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Development of a Robotic Exoskeleton Model Operated via Arduino for Mechanical Actuation

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ABSTRACT

In this paper, we present the design, development, and initial testing of a prototype exoskeleton model created for augmenting human strength and mobility, specifically for upper-body weightlifting applications. This model, crafted to fit a small articulated doll (approximately 11.9% the size of an average human), using a PLA-constructed frame, an Arduino control system, and a rope-pulley mechanism for movement, this design represents a practical approach to wearable assistive robotics. While primarily a proof-of-concept, the project aims to explore foundational principles of wearable robotics and mechanical augmentation in a simplified manner. The proposed exoskeleton can be served as a robotic tool in demonstrating the interaction between mechanical design and control systems. The exoskeleton design also contributes to the field of wearable robotics by addressing the specific needs of weightlifters, offering a practical and functional solution to enhance strength, reduce fatigue, and minimize the risk of musculoskeletal injuries during weightlifting exercises. Preliminary results discuss feasibility and working efficiency of this model while providing insights into potential applications and improvements in larger-scale wearable robotics. The exoskeleton's performance was assessed for vertical holding and lifting tasks, identifying challenges in torque, friction, and material choice, which inform future improvements in exoskeleton technology.

Keywords: Exoskeleton, Design, Upper limb, Prototype, Mechanical actuation

1. Introduction

In recent years, advances in technology have opened up exciting new dimensions in the field of robotics. One remarkable outcome of this progress is the development of robotic exoskeletons. These wearable systems, inspired by human skeletal system, are designed to support people by increasing their strength, endurance and mobility. Exoskeletons provide external support to help carry heavy loads and reduce the risk of physical injury [1]. As the exoskeleton robotic system helps to enhance the strength, endurance and mobility by assisting externally rather than replacing any limbs and work as a substitute, it can be regard as an orthoses bionic device.

Robotic exoskeletons are becoming especially valuable in practical settings like healthcare, factory work, and the military. In healthcare, they can assist patients with limited mobility, helping them move more freely or regain strength during rehabilitation [2]. In factories and construction site, exoskeletons support workers by reducing the physical strain of lifting heavy objects repeatedly, which helps prevent fatigue and injuries [3]. In military services, these devices enhance soldiers' endurance, allowing them to carry heavy gear over long distances with less strain [4].

Historically, exoskeleton research began with purely mechanical designs, such as Yagn's spring-powered support system from the 1890s [5]. Over time, developments led to powered systems like GE's Hardiman exoskeleton in the 1960s, which aimed to increase load-carrying capacity but faced significant limitations due to its bulky design and energy requirements [6]. Modern exoskeletons have progressed to include sophisticated, energy-efficient models such as DARPA's Exoskeleton for Human Performance Augmentation (EHPA), which is designed for military applications to improve soldiers' endurance and load capacity [7]. Berkeley Bionics which at present known as Ekso Bionics and Lockheed Martin produced HULC (Human Universal Load Carrier), a battery power low body exoskeleton to carry more than 80 kg loads also for military application [8]. French company RB3D, for the same reason developed Hercule which allowed user to carry 20 kg in each arm to travel at the speed of 4 km/hour. Aside from military application, exoskeletons are designed for non-military use and healthcare purpose [9]. HAL (Hybrid Assistive Limb) from Cyberdyne was developed for multiple purpose such as training the doctors, assisting disabled person and allowing workers to carry heavy load [10]. ActiveLink, a part of Panasonic developed MS-02 Power Loader and Powe Loader Lite (PLL-04) for heavy lifting and to support lower body respectively [11]. Tokyo University of Agriculture and Technology worked on exoskeleton robotic system to help the farmers and increase productivity [5]. ReWalk, formerly known as ARGO Medical Technology, developed ReWalk exoskeleton that is used to rehabilitate patient by supplying movements at hips, knees and ankles along maintaining the balance the body [12]. But recently more effective and efficient exoskeleton had been introduced such as REX by Rex Bionics, which is a pair of legs designed specifically for mobility impairment [13].

