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IMPROVING OCCUPATIONAL HEALTH OUTCOMES AND ENHANCING JOB SATISFACTION BY THE DESIGN AND DEVELOPMENT OF A PASSIVE OVERHEAD EXOSKELETON IN INDUSTRIES

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Abstract

Passive upper arm exoskeletons have gained recognition as a state-of-the-art technological advancement, providing a non-powered solution employing springs or elastic components to facilitate arm movements. Their pivotal role in assisting individuals with arm lifting contributes significantly to the recuperation of strength and mobility. Known for their lightweight design and simplicity, these devices efficiently assist muscles without external power sources. Taking cues from the established models, such as the Hilti exoskeleton, in this study the design is refined to simplify internal components and assembly, thus optimizing production. Incorporating insights from existing literature, the development process entails designing a detailed computer-aided design (CAD) assembly model using solid modelling software. The physical model of the exoskeleton was also developed to mitigate the physical strain and reduce the risk of work-related musculoskeletal disorders.

Keywords: Exoskeleton, computer aided design, work-related musculoskeletal disorders, muscle fatigue.

1 INTRODUCTION

Long periods of time spent in a static standing position are common in many industrial settings, including vehicle assembly lines. Over 50% of the workers at car manufacturing facilities spend more than half of their working hours standing or walking [Gell, N., et.al., (2011)]. Exoskeleton technology is at the forefront of innovation, blending engineering and biology to create wearable robotic systems set to enhance human capabilities across diverse fields. There are three types of exoskeleton joint torque profiles: entirely passive, fully active, and passive–active (also known as semi-active or semi-passive). In other words, fully passive exoskeletons only have the capacity to compensate for gravity, when their mechanism generates an assistive torque in the direction of flexion or abduction (which is a resistive torque in the direction of extension or motion) [Ali Nasr, Spencer Ferguson, John McPhee, (2022)]. Unlike their active counterparts, which rely on powered actuators, passive exoskeletons leverage mechanical principles to provide support and assistance without external power sources. Passive exoskeletons, which lack powered actuations and external devices, are becoming more commercially viable owing to their low cost, light weight, compactness, and resilience, however often suited for specialized activities [Dong Jin Hyun, et. al., (2019)]. The upper arm, with its intricate biomechanical structure and central role in daily activities, emerges as a compelling focal point for passive exoskeleton intervention. A related study indicated a better task performance and prolonged working time, and, consequently, less perceived fatigue, owing to the use of an occupational exoskeleton [Huysamen, K., et. al., (2018)]. In another study, increased productivity of welders and painters was reported with the exoskeleton usage [Butler, T. and Wisner, D, (2018)]. Shoulder exoskeletons were assessed by one more study for their impact on muscle activity during simulated squeeze riveting tasks. Anterior deltoid and medial deltoid muscle activity decreased when using exoskeletons [Michael J. Jorgensen, et. al., (2022)].

2 OBJECTIVE

In various industries, such as construction, material handling, automotive repair, and aircraft maintenance, workers are required to overuse their upper limbs. All overhead work requires the shoulder muscles of the individual to lift the arms and hold it in that position to proceed whatever work is being done. All additional weight or equipment in the hands would be added to the basic weight of the arms. Work-related Musculoskeletal Disorders (WMSDs) of the upper extremities are an important issue in the modern workplace. Workers performing a lot of overhead jobs must hold still for extended periods of time, while using their hands to apply force, which is known to increase the risk of WMSDs. If a muscle does not have the opportunity to rest, muscular tiredness develops quickly, even at modest power levels, impairing muscle performance. Constant muscular contraction can reduce blood flow, accelerating exhaustion [Huysamen, K., et. al., (2018)]]. The aim/objective of the present study is to develop the exoskeleton prototype for reducing muscle fatigue by transferring the load directly to the waist region, via the backbone structure of the prototype and improve the occupational health outcomes for the workers.

3 DESIGN CONSIDERATIONS

3.1 Principle of Operation

The primary role of the exoskeleton is to provide assistance to the user in carrying loads rather than solely bearing the entire weight burden. Once the load has been lifted, the user can adjust the position of their arms to their preferred height. This adjustment is facilitated by a sprocket, which interlocks with a pawl, effectively locking the assembly at a specific height determined by the user. This mechanism ensures that the necessary support for lifting the load is maintained. To disengage the sprocket from the pawl, allowing the user to lower their arms back to a resting position, a pawl and cable arrangement has been incorporated. This system enables the pawl to be disengaged from the sprocket, thereby facilitating the lowering of the user's arms with ease and comfort.

