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# Design and analysis of a passive upper limb exoskeleton for augmented construction worker strength

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## Abstract

Construction workers often operate at great heights, relying heavily on their muscles to support work-related weight. Over time, this leads to fatigue, and in worst-case scenarios, accidents occur when workers drop heavy objects due to exhaustion. This study then focuses on designing and implementing a passive upper limb exoskeleton to enhance worker performance and reduce fatigue in industrial environments. The exoskeleton utilizes a rack-and-pinion mechanism synchronized with natural arm movements to provide gravitational support. Key features include an adjustable range screw for easy disengagement and a ball-and-socket joint for arm dexterity. The exoskeleton is customizable through torque adjustment, ensuring user-specific support. Three different designs were created in SolidWorks and evaluated in Ansys simulation to select the best one. These designs incorporated materials such as carbon fiber and nylon. Loading tests were conducted on the designs, and for the best design, the maximum deformation for carbon fiber was 0.8mm, while for nylon, it was 1.17mm. The maximum stress for carbon fiber was 11.9 MPa, while for nylon, it was 18.16 MPa. The factor of safety for the carbon fiber material was 2.1, while for nylon, it was 1.38.

**Keywords:** Passive; Exoskeleton; Ergonomics; Overhead tasks

## Introduction

In industrial settings, workers often engage in physically demanding tasks that require sustained arm elevation and the handling of heavy tools. These activities can lead to significant fatigue, muscle strain, and a higher risk of injury [1]. According to [2], in order to mitigate these issues, the development of passive upper limb exoskeletons has gained attention. These devices are designed to support the arms during strenuous activities, reducing the physical burden on workers and enhancing their performance [2]. Safety and comfort of workers should be prioritized as one of the most important factors by designing the working environment and the equipment ergonomically. This significantly improves the efficiency of the worker which contributes to the financial benefits of the company [3].

The primary aim of this study is to design a novel passive upper limb exoskeleton that provides effective gravitational support for the arms, particularly during overhead tasks and extended tool use. Unlike active exoskeletons, which rely on powered actuators, passive exoskeletons use mechanical systems to achieve the desired support without the need for external power sources. This approach not only simplifies the design but also reduces the cost and maintenance requirements of the device.

The proposed exoskeleton leverages a rack and pinion mechanism that is synchronized with the natural movements of the user's arms. As the arms are raised, a rack descends in response to the rotating pinion, providing the necessary support. The design includes features such as an adjustable range screw for easy disengagement and a ball-and- socket joint to maintain arm dexterity. Additionally, the exoskeleton can be customized through torque adjustment, allowing users to tailor the support to their specific needs.

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This study builds on existing research that has demonstrated the benefits of exoskeletons in reducing muscle activity and preventing injuries. By focusing on a passive design, it aims to create a practical, cost-effective solution that can be readily adopted in various industrial applications. The ultimate goal is to enhance worker safety and efficiency, particularly in tasks that involve prolonged arm elevation and tool handling.

## Related Literature

Musculoskeletal disorders arise when worker fatigue exceeds the body's recovery capacity [3]. This issue is prevalent in the construction industry, where prolonged use of heavy tools and repetitive lifting are common ( [4]; [ 5 ] ; [ 6 ] ). Despite automation, certain complex tasks still require human agility and flexibility ( [7]; [8]; [9]). A passive exosuit is proposed to combine human agility with machine power, mitigating the effects of strenuous tasks.

A passive upper limb exoskeleton is a wearable device that supports workers' arms during strenuous or repetitive tasks, distributing the load throughout the body ( [11]; [12]; [13]). Its main goal is to reduce the risk of musculoskeletal disorders in industrial workers [14] [15]. Over time, exoskeleton designs have evolved from medical rehabilitation to industrial strength enhancement [16]. Various prototypes like SKELEX 360-FR and Mate-XT have been developed, but most support overhead tasks, not lower arm positions [17]. Additionally, high costs limit their affordability for companies in developing countries [18].