Upper-body exoskeletons are particularly useful in industries where lifting, holding, or moving objects repeatedly can cause physical strain which is observed in manufacturing and construction, as the workers often need to lift heavy tools or materials throughout the day. By wearing an upper-body

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exoskeleton, these workers receive added support, which helps prevent fatigue and reduces the risk of injuries, especially to the shoulders and lower back [3,14]. Also in healthcare, upper-body exoskeletons are used for rehabilitation, helping patients rebuild strength after an injury or surgery by guiding and assisting their arm movements [15]. Similarly, in military settings, these exoskeletons help soldiers carry equipment over long distances, enhancing their endurance while minimizing physical strain [4].

This project addresses these challenges by developing an upper-body exoskeleton prototype specifically aimed at assisting in weightlifting tasks. Constructed on a small scale for initial testing, this exoskeleton integrates a PLA frame with an Arduino-controlled motor and a rope-pulley system to create a functional and accessible model. This prototype demonstrates essential principles of wearable robotics, offering insights into how mechanical design and control systems can enhance strength and endurance. Furthermore, it serves as an educational tool for exploring the fundamental requirements of scalable exoskeleton systems.

This paper details the design, construction, and performance testing of a prototype exoskeleton model. It discusses the design process, challenges encountered, and the results of initial tests, particularly in terms of weight-holding and lifting capabilities. The paper concludes with a discussion on potential scalability for real-life applications and identifies areas for future improvement.

2. Principle of Exoskeleton System

Exoskeleton robotic system works in interactive way with human's strength, endurance, mobility. Thus, the system uses both human strength and mechanical assistance to achieve efficiently greater outcome.

In working the robotic system transfers external loads onto the exoskeleton frame, which reduces load and minimizes strain on the human body. The actuation system provides torque and lifting force (F_e). The user uses their natural strength (F_h) to initiate and control the robotic system. The combining forces of the user and exoskeleton generates the total force (F), that is, exerted force applied by the exoskeleton robotic system, as in Eq. (1). This exerted force enables the user to perform tasks that exceed their natural physical capabilities, such as lifting heavier objects, holding weights for extended durations, or performing repetitive movements with minimal fatigue, as in Fig.1.

$$F_e + F_h = F \tag{1}$$

The exoskeleton's lifting ability, as in Fig.1, is expressed as a percentage:

$$Lifting\ ability = \frac{Lift\ angle}{Maximum\ lift\ angle} \times 100\% \tag{2}$$

For example, as maximum lift angle is 90^0, if the lift angle achieved is 45^0 the lifting ability is 50%.
Similarly, during load holding vertically, the system's slippage can be quantified as:

$$\%\ Slip = \frac{Slip\ length}{Pin\ length} \times 100\% \tag{3}$$

Where a slip length (S) of 5 mm corresponds to a 25% slip rate, as pin length (L) of hand hook is 20 mm.
The system's effectiveness in resisting slippage and holding the load vertically can be quantified as:

$$Holding\ ability = \left(100 - (\%\ Slip)\right)\% \tag{4}$$

Corresponding to previous example, the holding ability would be 75%.

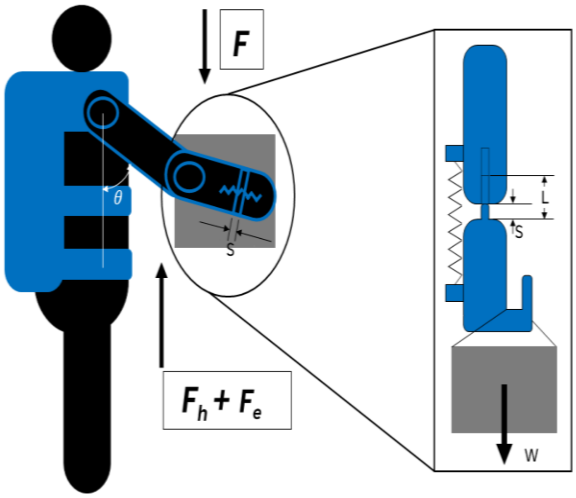

Fig.1 Basic principle of the exoskeleton system for both weight lifting and vertically weight holding.