3.2 Support Structure

Just as the human body relies on the backbone to maintain upright posture and provide essential support, the exoskeleton design in this study integrates a similar "backbone" structure to ensure continuous wearer support. This backbone structure also serves as a load-bearing member, akin to the function of the human body's backbone. However, instead of a single backbone, the assembly is divided into two parts, each assisting one hand. This segmentation allows for independent movement of both hands and simplifies the overall assembly complexity. With careful consideration of ergonomics, the housing is strategically aligned at an angle of 10 degrees to the joint, ensuring that the backbone structure runs parallel to the muscles in the human back. This alignment optimizes comfort and efficiency by mimicking the natural biomechanics of the wearer's body. Thus, the incorporation of this backbone structure, not only enhances support, but also prioritizes ergonomic considerations, resulting in a more intuitive and user-friendly exoskeleton design.

3.3 Rotation in the Top Plane

Fig.1. Top View of Assembly

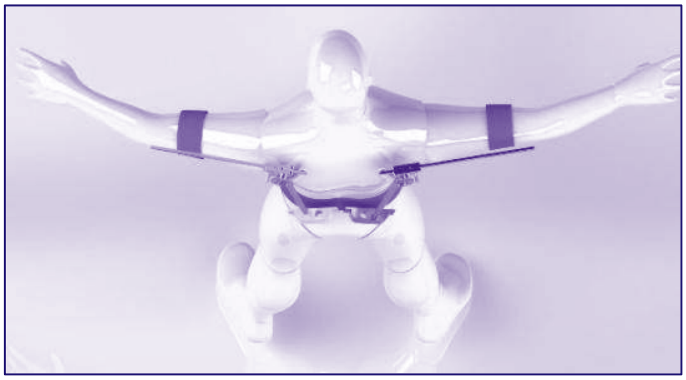
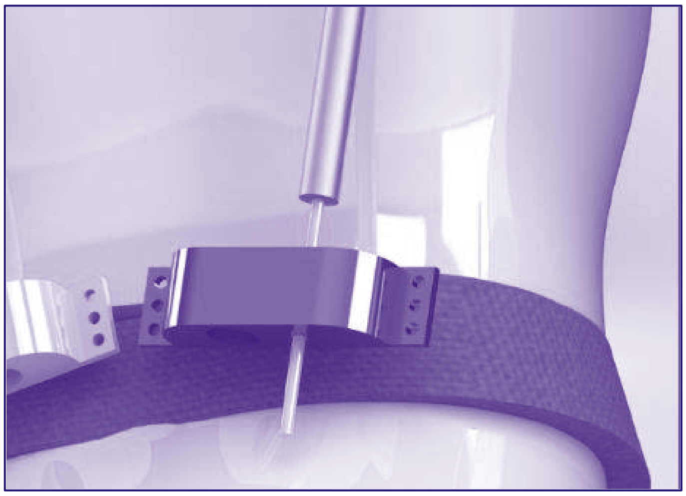


Fig.2. Rear View of Housing



To ensure that the exoskeleton offers maximum range of motion across 2 axes, including rotation within the ground plane of the wearer, a specialized mechanism is implemented. This functionality is achieved through the use of a partially threaded stud or pin. This partially threaded stud is strategically integrated into the design to facilitate rotational movement within the ground plane of the wearer. By allowing rotation along this axis, the exoskeleton enables enhanced maneuverability and flexibility during use. The design feature, as shown in figure 1 and 2, enhances the overall versatility and usability of the exoskeleton, ensuring optimal performance across various tasks and environments. This design prioritizes keeping a stud securely positioned within a component called the backbone. The pin itself has two sections: a threaded portion that screws tightly into the lower end of the backbone, and a free portion that fits tightly into a designated hole within a separate piece called the waist belt housing. To ensure the pin doesn't move up and down along its axis, a step (collar) is provided at one side and threads on the other for bolting. These act like clamps, effectively preventing any unwanted axial movement between the pin and the backbone. This design offers a secure attachment, while potentially allowing the pin to rotate within the housing, depending on the specific design.

4 COMPONENTS

4.1 Upper Arm Link

It is an integral part of the lever mechanism, which connects the fulcrum with the load (Handheld equipment). A rectangular cross section is selected for the link, such that it will resist the bending moment as shown in figure 3.

4.2 Joint

The function of the joint, as shown in figure 3 is to act as the pivot for the link. It incorporates the links and the backbone assembly, which is connected to the joint via the pivot pin.