### *1.1.* Causes of upper limb injuries in industry

The construction industry is divided into three categories: building constructions (residential and non-residential), various industrial constructions (mines, refineries, power plants), and infrastructures (dams, bridges, large workstations [19]. These industries depend on their ability to be agile for growth. This agility can be enhanced in many ways one of which is designing for the ergonomics of the worker [20]. According to [3], upper limb musculoskeletal disorders (MSDs) in construction arise from repetitive motions, awkward postures, forceful exertions, and prolonged strain Specific activities associated with upper limb MSDs in construction. Construction workers frequently engage in manual handling tasks, such as lifting, carrying, and moving heavy loads. These activities can lead to overexertion of the muscles in the arms and shoulders, especially when proper lifting techniques are not followed [4].

### 1.2. Other existing exoskeletons

#### *1.2.1. Hyundai Vest exoskeleton [20]*

The H-vex exoskeleton was developed with input from automotive industry workers. It features two main mechanisms: a multi- linkage passive mechanism using three parallel springs for energy storage and assistive torque, and a polycentric linkage for shoulder movement that mimics the natural movement of the shoulder joints. The multi-linkage mechanism, with a stiffness of 33.6 N/mm, stores energy during arm lowering and releases it during arm elevation. The polycentric linkage addresses shoulder kinematics, avoiding misalignment by dynamically adjusting the center of rotation. The H-vex's effectiveness in reducing muscle activation during overhead tasks was validated using surface electromyography.

#### *1.2.2. Panto-Arm Exoskeleton [21]*

Developed by Virginia Tech's Mechanical Engineering department, the Panto-Arm exoskeleton provides gravity compensation for diverse arm orientations. Key features include a pantograph linkage mechanism with two links along the upper arm and forearm, a webbing strap, and a gas spring. This setup allows for support of the arm or a tool held in various positions, emphasizing minimal force when the arm is beside the body. The exoskeleton weighs 6.1 kg, costs approximately $5600, and uses a torque transmission mechanism to reduce force output at the hand.

#### *1.2.3. Mechanical Design of Passive Arm- Support Mechanism [22]:*

Developed by Huazhong University of Science and Technology, the passive arm support mechanism weighs 2.7 kg and offers flexibility with a user-operated locking/unlocking system. The design features a ratchet bar mechanism, pulleys, and a rope to convert upper arm rotation into linear motion.

The exoskeleton supports the arm when raised and allows free movement when the arm is lowered, controlled by the pawl module's position. The system's effectiveness was validated using software simulations, showing reduced shoulder force and torque, indicating potential relief from muscle fatigue. Surface electromyography confirmed reduced muscle activity during manual lifting tasks. Design optimization for such is key to ensure the right quality of materials and geometry is used to serve the purpose, whether it's a mechanical design or a process design. The parameters should be tested to determine the best combination and orientation [9].

*1.2.4. The ACASS [23]*

It is an advanced arm support exoskeleton with a latch-spring mechanism for adjustable torque, a 2-DOF yaw-pitch structure for shoulder movement, and a slider-crank- based CBM( counter-balance mechanism). It enhances arm strength assistance, reduces muscle strain, and offers faster torque adjustment compared to its predecessor, making it suitable for various tasks, with potential for construction-specific adaptations. The existing passive exoskeletons often have limited arm elevation angles, restricting their use in tasks like picking up bricks or working below shoulder level. This limitation highlights a significant gap in the industry: most commercially available exoskeletons are tailored for overhead tasks in the automotive sector, neglecting the needs of the construction industry where upper limb musculoskeletal disorders are common.

## Research methodology

The primary aim of this project was to design and develop a passive upper limb exoskeleton to support industrial workers during overhead tasks and prolonged tool handling, thereby reducing fatigue and enhancing performance. Optimization of the design was done by comparing parameters that determine that determine the design efficiency, a method also proposed by [5] even though it was applied in process parameter optimization.