3. Methodology

The exoskeleton prototype was designed to support upper-body weightlifting tasks (i.e. lifting the weight and holding the weight vertically). Design considerations included durability, weight distribution and ease of control. The exoskeleton framework was constructed from PLA (Polylactic Acid) plastic due to its lightweight properties and compatibility with 3D printing technology. PLA provided the structural strength needed for the prototype while keeping costs low and allowing for iterative adjustments in design. The frame was designed using CAD software, with dimensions tailored to fit a small articulated model, providing a scalable, proof-of-concept model.

3.1 Mechanical structure and components

Mechanical frame was constructed by considering three parameters such as:

(i) Dimensions of the articulated doll, as in Fig.2
(ii) The body weight (120 grams)
(iii) Load lifting capacity of the body (0 N)

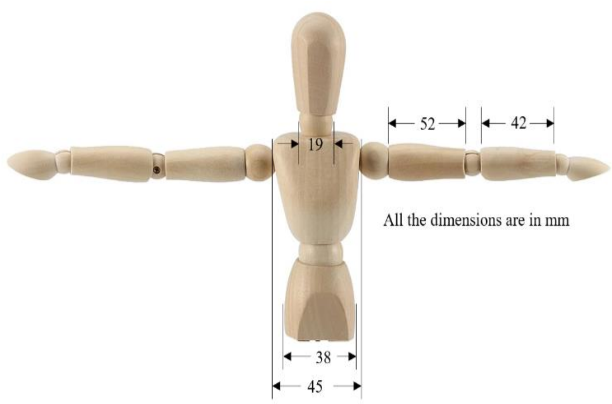

Fig.2 Dimensions of articulated doll [16].

The mechanical structure consists of, as in Fig.3 (a), base frame which is the central framework that connects all the arm components. It ensures stability and structural integrity, supporting the overall exoskeleton design.

The pivot points of the upper arm, forearm, and other moving parts are connected via joints. The joints allow rotational movement, mimicking the natural motion of the human arm, which ensure smooth transitions between different angles for ergonomic use.

Upper Arm is a structural section corresponding to the user's upper arm. It provides torque for lifting tasks, which plays a critical role in transmitting forces to the forearm.

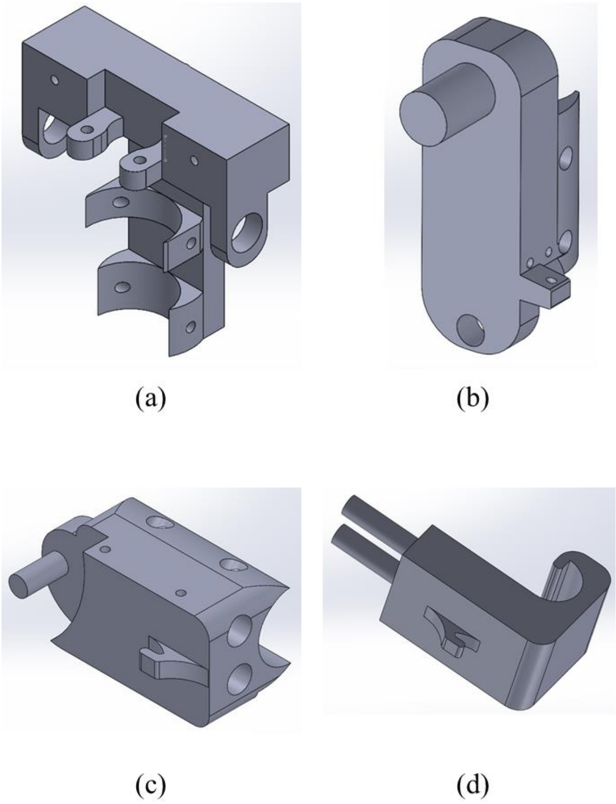

Fig.3 (a) The base frame, (b) the upper arm, (c) the forearm and (d) the hand hook parts of the mechanical structure.

Forearm of the exoskeleton aligned with the user's forearm, works in conjunction with the upper arm to provide support during lifting and houses essential mechanisms like the spring for holding tasks and also incorporates connection points for the hand hook and other components.

