulted in an exoskeleton that is optimally designed for a challenging environment and/or for an operation with varying tasks (Mudie *et al.*, 2022). Recent discussions on the need for systematic methods to introduce exoskeletons at workplace and the recommendation for using a user-centred design approach for designing exoskeleton also highlight the need for considering the work environment and the user-task-environment interaction when designing exoskeleton (Bornmann *et al.*, 2020; Dahmen *et al.*, 2018).

In this study, the systems approach was adopted to develop the design of the exoskeleton. This approach enable us to include the interactions between different elements interacting with the operators, including the tasks, the pole, and surrounding objects such as uneven ground, trees, hanging fronds, and objects on the ground, within its design criteria. Apart from the challenging oil plantation environment, the harvesting task itself is unique compared to the typical overhead task for which upper limb or shoulder exoskeletons are designed. Many upper limb exoskeletons aim to assist static overhead tasks by holding the arm for an extended duration. The harvesting of FFB involves dynamic and forceful pushing and pulling of the manual pole. Although forceful pulling can be reduced when using a motorised pole, carrying the pole and aiming it prior to cutting are still required. Hence, the proposed design is expected to still be applicable as the exoskeleton is intended for assisting the shoulder and elbow joints during harvesting. Furthermore, an on-body deactivation is included for the user's convenience and ease-of-use, in anticipation of the exoskeleton being worn throughout a long harvesting shift and that the user's movements are not limited to harvesting.

Design limitations. There are a few limitations in the current design. First, pole pushing and pulling is a bi-directional movement and is extremely frequent in harvesting. In this design, assistance is provided in one direction without interrupting the movement in the opposite direction. However, optimal assistance would be assisting in both directions. Therefore, alternative designs can be explored to assist in pushing and pulling, seamlessly.

Second, changes to the spring specification are limited to the spring casing and assembly frame dimensions, and the amount of assistive force is determined exclusively by the angle of the arm assembly. Future work on this design includes building passive mechanisms that can tune the assistive force to match the load experienced on each shoulder.

Current challenges in exoskeleton design. One of the key challenges in exoskeleton design is addressing the effects of complex and dynamic human-machine interactions on the user, the exoskeleton and the environment, especially over an extended duration (Howard *et al.*, 2020; Mudie *et al.*, 2022; 2018; Theurel *et al.*, 2018). Furthermore, industry players, including plantation owners and harvesters themselves, frequently inquire about the exoskeleton-wearing effects on workers' efficiency and field productivity. The answer to this question is not available, yet. Since the exoskeleton is constantly in physical contact with the user, it is important to elucidate the system's effects on the users, users' adaptation (physical and cognitive adaptation) to the system over time, and how these interactions translate into field and worker productivities. Common evaluation approaches on short-term effects include experiments involving human participants that are performed within relatively controlled environments, or simulations using complex modelling systems, such as seen in Hansen *et al.* (2018); Schmalz *et al.* (2019), and Theurel *et al.* (2018). Both approaches do not illustrate the real effects of exoskeleton wearing in the field. To date, reports on field effectiveness of exoskeletons are still limited, and when available, the assessment criteria varied, preventing one-to-one comparison.

Designing a functional and effective exoskeleton requires input and insights from multiple stakeholders and academic disciplines. Further work includes performing biomechanical investigation using computer simulations to better understand how and why users adapt to exoskeleton wearing when harvesting, modifying the structural design toward a leaner arm assembly and performing field tests involving experienced and non-experienced harvesters to elucidate the usability and reliability of the exoskeleton for harvesting operation and productivity. The outcomes of these tasks will be used to optimise the overall exoskeleton design so that it fits the user, the tasks, the operation, and the work environment appropriately.

CONCLUSION

Successful adoption of exoskeleton technology is partly contributed by the alignment between the design of the system, the tasks, the user's movements and the working environment, and the impact of the technology on workers' efficiency and field productivity. It is also easy to imagine that poor alignment between an exoskeleton design, users' needs and work environment will result in technology rejection altogether. In the proposed design, the working environment and the user's movement during harvesting were incorporated into the design criteria via the systems approach. This aspect is largely missing in designing exoskeletons for challenging environment, partly contributing to poor applicability in the actual environment.

For this proposed design, the muscle activity during a complete harvesting task involving walking with a pole and cutting the FFB was observed to determine the targeted area requiring assistance. The exoskeleton is designed to assist harvesting task and minimise movement interruptions throughout the exoskeleton-wearing duration. Therefore, assistive force is provided in the upper arm region to benefit the shoulder and elbow joints, and no component is placed above the shoulder and below the waist that may interrupt pole movement. Moreover, an on-body deactivation mechanism is designed for the user's convenience, which allows users to release the arm without doffing the system by moving the arm linkage assembly into the lower non-assist region.

A detailed biomechanical investigation on the effects of the exoskeleton on the user's movements during field harvesting, and a comprehensive field assessment to determine the effects of exoskeleton usage on the harvester's efficiency and harvesting productivity are imperative to determine the overall impact of exoskeleton usage for harvesting. The need for technology to make harvesting more efficient is urgent. While full mechanised solutions are being developed, exoskeletons present an immediate alternative to enhance skilled harvesters. The exoskeleton design presented in this article is an initial attempt at exploring this alternative; further iterations and design concepts are inevitable. The combined outputs from biomechanical analysis and field tests should be synthesised for more accurate and faster exoskeleton development; that is an exoskeleton that can effectively assist harvesting, and enhance harvesters' performance and field productivity.

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