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Short Communication

Finite Element Analysis and Comparative Evaluation of Two Passive Exoskeleton Designs for Oil Palm Harvesting

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Abstract: This study presents a finite element analysis (FEA) of two passive exoskeleton designs developed to reduce physical strain during oil palm harvesting. Static load simulations (50 N) were conducted using SolidWorks Simulation to evaluate von Mises stress, total deformation, and reaction forces. The models were built from 1060 alloy and ABS-PC materials. Results indicated that Exo_Full-ASM demonstrated lower stress (8.70×10^7 N/m²), strain (1.01×10^{-3}), and displacement (17.1 mm) compared to Exo_Full-ASM 2, showing superior load redistribution and structural stability. These findings suggest Exo_Full-ASM is more suitable for heavy harvesting tasks. Future work will include field trials and EMG analysis to validate ergonomic performance.

Keywords: harvesting; oil palm; passive exoskeleton

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1. Introduction

Malaysia has established itself as one of the world's leading producers and exporters of palm oil, with the oil palm sector serving as a vital component of the national agricultural economy. The extent of palm oil cultivation in Malaysia has expanded significantly, exceeding 5.67 million hectares, which corresponds to approximately 17% of the country's total land area (Senawi *et al.*, 2024). This considerable area includes many mature oil palm trees, which can exceed five meters in height, presenting unique harvesting challenges. Despite advances in plantation mechanisation, the harvesting of Fresh Fruit Bunches (FFB) continues to rely heavily on manual labour, particularly in regions where the terrain complicates the use of machinery (Rahim *et al.*, 2023; Forest *et al.*, 2024).

Manual harvesting is labour-intensive, requiring substantial physical exertion from workers. This reliance on manual labour not only increased physical burden on harvesters, who engaged in repetitive and strenuous upper body movements, but also raised concerns regarding their health and safety (Bhuanantanondh *et al.*, 2021). These types of tasks expose workers in the harvesting sector to a high likelihood of developing musculoskeletal disorders at the shoulders, lower back, and arms due to the harsh working postures and awkward sitting stances used when manually harvesting FFB with the Cantas (Chan *et al.*, 2022). Increasing concerns about employees' health and productivity have led to calls for sophisticated ergonomic mitigation measures to enable the well-being of workers in the region (Bhuanantanondh *et al.*, 2021; Nambiappan, 2018).

Given these challenges, recent studies have emphasised the necessity for sophisticated ergonomic interventions to protect worker health and enhance productivity (Meor Saedin *et al.*, 2025; Thamsuwan *et al.*, 2020). Passive exoskeletons, which assist body movement and redistribute loads without external power sources, present a promising solution due to their low cost, lightweight design, ease of maintenance, and practicality for both smallholders and larger plantations in Malaysia (De Bock *et al.*, 2022; Du *et al.*, 2022). These devices are especially beneficial in the context of agriculture in Malaysia due to their attributes of being low-cost, lightweight, easily maintained, and practicality to smallholders and larger plantations (Nawik *et al.*, 2015). Despite global advancement in research on exoskeleton technology, there is still a gap in passive systems designed for the Malaysian agricultural sector (Forest *et al.*, 2024). More research on mechanical performance and additional features of passive exoskeleton designs, particularly finite element analysis (FEA), is required so that these devices can properly match the local harvesting activities (Nawik *et al.*, 2015; Pramana *et al.*, 2021).

This study intended to apply finite element analysis toward two designs of passive exoskeletons aimed at assisting upper limb movements to enable better oil palm harvesting. Models were analysed for stress concentration and deformation patterns as well as stress transfer during simulated conditions, such as a static load of 50 N. The outcome of these designs will contribute to the development of ergonomic devices to relieve physical stress, improve safety, and increase productivity among Malaysian oil palm harvesters (Pramana *et al.*, 2021). Further stages of the study will be on validation through field testing and EMG analysis, which is designed to optimise the performance of these passive systems for actual usability in the field.

1.1. The Design Consideration

The proposed passive exoskeleton system integrated biomechanical support mechanisms in order to address ergonomic problems of the oil palm motorised harvesting tool (Figure 1). The configuration employed an articulated shoulder-load redirecting mechanism consisting of elastic materials and precisely engineered linkages that redirected approximately 40-60% weight moment of the tool. The system employed passive energy-storing components that were used to recover and release stored kinetic energy under cyclical cutting motions to support the motion's efficiency. The structure utilised anti corrosion materials (carbon fibre reinforced polymers) with selective reinforcement of aluminium alloy, with an overall system weighing less than 4.5 kg and requiring structural integrity. All load-bearing interfaces utilised waterproof bearings and corrosion-proof fasteners that could tolerate tropical operating environments. The strict mechanical philosophy of design eliminates electrical components, is highly reliable and minimises the need for maintenance. Future design iterations can explore variable-stiffness elements and posture-dependent torque profiles to offer improved ergonomic support for various harvesting tasks.