Hand hook positioned at the end of the forearm. This segment secure and manipulate loads or tools during operation and ensures a strong and reliable grip for various applications such as lifting and holding due to its J-shape hook.

Spring is integrated into the arm mechanism to assist in holding heavy loads by absorbing the weight of the load and maintains stability especially during static vertical holding tasks.

The design of mechanical structure is ergonomic. The assembly of these parts in CAD software, as in Fig.4, confirms the suitability of the design for its purpose.

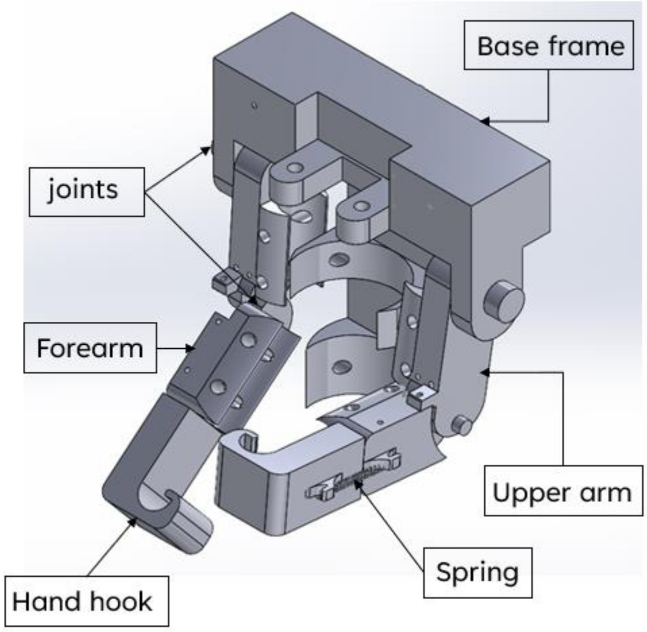

Fig.4 CAD design of assembled mechanical structure.

3.2 Control system

An Arduino Uno microcontroller was used to operate the exoskeleton's functions, allowing precise control over movement. As in Fig.5 the control system included:

Two 12V DC motors with a rated speed of 500 RPM were selected to power the exoskeleton weight lifting.

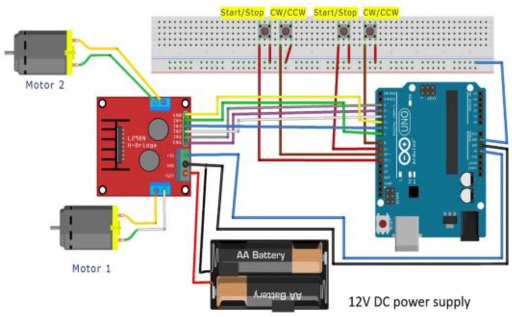

Fig.5 Electrical control system.

The motor driver (L298N) was connected to the Arduino, which enabled direction and speed control through a series of push-button switches.

Four push buttons allowed the operator to control the movement direction and start/stop actions of each motor.

3.3 Assembly

The CAD-designed parts were printed using PLA, forming the exoskeleton's mechanical frame. Components were assembled according to the CAD model, with joints aligned to enable natural arm articulation. The pulley system was threaded through the joints to transmit motor force to the arms.

Fig.6 Assembly of exoskeleton.

The Arduino and motor driver were programmed and connected, then integrated with the push-button switches for operator control, as shown in Fig.6.

4. Performance Test and Result Discussion

The exoskeleton prototype underwent two types of tests which focused on two primary functions such as vertical holding and active weightlifting.

4.1 Vertical holding test

The vertical holding test aimed to assess the exoskeleton's ability to support static load without motor assistance. Loads were gradually increased to determine the maximum load the exoskeleton could hold in a steady in vertical position.

The exoskeleton held loads up to 500 grams successfully. At higher loads, slight slipping occurred due to limited friction control within the structure, although the high-stiffness spring attached to the arms contributed significantly to load stability.

