A Completely Portable and Concealable, Lightweight Assistive Exosuit for Upper Limbs*

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Abstract— **Exosuits are a relatively new trend in wearable robotics to answer the flaws of their exoskeleton counterparts, but they remain impractical as the lack of rigidity in their frames makes the integration of crucial components into a single unit a challenge. While some simple solutions exist, almost all current research focuses on the output performance of exosuits rather than the needs of potential beneficiaries of this technology. To address this, a novel mechanism of complete portability for exosuits was developed and tested to improve exosuit practicality and adoption. Designed for elbow flexion, the device produced 12.21-13.66Nm of assistive torque and could be mostly concealed by the wearer's clothing without impacting performance. The proof-of-concept design proved successful and demonstrated many advantages over current portability methods, particularly in size and convenience, weighing only 1.7kg. This device provides the sense of normalcy crucial for a technology to seamlessly integrate into the daily lives of its end users. It is extendable and upgradeable with access to advanced materials and manufacturing methods.**

Clinical Relevance— **Exoskeletons are currently the only marketed wearable robotic device for full limb support. This research is the foundation for a new series of exosuits that could drastically enhance the adoptability, accessibility, and versatility of exosuits in physical rehabilitation and general physical enhancement, becoming a superior alternative or addition.**

I. INTRODUCTION

Wearable robots started out in the form of exoskeletons with rigid frames worn by people to assist in physical activities [1]. This is particularly useful for the medical industry, where individuals disabled by injury, disease, and age often suffer in living standards and struggle to return to normal life. Exoskeletons have been able to provide solutions for sufferers to walk again, but generally struggle to be practical in upper limb applications due to their size and weight. Soft wearable robots (SWRs), or exosuits, have seen much growth in recent years as a solution to the problems posed by the implementation of exoskeletons [2]. They replace the rigid frames of their counterparts with compliant fabrics and actuators to achieve the same goals. However, despite the obvious benefits, SWRs are still impractical because the lack of rigidity results in lower force outputs and no obvious anchoring for heavier components, especially regarding portability [3].

Few soft upper-body (UB) systems have achieved complete wearability (maximum comfort and convenience) and complete portability (no external components or tethers) for shoulder and/or elbow orthosis according to extensive reviews of UB robotics [3, 4], although the majority of UB SWRs in those studies demonstrated proven results in rehabilitation and assistance for sufferers of both mild and debilitating physical conditions. It appears that portability and wearability are inversely proportional factors since completely portable solutions either implement a heavy and/or bulky backpack for housing all major components and power sources, or attach them to rigid structures, such as wheelchairs, that only exist for some users [5]. Hybridized systems combining multiple actuation methods [6, 7], while effective for performance reasons, have added complexity that further diminishes the options for portability, requiring multiple housing and power sources to maintain each subsystem. Other reviews [8] have neglected accounts of the portability of the power supplies and their placement in wearable devices, making it difficult to identify any explicit effects that portability would have on those systems. Therefore, tethering becomes a major cause for concern for elderly or physically dependent individuals who would struggle with activities of daily living should they be required to carry loads for devices that would otherwise be improving their livelihoods. Furthermore, an acceptable solution must conform to the psychological needs of its prospective users not just the physical. Part of that is achieving a level of normalcy for those who need it most and elderly citizens have described feeling alienation from using indiscrete medical assistive devices according to Shore's et al. findings [9]. Comfort and convenience are paramount for the integration of beneficial new technology into the lives of individuals.

Currently, there do not exist any pure exosuits (completely soft frames) for commercial use because it is very difficult to develop cohesive SWRs without sacrificing their main advantages in weight, compactness, and wearability. Our solution addresses the major downsides of exoskeletons and current SWR research; decentralizing all components and aiming to increase the practicality and adoptability of UB exosuits as a marketable technology for medicine and rehabilitation. This is a multifaceted problem of finding the appropriate balance between wearability, portability, user-friendliness, and accessibility. As a starting point, this research addressed the largest concern of achieving complete portability in exosuits while maintaining comfort, lightweight, and concealability, with reasonable assistive forces. The requirement of concealability was determined to be the easiest method by which the need for normalcy in wearing the devices could be achieved without introducing unnecessary or inefficient complexities. A novel design of UB exosuit for elbow flexion, using electric motor and cable driven actuation

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was devised, and constructed by following a prototyping methodology. To be the most effective, this device is intended for users with physical weakness who still retain mobility in their limbs and not for those who have lost all motor control. The implications of this work could pave the way for a new series of exosuits that could see commercial viability, which would improve the lives of thousands of people, particularly the injured and elderly, who are a rapidly growing demographic globally.