Fig.3. Lever Mechanism

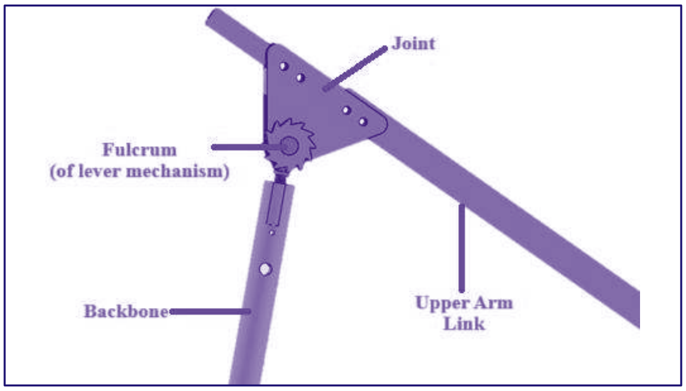
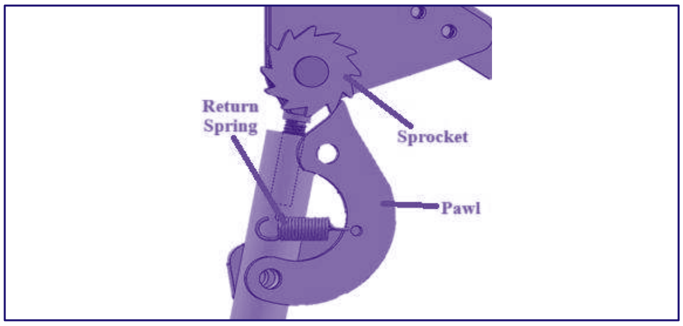


Fig.4. Ratchet Mechanism



4.3 Ratchet Mechanism

The ratchet mechanism, as shown in figure 4 is the primary load bearing component of the exoskeleton. It consists of the Sprocket, Pawl and Spring. The Sprocket is integrated with the joint to prevent any relative motion between them. The Sprocket and the Pawl mesh together to provide the required locking mechanism to carry the load. The Pawl is attached to the backbone with a spring, which acts as a return mechanism to keep the Pawl constantly in mesh with the sprocket.

4.4 Backbone

It is the main support structure of the exoskeleton. It transfers the load from the pivot point of the lever mechanism to the waist belt housing provided on the waist belt. It is inclined to such an angle as to provide maximum support in parallel to the V-shape of the torso of the human body. The two backbones form a V-shape resembling the structure of the upper human torso.

4.5 Lever Mechanism

The class 1 lever mechanism, where the fulcrum is in the middle, is provided to aid the sprocket mechanism in carrying the load applied to it. The spring serves a dual purpose: firstly, it provides additional support for the loads encountered during operation, thereby augmenting the stability and reliability of the exoskeleton. Secondly, in the event of a failure within the ratchet assembly, the spring acts as a backup mechanism, ensuring continued functionality and safety of the exoskeleton. This innovative design feature enhances the overall robustness and dependability of the exoskeleton during its operation.

4.6 Harness

Fig.5 Isometric View of CAD

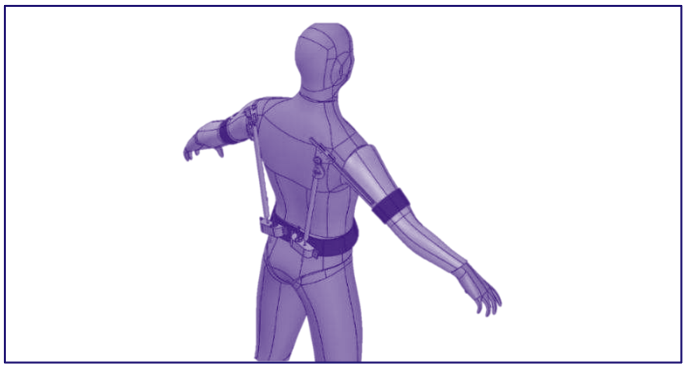


Fig.6 Rear View in Idle Position

The harness is worn by the user, which basically provides connection points to the load carrying members and protects the wearer from metal objects. The waist belt housing is attached to the waist belt, via rivets. The links are connected to the arms, via the arm restraints. The "Back X" provides additional support to the wearer's back, keeping it in an upright position and preventing fatigue. This Back X can be seen in figure 6 and 7 as black belts. The various views of the entire exoskeleton assembly can be seen in figures 5 to 8. It can be seen in figure 5 that the exoskeleton is mounted on the back of a mannequin, which is designed according to average human male dimensions. The black belts on the waist (waist belt) and the arms (arm restraints) signify attachment points of the exoskeleton with the wearer's body.