4.2 Weight lifting test

The weightlifting test evaluated the exoskeleton's capability to actively lift weights through motor-driven actuation. Here, the motors applied force to the exoskeleton system, simulating a lifting motion.

The exoskeleton successfully lifted weights up to 250 grams. Beyond this point, the limitations of the motor's torque became apparent. Performance deteriorated significantly at higher weights, primarily due to limitations in motor torque and high friction, since the exoskeleton was able to lift weights of 500 grams but the lift ability is much less. High friction within the 3D-printed pulley path further limited lifting capacity, as the rough surface generated resistance that inhibited smooth movement.

The observations from both tests are accumulated in Table 1. From the observations slip percentage, holding ability and lifting ability of the exoskeleton robotic system are calculated using Eq. (3), Eq. (4) and Eq. (5) respectively. Notably, during testing, no external forces were applied in conjunction with the exoskeleton system. In a real-world scenario, this means that the user did not contribute any force themselves (i.e., $F_h=0$); instead, the force exerted was entirely provided by the exoskeleton's actuation system (i.e., $F_e=F$).

Table 1 Performance evaluation of exoskeleton prototype in weight holding and lifting tasks.

Mass (*g*)	Slip Length (mm)	Slip (%)	Holding Ability (%)	Lifting Angle (°)	Lifting Ability (%)	Overview
0	0	0	100	90	100	Highest stability and efficiency under no load
100	0.8	4	96	90	100	High performance and high stability
200	1.5	7.5	92.5	90	100	Slight reduction in holding efficiency; fully operational in lifting.
250	1.8	9	91	90	100	Good performance; slight strain noted.
300	2.3	11.5	88.5	77	85.56	Reduced lifting efficiency; strain evident.
350	2.9	14.5	85.5	68	75.56	Performance declining; friction and strain increasing.
400	3.2	16	84	52	57.78	System nearing limits; noticeable strain.
450	3.6	18	82	33	36.67	Motor struggling; spring adjustment needed.
500	3.9	19.5	80.5	13	14.44	Severe strain; system at critical performance level.

Note. The lifting and holding test were conducted on one arm of the exoskeleton rather than both arms.

The performance tests reveal that the exoskeleton robot demonstrated a stronger capacity for holding weights in a steady vertical position than for actively lifting them. As shown in Fig.7, the ability to hold weight (orange line) remains high even as the mass increases, while the ability to lift weight (blue line) declines gradually beyond a certain load.

This outcome of holding ability is primarily attributed to the role of the spring attached to the arm, which effectively supports the load due to its stiffness. The stiffness property of spring resists slipping, even under heavier loads, thereby stabilizing the exoskeleton in vertical holding scenarios. If a spring with relatively lower stiffness were used, slipping would likely occur at lower weights, reducing the exoskeleton's capacity to hold the load securely.

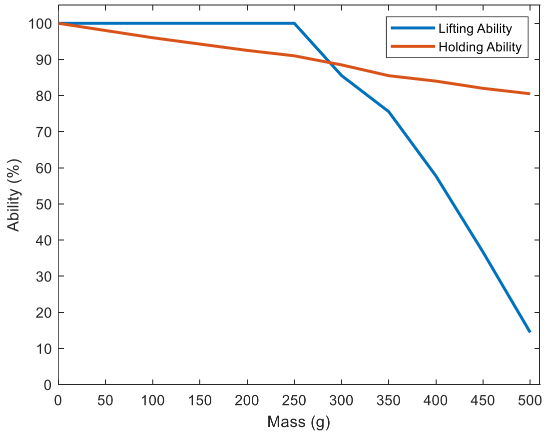

Fig.7 Relation between the lifting ability and holding ability of the exoskeleton system.

Thus, the exoskeleton's weight-holding capability can be adjusted by selecting springs with different stiffness levels. For applications requiring higher load capacity, a spring with greater stiffness would be suitable to prevent slipping. Conversely, for lighter loads, a lower-stiffness spring would be more economical and practical, providing sufficient support without unnecessary rigidity.