**Table 1** Research methodology by objectives

| **Objective** | **Methodology** | **Tools** |
|---|---|---|
| Design a lightweight exoskeleton | Development of initial design concepts and topology optimization for material reduction.<br>Evaluation of different configurations | CAD software (SOLIDWORKS & ANSYS)<br>Literature review |
| Ensure arm dexterity | Incorporate a ball-and-socket joint mechanism and simulate a range of motion | SOLIDWORKS & ANSYS |
| Customizable Support Mechanism | Develop a system with adjustable torque settings<br>Test the system under various load conditions to ensure adjustability | Literature review<br>Finite Element Analysis |
| Develop a prototype | Manufacture a prototype based on the finalized design | Manufacturing Tools (3D Printer, CNC Machines |

## Exoskeleton design

Several possible designs were made and evaluated. These include:

### 1.3. Design concept 1: Shoulder torque generating mechanism

The design features a rack and pinion mechanism with a helical spring for torque generation, adjustable via a torque adjustment screw. It includes a ball and socket joint at the waist for natural arm movements and a range adjustment screw latch for customizable support. Advantages include simplicity, adjustability, and natural motion. Disadvantages involve potential discomfort, limited torque variability, and frequent adjustments needed. The design is shown below in Figure 1.

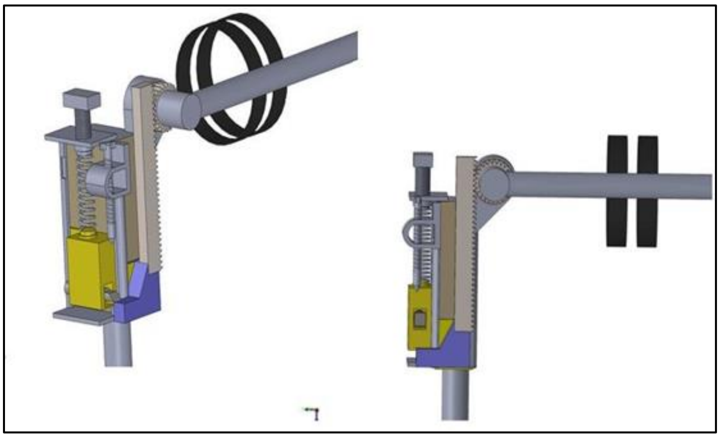

**Figure 1** Rack and pinion mechanism

### 1.4. Design Concept 2: Bowden cable and pulley arm mechanism

It utilizes a single Degree of Freedom (DOF) joint at the shoulder, complemented by a ball and socket joint at the waist to enable intricate glenohumeral joint movements. A Bowden cable and helical spring combination generates and transmits torque to the arm. The spring stores energy during extension and releases it as it returns to its original length. When the user carries a load, the spring compensates for movement against gravity by pulling down the Bowden cable via a pulley system, which also offers mechanical advantage and redirects force for arm support. Figure 2 shows the front view and side views of the design.


**Figure 2** Bowden cable and pulley arm mechanism

### 1.5. Design Concept 3: Back torque generator with pulley system

This design employs Bowden cables for torque transmission from the back to the arms, strategically placing the torque generator at the back to alleviate strain on the shoulder or arm. The design is shown below in Figure 3.