II. METHODOLOGY

A. *Frame Construction and Motor Selection*

The frame was constructed from three pieces: compressive forearm sleeve, compressive elbow sleeve, and shoulder brace, which can be seen in Fig. 1(a), and Fig. 4 for rear. These were linked together with elastic braiding between them to form a single unit. To be cable driven, anchor loops and guides made from cut canvas straps were stapled in two rows along the inside of the arm on each component, up along and over the shoulder brace, with guides on the top of the scapula. The main anchor point was a single loop stapled in line with the forearm at the wrist of the forearm sleeve. This configuration allowed for a single length of cable looped through both rows of guides around the wrist anchor that could be pulled from both ends simultaneously by the motor to lift the forearm.

For a compact design that maximized portability, a DC motor (FIT0186, DFROBOT) was chosen as the preferred actuation method for its high power-to-weight ratio and ease of control. A spool of dimensions 45mm length, 30mm diameter ends, 12mm outer and 6mm inner shaft diameters, and two 3mm equidistant holes through the shaft, was 3D printed to fit the motor. Each end of the cable threaded through the small holes and tied at the other end. The spool was secured to the motor shaft with a tightening bolt through an extrusion on one side of the spool (see Fig. 2). The motor, held to the waist of the subject, pulled on both ends of the cable down the back of the wearer, using the shoulder as leverage.

Cable selection went through a few different materials as there were many factors to consider. Ideally, thin Bowden cables were intended for this application, but they proved too stiff to effectively wind around the spool. The most effective cable was one made from Dyneema rope, commonly used in maritime for its high tensile strength and minimal deformation. To minimize frictional effects of the cable sliding, a braided nylon sheath that could easily flex and stretch was fitted first before passing the cable through the guides.

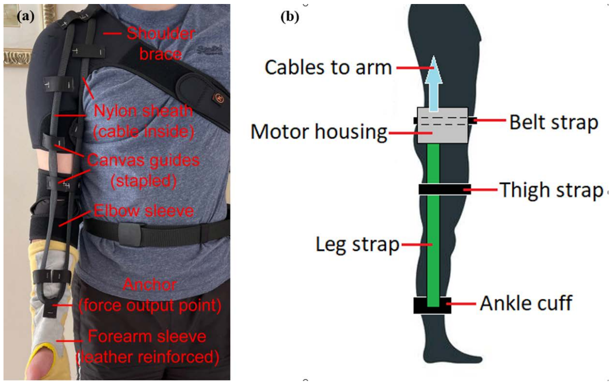

Figure 1. (a) Soft frame. (b) Leg attachment concept.

B. *Complete Portability and Maximum Concealability*

As previously stated, the most common solution to portability for exosuits is consolidating components into backpacks worn by the subject, which severely downgrades the wearability of these devices. An issue found during prototyping was the motor would pull itself towards the arm it tried to lift because it was far lighter, which is the opposite of what was intended. To effectively counterbalance the motor and prevent this problem, inspiration was taken from exosuits used for leg movement assistance. Asbeck et al. [10] were able to achieve a very sleek, lightweight, and wearable leg exosuit by simply using straps and belts of compliant, comfortable materials to wrap around the thigh for security and use a foot/shoe attachment as an anchor. This design presented an elegant solution to the problem of counterbalancing the motor; the weight of the wearer's leg – which was far heavier than the arm and motor combined – could serve as the counterbalance if properly secured to the motor. The basic concept was to use a long, adjustable strap that was attached to the user's ankle by an ankle cuff, held to the thigh by Velcro or other securing mechanism, and connected to the motor's housing, which could be attached to a belt as seen in Fig. 1(b).