Fig. 7 Rear View in locked position

Fig. 8 Side View during overhead work

5 MATHEMATICAL ANALYSIS

5.1 Upper arm link

According to bending equation,

$$\frac{\sigma}{y} = \frac{M}{I}$$

Considering weight of the machine to be 2.5kg

$$M = 2.5\ X\ 9.81\ X\ 310$$

$$= 7602.75 \text{ N mm}$$

Considering rectangular cross section of the link, assuming length and breadth of the cross-section to be b and h respectively.

$$y = \frac{h}{2}$$

$$I = \frac{bh^3}{12} = \frac{5\ X\ 15^3}{12} = 1406\ mm^4$$

Hence, Induced stress in the aluminium 6061-T6 material (Yield stress=240MPa) is

$$\sigma = \frac{M\ X\ y}{I} = \frac{7602.72\ X\ 7.5}{1406.25} = 40.548\ N/mm^2$$

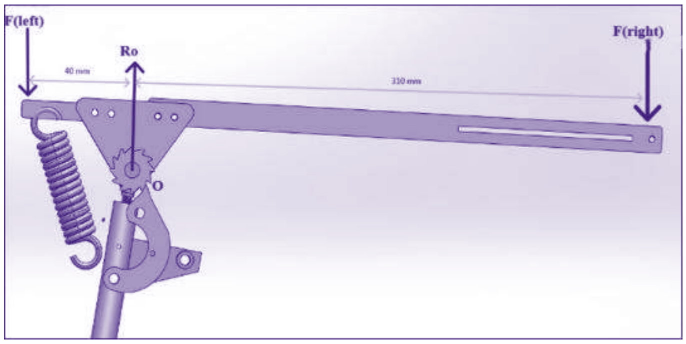
$$\text{Design Stress } \sigma = \frac{240}{1.5} = 160\ N/mm^2$$

Since Induced stress is less than the design stress, therefore the design is proved to be safe.

5.2 Joint

The load considered in one hand was 2.5kg.

Fig.9 Free body diagram of lever and joint assembly



From free body diagram in figure 9,
Force on right link= $F_{right} = 2.5 \times 9.81 = 24.525N$
Torque about pivot point O= $2.5 \times 9.81 \times 310 = 7602.75\ Nmm$
Radius of sprocket= 13 mm
Therefore, Tangential force on sprocket $= \frac{7602.75}{13} = 584.82\ N$
Now, Equating moments about pivot point O

$$2.5 \times 9.81 \times 310 = F_{left} \times 40$$

Force on left link= F_{left}=190 N

$$\sum F_x = 0$$

Upward reaction from pivot point $R_o = 190 + (2.5 \times 9.81) = 214.52\ N$

5.3 Pivot Pin

Material: Stainless Steel SS-304
Yield stress $\sigma_{yt} = 205\ MPa = 205\ N/mm^2$
Since there are no dynamic/ shock loads on it, assuming FOS=1.5
Therefore,

$$\sigma_t = \frac{205}{FOS} = \frac{205}{1.5} = 136.667\ N/mm^2$$

$$\tau = 0.5 \times \sigma_t = 68.33\ N/mm^2$$

$$[\tau] = \frac{Force}{Area} = \frac{2.5 \times 9.81}{\frac{\pi d^2}{4}}$$

$$d = 0.676\ mm$$

The diameter of pin selected was 4 mm, therefore the design is proved to be safe.

6 CONCLUSIONS

In this study, the design, development and implementation of upper body passive exoskeletons for overhead applications has been carried out. The developed design represents a significant advancement in workplace ergonomics and occupational health. These wearable devices offer a promising solution to mitigate the physical strain and reduce the risk of work-related musculoskeletal disorders (WMSDs), particularly in tasks involving overhead work. The versatility and affordability of passive exoskeleton designs make them increasingly viable options for a wide range of industries, from manufacturing and construction to healthcare and beyond. As research continues to refine these technologies and address specific ergonomic challenges, the integration of passive exoskeletons into workplace environments holds the promise of improving occupational health outcomes and enhancing overall job satisfaction for workers engaged in overhead tasks.

ABBREVIATIONS

σ	Design stress
τ	Shear stress
y	Distance from neutral axis
M	Bending Moment
I	Area moment of Inertia
b	Breadth of cross-section
h	height of cross-section
σ_t	Tensile stress
d	Diameter of pivot pin
E	Young's Modulus
σ_{yt}	Yield Stress

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