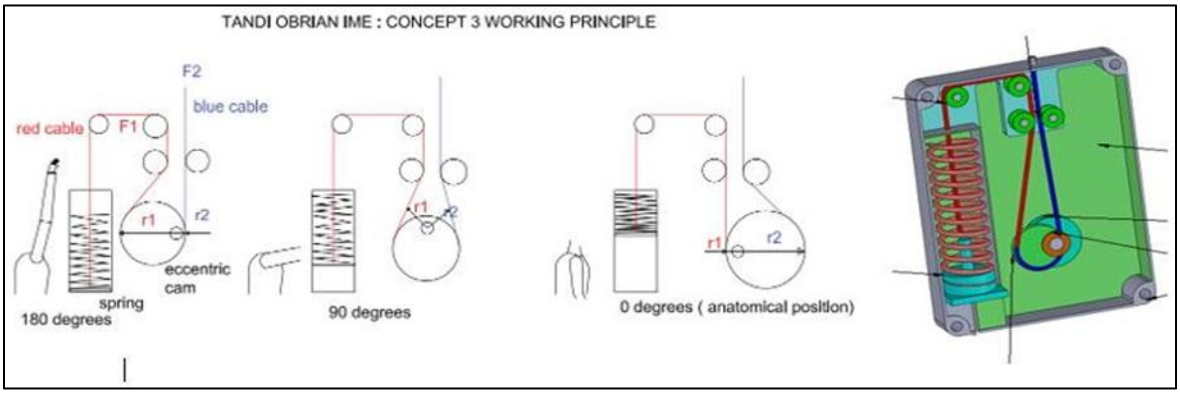


**Figure 3** Back torque generator with pulley system

The design has a single Degree of Freedom (DOF) joint at the shoulder and a ball and socket connection at the waist, this design optimizes support and mobility. The torque generator uses a helical spring, rollers, and an eccentric CAM to balance and enhance force distribution for arm movement. It leverages the variations in cable tension caused by the eccentric CAM as the arm is moved, as shown in the diagram.

## Results

Design calculations were carried out based on two tasks by calculating the force required to carry out these tasks without the exoskeleton arm and then calculating the exoskeleton torque with a safety factor

### 1.6. Torque calculations results

Two tasks were used to test the design of the exoskeleton as compared to carrying out the task without. The tasks are shown below in Figure 4.

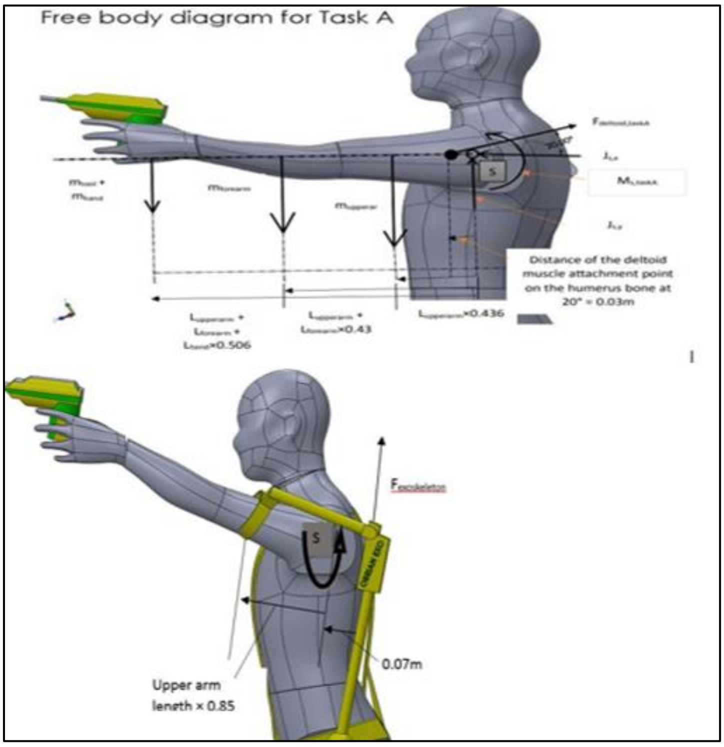


**Figure 4** Tasks A and B with exoskeleton and without

The results show that the exoskeleton significantly reduces the force needed to carry out a task by an operator. The results are shown below in Table

**Table 2** Results for the tasks A and B with and without the exoskeleton

| Task | Weight of worker | Force needed for the task |
|---|---|---|
| A | 500 | 47.75 |
| A | 1000 | 33.75 |
| B | 500 | 29.13 |
| B | 1000 | 19.32 |

### 1.7. Design validation

A factor of safety of 2 was used in the design and validation. Using a force of (47.75 × 2) ,the design was tested for total deformation, stress and strain in ANSYS workbench. The results are shown in the image.