The forces applied to the system during harvesting are critical for the determination of the biomechanical load on the worker. The force of gravity (Fg) is the primary downward force of the total weight of the harvesting tool. The worker compensated this force by exerting a force (FT), not only to counteract the gravity, but also for the vertical component of the acceleration in the downward direction. The normal force (FN) is the upward force of the ground to counteract the weight of the system, with consideration for the vertical component of the acceleration. These forces play a vital role in the guidance of exoskeleton design, ensuring effective load redistribution as well as promoting ergonomic performance for reducing the workload faced by the worker during harvesting.



Figure 1. Oil Palm Motorised Cutter during harvesting operation

The gravitational force (Fg) of the harvesting tool was calculated using its mass (m) and gravitational acceleration (g), as shown in Equation (1). For a tool mass of 7.8 kg and gravitational acceleration of 9.81 m/s², the gravitational force was estimated to be 76.5 N. Assuming that 60% of this force was transferred to the exoskeleton through the load-redistribution mechanism, the estimated supported force was 45.9 N. A nominal static load of 50 N was subsequently used in the finite element analysis (FEA) as an approximate representation of this load.

Summary of Forces:

$$(i) - The\ gravitational\ force\ Fg = (m_{tool})g = (7.8kg)(9.81) = 76.5N$$
$$= 76.5N\ x\ 60\% = 45.9N\ \approx 50N \quad (1)$$

2. Materials and Methods

2.1. Design Software and Modelling

This study presents two designs of passive exoskeletons, ExoFull-ASM and ExoFull-ASM 2 (Figure 2), to relieve strain on the shoulders and back while performing oil palm harvesting tasks. Both designs aimed to redistribute load through anatomical routes. Consideration of Computer Aided Three-Dimensional Interactive Application (CATIA) software (Dassault Systèmes, France) in the design and modelling stage constituted a large part of the study. Both exoskeletons were designed and developed in CATIA with characteristics that allowed measurable control of geometrical features, joint structure and lower limb mobility. Even though both prototypes originated from the same idea, there were distinct designs, particularly at the lower body. Both prototypes contained modular frames constructed from a strong but lightweight 1060 aluminium alloy and durable ABS-PC joint housings. The mechanical properties used in the simulation are listed in Table 1. These materials had optimal strength-to-weight ratios and improved the user's mobility due to their designs with elastic joints that permit the user to create natural arm-cuts during harvesting procedures.



(a) (b)

Figure 2. Passive Exoskeleton (**a**) ExoFull-ASM; (**b**) ExoFull-ASM 2

2.2. Finite Element Analysis (FEA)

The mechanical performance of both exoskeleton designs was measured through FEA simulation via SolidWorks Simulation under realistic loading conditions. Finite-element models were generated using the blended curvature-based solid mesher in SolidWorks Simulation. Each model used solid tetrahedral elements (Tetra10) with an average mesh size of 3 mm, refined to 1.98 mm near joint regions. The Exo_Full-ASM 2 mesh contained ≈ 98 300 elements and 191 900 nodes. Mesh-convergence checks (< 5 % variation in von Mises stress) confirmed mesh independence. Boundary conditions fixed the hip and lower-back interfaces to replicate actual wearing constraints, while a static vertical load of 50 N was applied at the upper-arm link representing the harvesting-tool weight. Reaction forces were recorded at the fixed supports. Model accuracy was cross-checked by verifying equilibrium between applied and reaction forces. A static load of 50 N, considering 60% Fg or the combined weight of the harvesting tool, was applied to both exoskeletons. These static load cases focused on important physical parameters (mainly Von Mises stress distribution, total deformation, and reaction forces at joints), while considering boundary conditions - the model was fixed at the hip and lower back to account for real-world wear. A static vertical load of 50 N was placed to simulate the combined weight of the harvesting tool to closely examine the design model's structural performance.

Evaluation metrics to assess these designs focused on the determination of stress concentration areas, along with estimating potential fatigue life, which gives information about possible areas of failure and longer-term durability for repetitive loading. Comparison of both models as a function of mechanical performance, load distribution, etc. and key elements, such as efficiency of load transfer at joints in a structure and bending moment values of the bending moment diagram were made. This review process ensured improvement in operational efficiencies and reduction of physical demands on the user associated with the increasing risk of accruing musculoskeletal injury from repetitive harvesting activity.

Figure 3 illustrates the Finite element model of the applied boundary conditions and external load. The model is constrained at the mounting regions of the structure. A vertical static load is applied at the tool-attachment point on the upper arm link (indicated by the purple arrow). Reaction forces are obtained from the constrained regions.