On the other hand, the exoskeleton's limitations in actively lifting weights were largely due to two key factors. One of them is due to surface friction as the roughness of the 3D-printed pulley and stiff wire pathway introduced significant friction, which hindered the wire's movement and limited the system's ability to lift heavier loads. The friction in the pathway generated resistance that the motor had to overcome, making it difficult to achieve smooth lifting. Another one is the limiting torque of motor. The gear motor used in the prototype lacked the torque necessary to lift heavier weights. Without sufficient power, the motor struggled to create the force required to overcome the load, especially under conditions of increased friction.

Motor power is a critical factor in achieving effective weightlifting with an exoskeleton, as the drop in lifting ability in Fig.7 indicates the system's limited torque and motor efficiency under heavier loads. Employing motors with higher torque would enable the exoskeleton to lift heavier loads more effectively and with greater control. However, the high friction present in the pathway remains a substantial limitation. Even though the structure was manufactured using 3D printing, the resulting surface roughness added resistance that interfered with smooth movement, especially along the sections where the rope traveled.

If the roughness can be minimized and friction is reduced, the efficiency of the exoskeleton robot will increase drastically. For better improvement in the lifting efficiency of the exoskeleton, reduction of friction along the rope pathway is essential. Using smoother materials, post-processing the 3D-printed parts to reduce surface roughness, or incorporating low-friction coatings or bearings could help minimize resistance and enhance the system's overall performance. With friction reduced and a more powerful motor, the exoskeleton's ability to lift weights could be increased substantially, making it more suitable for real-life applications.

5. Scaling and Adaptation for Human Use

To adapt the prototype exoskeleton model for practical, real-life use in fields like manufacturing, healthcare, and logistics, several key enhancements are essential. Scaling involves optimizing the exoskeleton for durability, functionality, and user adaptability to meet the physical demands of human weightlifting and other strenuous tasks.

5.1 Dimensional scaling factors

As the articulated doll is approximately 11.9% the size of a human, the main scaling factor will be 8.4 which leads the dimensional scaling factor of exoskeleton system.

The real-life applicable exoskeleton's length, width, height will be 8.4 times the developed model prototype. Exoskeleton's surface area and volume will be 70.56 and 592.7 times the model prototype respectively.

5.2 Enhanced structural material

The weight of exoskeleton would also increase 592.7 times, if PLA is used. Hence to make it light weight and strong, materials with light weight property and high strength (such as Titanium, Carbon fiber composite, Aluminum alloys etc.) should be used.

5.3 Enhancing other factors

To adapt the exoskeleton for human use, several key factors must be improved and developed as well. These include upgrading the motor to provide higher torque for load-bearing, integrating sensors for real-time feedback and precision control, enhancing battery capacity for prolonged use, improving ergonomic design for comfort and safety, and implementing fail-safe mechanisms to prevent accidents. These modifications are essential for ensuring the system's functionality, efficiency, and safety in practical applications.

6. Conclusion

The development of this upper-body exoskeleton prototype is important for strength support and injury prevention. The successful design and construction of a small-scale exoskeleton model for upper-body weightlifting, using a PLA frame, Arduino-controlled motors, and a rope-pulley mechanism demonstrate key principles in exoskeleton design and control integration focusing on user centric functionality and mobility enhancement. Performance tests showed that while the exoskeleton could hold lighter loads effectively, heavier weights posed challenges due to motor torque limits and friction in the exoskeleton base frame system.

The design structure introduces a cost-effective and accessible approach to an exoskeleton robot using widely available Arduino technology. By emphasizing enhanced human-machine interaction, this development advances the field of wearable robotics and addresses key challenges in usability and efficiency.

There are some limitations in this development that highlight the importance of optimizing motor selection, material choice, and friction management for improved load capacity and maneuverability. Despite these limitations, the prototype proves valuable as a weight lifting tool, useful for workers to carry heavy weight without any severe body strain and fatigue. Additionally, this model may serve as a solution for individuals with mobility impairments, enabling them to regain independence and perform daily activities with ease.

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NOMENCLATURE

F_e : lifting force of exoskeleton, gf
F_h : natural strength of human, gf
F : total force, gf
θ : lift angle, ^{0}
S : slip length, mm
L : hand hook’s pin length, mm