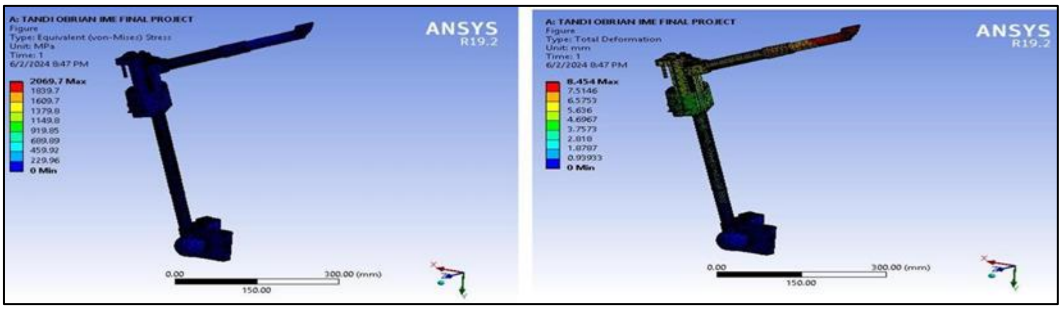


**Figure 5** Design stress and strain analysis for the design

The rack and pinion was tested for material selection and the results are shown below:

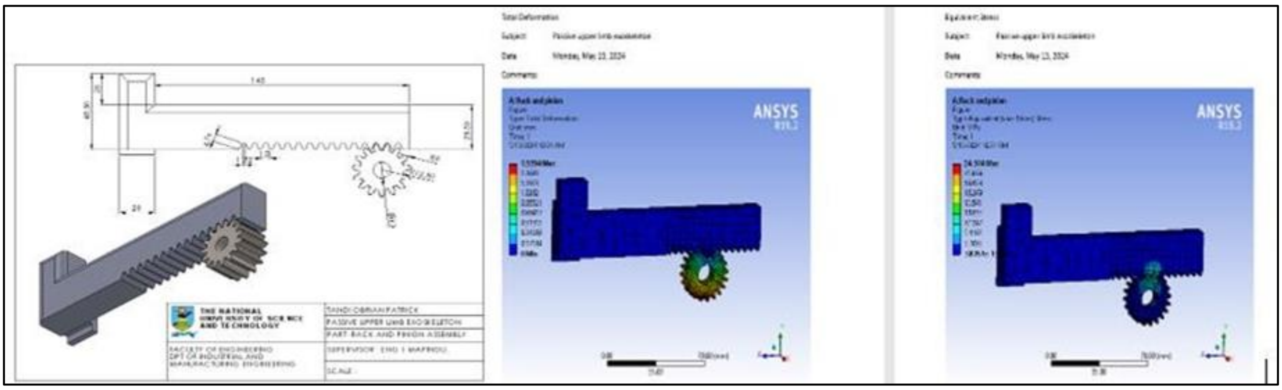


**Figure 6** Rack and pinion analysis

Results for the comparison of nylon material strength (cheaper) against carbon fibre (expensive) are shown in the graph. Nylon is comparable to carbon fibre for the rack and pinion mechanism hence it is the better option.