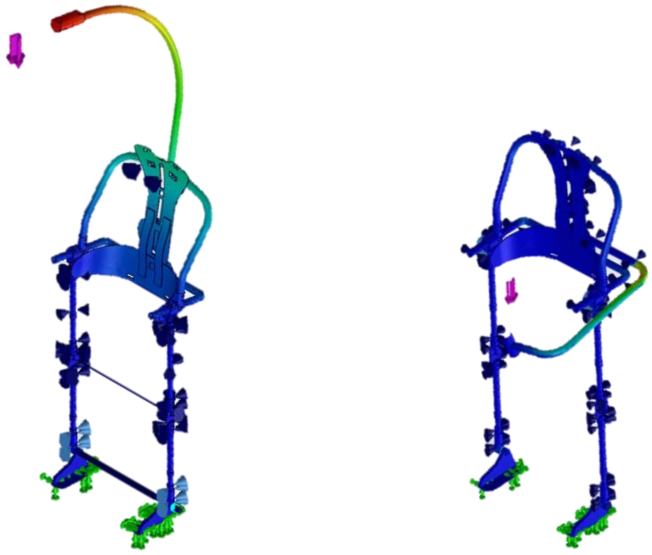


Figure 3. Comparative mechanical response of Exo_Full-ASM and Exo_Full-ASM 2 under a 50 N static vertical load.

Table 1. Mechanical properties of materials used in the analysis

Material	Young's Modulus (GPa)	Yield Strength (MPa)	Poisson's Ratio	Density (kg/m^3)
1060 Alloy	69	27	0.33	2710
ABS-PC	2.1	46	0.37	1050

3. Results and Discussions

Finite element results for both designs under a 50 N static vertical load are summarised in Table 2. Exo_Full-ASM recorded a peak von Mises stress of 8.699×10^7 Pa (≈ 87 MPa), maximum strain of 1.013×10^{-3}, and maximum displacement of 17.1 mm. Exo_Full-ASM 2 recorded a peak von Mises stress of 5.568×10^8 Pa (≈ 557 MPa), maximum strain of 1.793×10^{-2}, and maximum displacement of 18.51 mm.

The substantially higher stress and strain in Exo_Full-ASM 2 indicate localised stress concentrations and greater deformation under the same loading condition. Lower displacement in Exo_Full-ASM implies higher stiffness and better structural stability, as the design resists deflection more effectively when subjected to the same static load. A stiffer frame ensures that external forces are distributed efficiently through the exoskeleton structure without excessive bending or flexing, reducing the risk of mechanical failure and improving user stability during harvesting movements.

Reaction forces measured at the constrained hip and lower-back supports were higher in Exo_Full-ASM (112.87 N) than in Exo_Full-ASM 2 (74 N). This result shows that Design 1 transfers a greater portion of the applied load to the wearer's support interface, consistent with its higher stiffness and better load-transfer capability. Because reaction-force magnitude depends on support geometry and constraint location, both reaction forces and deformation values are reported to provide a complete description of structural performance.

The higher forces observed in the y-direction for Exo_Full-ASM 2 (≈ 62.9 N) suggest uneven load distribution through the joints and supports, which may contribute to local stress peaks. Overall, these findings confirm that Exo_Full-ASM performs more reliably under heavy-duty or repetitive harvesting loads, whereas Exo_Full-ASM 2 tends to become less stable and experiences higher stress concentrations.

While the first exoskeleton design demonstrated superior mechanical behaviour under static conditions, the second design remains advantageous in weight distribution and could be improved through structural optimisation, particularly by refining connection geometry and selecting materials with higher yield strength.

It must be emphasised that this investigation employed linear-elastic static analysis only. Dynamic loading, fatigue behaviour, and user device interactions were not considered. Therefore, future work should include dynamic FEA and experimental validation (e.g., EMG and field trials) to fully evaluate ergonomic performance and long-term durability under real harvesting operations.

Table 2. Mechanical properties of materials used in the analysis

Parameter	Exo_Full-ASM	Exo_Full-ASM 2	Remarks
Maximum Stress (N/m²)	8.699×10^{7}	5.568×10^{8}	Higher stress in the second design.
Maximum Strain	1.013×10^{-3}	1.793×10^{-2}	More strain in the second design.
Maximum Displacement (mm)	17.1	18.51	Higher displacement in the second design.
Reaction Force (N)	112.87	74	Better applied forces redistribution in Exo_Full-ASM.

4. Conclusions

The comparative static FEA indicates that Exo_Full-ASM (Design 1) outperforms Exo_Full-ASM 2 (Design 2) in terms of lower peak von Mises stress, lower maximum strain, and lower or comparable displacement under the applied 50 N static load. These results point to better static structural stability and load redistribution in Design 1. Exo_Full-ASM 2 exhibited localised high stresses and larger strains, indicating the need for further structural refinement. Although the findings provided considerable evidence of mechanical improvement, the effectiveness of the exoskeleton needs further validation in an actual field situation. Future work will incorporate experimental trials and EMG data to access real life muscle activation and users' feedback. This will provide direct insights into the biomechanical benefits of the device, aiding in future development. Overall, findings from this study highlighted the benefits of passive exoskeletons, being practical and low-energy solutions that can lead to greater worker safety and productivity within the agricultural industry, specifically in the demanding environments faced by workers in oil palm plantations.

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