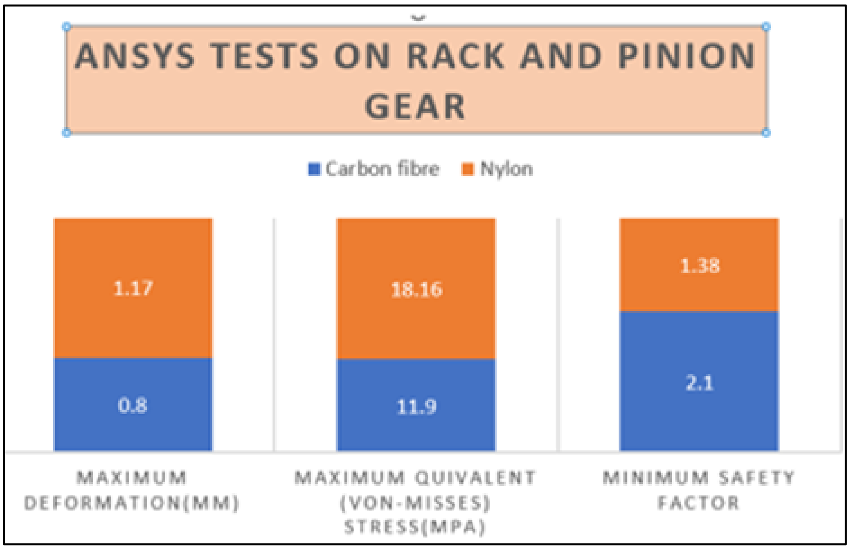


**Figure 7** Material comparison results

### 1.8. Mass of the exoskeleton

The total mass of the exoskeleton after topology optimization of parts in ASNSYS was found to be 2.6kg and was then compare to the other existing exoskeletons. The results of the comparison are presented graphically below.

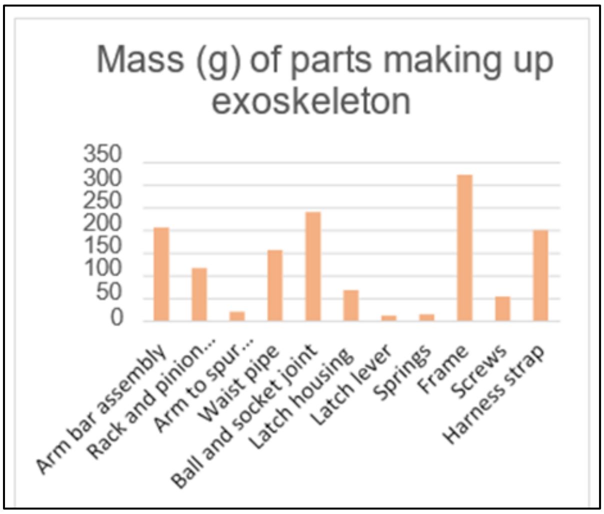


**Figure 8** Mass of exoskeleton parts

### 1.9. Comparison with other designs

A (BOM) was prepared for the exoskeleton parts and the resulting total price for the exoskeleton including material cost, fabrication cost and miscellaneous cost was US $387. Comparing with the existing exoskeletons, the device is much cheaper and hence meets the objective of designing a low cost exoskeleton.

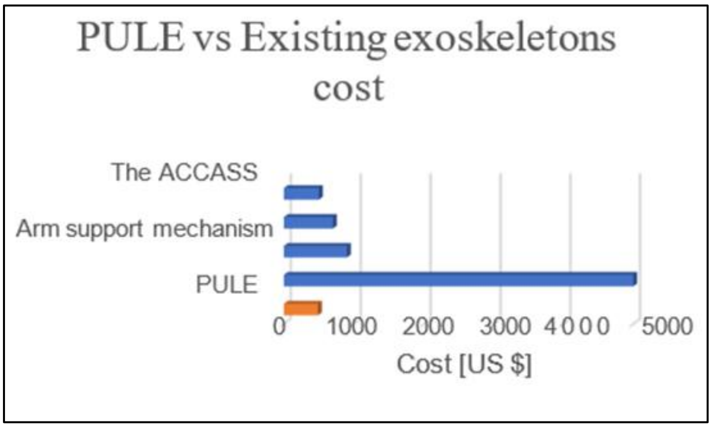


**Figure 9** Cost comparison with other designs

*Recommendations*

Further testing and validation, there is a need to conduct extensive field testing in diverse industrial environments to validate the exoskeleton's performance and gather user feedback for potential design improvements.

Further exploration of the use of advanced lightweight materials to reduce the overall weight of the exoskeleton without compromising its strength and durability.

Development of a range of sizes and adjustment options to ensure a better fit for a broader range of users, enhancing comfort and effectiveness.

Conduction of a detailed cost-benefit analysis to assess the economic viability of large-scale implementation and identify areas for cost reduction.

## Conclusions

The development of a passive upper limb exoskeleton aims to enhance worker strength and provide ergonomic support during physically demanding tasks, particularly overhead work and prolonged tool handling. The innovative design integrates a rack and pinion mechanism synchronized with natural arm movements, providing gravitational compensation and support. This mechanism, combined with a customizable spring support system, enhances user safety and comfort, ensuring ease of use and emergency disengagement when necessary. The ball-and-socket joint further preserves arm dexterity, allowing users to perform intricate tasks effectively. The adjustable features of the exoskeleton make it versatile and adaptable to various user needs and different industrial applications.

## Compliance with ethical standards

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*Disclosure of conflict of interest*

No conflict of interest to be disclosed.

*Statement of Informed consent*

Informed consent was obtained during experiments for data collection.

## References

[1] N. Lop, N. Salleh and F. a. S. M. 2. Zain, “Ergonomic risk factors (ERF) and their association with musculoskeletal disorders among Malaysian construction trade workers:Conceters,” International journal of academic research in businessand social sciences, pp. 1269-1282, 2019.

[2] J. Theurel, “Occupational Exoskeletons: Overview of Their Benefits and Limitations in Preventing Work-Related Musculoskeletal Disorders,” Occupational Exoskeletons: Overview of Their Benefits and Limitations in Preventing Work-Related Musculoskeletal Disorders, 2019.

[3] T. Muhla, G. Kanyemba, I. Mapindu, N. Chinguwo and D. M. *. a. W. Goriwondo, “Enhancing safety in zimbabwean manufacturing industry: The role of human factors engineering in reducing workplace accidents,” Open Access Research Journal of Science and Technology, vol. 13, no. 2, pp. 19-30, 2025.

[4] O. D.O and Okafor, “Musculoskeletal disorders, workplace ergonomics and injury prevention,” In Ergonomics-new insights. IntechOpen, 2023.

[5] Antwi-Afari, L. M.F., A. H., L. D. S., Y. Yu, H. Mi and I. Wuni, “. Assessment of a passive exoskeleton system on spinal biomechanics and subjective responses during manual repetitive handling tasks among construction workers.,” Safety science, p. 142, 2021.

[6] G. Alberico, “ Development of an intervention framework for design, implementation and adoption of occupational exoskeletons,” 2022.

[7] L. Bogunovic, M. Jimenez and J. Law, “Shoulder Anatomy and Biomechanics,” In the female athlete, pp. 177-190, 2020.

[8] T. Salama and H. Said, “Agility assessment framework for modular and offsite construction,” Construction innovation, 2023.

[9] M. Gull, S. Bai and T. Bak, “A review on design of upper limb exoskeletons,” Robotics, p. p.16, 2020.

[10] M. Gómez, A. Casado and d. Diego, “Anatomical and molecular analyses of the deltoid muscle in chimpanzees (Pan troglodytes) and modern humans (Homo sapiens): Similarities and differences due to the uses of the upper extremity,” American journal of primatology, vol. 84, no. 7, p. 23390, 2022.

[11] P. Maurice, J. Čamernik, D. Gorjan, B. Schirrmeister, J. Bornmann and L. Tagliapietra, “Objective and subjective effects of a passive exoskeleton on overhead work. IEEE,” Transactions on Neural Systems and Rehabilitation Engineerin, pp. pp.152-164, 2019.

[12] N. Maano, “ Approaches to Improve the Occupational Health and Safety in the Construction Industry of Windhoek, Namibia,” 2017.

[13] R. Mugandani and P. Mafongoya, “The 5As: assessing access to animal-drawn conservation agriculture planting equipment by smallholder farmers,” Environment, Development and Sustainability, pp. 4881-4898, 2021.

[14] E. Williams, “Diaphragmatic electromyography during a spontaneous breathing trial to predict extubation failure in preterm infants,” Pediatric Research, vol. 92, no. 4, pp. 1064-1069, 2022.

[15] O. Brumelis, “Hike much,” 2022. [Online]. Available: https://hikemuch.com/average-torso-length/. [Accessed 2 June 2024].

[16] S. Toxiri, N. M. M. Lazzaroni, J. Fernández and M. Sposito, “Back-support exoskeletons for occupational use: an overview of technological advances and trends,” . IISE Transactions on Occupational Ergonomics and Human Factors, pp. 237-249, 2019.

[17] K. Kim, W. Lee, D. Kim and J. Song, “Wearable Arm Strength Supporter based on Adjustable Counterbalance Mechanism using a Spring Latch Module,” In 2022 19th International Conference on Ubiquitous Robots (UR), pp. 94-97, 2022.

[18] A. Okunola, A. Afolabi, A. Akanmu, H. Jebelli and S. Simikins, “. Facilitators and barriers to the adoption of active back-support exoskeletons in the construction industry,” Journal of safety Research, 2024.

[19] M. Geraldi, A. Melo, R. Lamberts, E. Borgstein, A. Yukizaki, A. Maia and A. Soares J.B. dos Santos Junior, “Assessment of the energy consumption in non-residential building sector in Brazil,” Energy and buildings, no. 273, p. 112371, 2020.

[20] T. Muhla, I. Mapindu, M. Munyau, D. Mashava, S. Mhlanga and W. Goriwondo, “Agility as a strategy in Zimbabwean manufacturing industries,” Zimbabwe Journal of Science & Technology, pp. 65-76, 2023.

[21] B. Choi, J. Park and J. Kim, “Assessment of an arm-support exoskeleton on physical demands, task performance, and usability during simulated agricultural tasks,” International Journal of Industrial Ergonomics, vol. 101, p. 103569., 2024.

[22] J. Hull, R. Turner and A. Simon, "A novel method and exoskeletons for whole-arm gravity compensation," IEEE Access, vol. 8, pp. 143144-143159, 2020.

[23] Z. Du, Z. Yan, T. Huang, Z. Zhang, Z. Zhang, O. Bai, Q. Huang and B. Han, "Mechanical design and preliminary performance evaluation of a passive arm-support exoskeleton," In 2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS, pp. pp. 3371-3376, 2020.

[24] N. Tayisepi, L. Mugwagwa, A. N. Mnkandla, I. Mapindu and T. M. Muhla, "Experimental Investigation and Simultaneous Optimisation of Honing Parameters of Dry Cast Iron Cylinder Relining Sleeves of Motor Vehicle Engine Blocks for Surface Finish and Energy Use," Computational Engineering and Physical Modeling, vol. 7, no. 4, pp. 88-103, 2024.

[25] W. Lee and D. Kim, "Wearable Arm Strength Supporter based on Adjustable Counterbalance Mechanism using a Spring Latch Module.," In 2022 19th International Conference on Ubiquitous Robots (UR), pp. 94-97, 2022.

[26] N. Tayisepi, R. Svosve, G. Tigere, A. N. Mnkandla and I. Mapindu, "Comparative Optimisation of the Cutting Parameters for Surface Quality and Energy Efficiency during the Machining Manufacturing of Teak, Saligna and Pine Wood Materials," Journal of Engineering Research and Reports, vol. 25, no. 11, pp. 73-87, 2023.