Thus, once the leg strap was shortened to fit the wearer's leg length, the tension produced in the strap as a reaction to the pulling force the cables exerted on the motor, kept the housing vertically in place. With this arrangement, the belt was alleviated of all loads apart from the weight of the motor and its housing when not engaged. Wrapping around the foot instead of the ankle was possible but as concealability was a factor and the device was intended for small loads, the ankle attachment was favorable, particularly when it did not present notable discomfort after prolonged use. The arm components and leg attachment of this exosuit were already concealable, so long as the cables were not obstructed nor the leg strap and that was the next challenge. The solution lay in the use of pouches that could be attached to the belt that came with inbuilt straps for wrapping around the belt and snapping back onto the pouches (like the "hammock" in Fig. 2, explained later). This made it possible to adjust the positions of the pouches to suit the wearer, so long as any wired connections between them had enough slack to prevent tension and possible breakage. While an obvious choice for holding the electrical equipment and power supply, the motor required an innovative alteration to its pouch seen in the top left of Fig. 2.

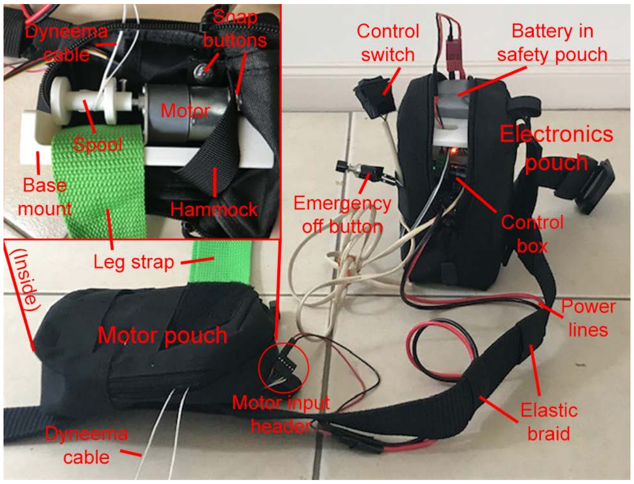

Figure 2. Annotated photo of belt assembly.

The motor required a mount to secure it and the leg attachment needed to wrap around the mount to supply the opposing reaction force from the weight of the leg. The mounting base was a 3D printed piece that was simply a rectangular block onto which the motor mounting L-bracket could be fixed using M3 bolts and nuts, a front lip to prevent the leg strap from sliding off, and a raised end with a half cylindrical cutout to support the back of the motor and prevent it from twisting should the bracket bolts come loose. There was no need for walls around the motor as they would only make wearing the pouch uncomfortable. The pouch needed to be rotated horizontally to fit the base, and to keep the base centered within, a canvas strap fitted to the sides of the pouch with snap buttons served as a "hammock", with a third button to fix the back of the base to the end of the pouch (right side of the motor in Fig. 2). In this manner, the zipper could be used to effectively conceal the entire assembly within the pouch from above, being left partially open at the bottom to accommodate the leg strap, and two tiny holes poked in the top for the cable to pass through without the need to unzip it.

C. *Electronics and Software*

The electrical components involved a simple Arduino and motor controller configuration that responded to a single pole, double throw (SPDT) switch for controlling motor direction, which had three positions that behaved as forward-stop-reverse. A push button for emergency stopping was added to cut power to the motor if needed. Both were operated by the wearer's free hand. As control was not in the scope of this research, this device did not require intention detection. The power source was a 5000mAh, 4-cell, hard cased LiPo battery pack. The electronics pouch in Fig. 2 contained all electrical parts; the Arduino and motor controller inside a 3D printed case, and the LiPo battery inside a padded, protective pouch. It was attached to the belt on the opposite side of the arm frame (left), with power lines running along the belt to the motor pouch that were held to the belt by moveable elastic braids. The control switch and emergency off button were affixed to the outside of the electronics pouch for easy access.

III. RESULTS AND DISCUSSION

A. *Portability and Concealability*

The culmination of three prototypes resulted in a unique device that has achieved its main goal of complete portability in exosuits without the need for cumbersome backpacks using a novel design and promising achievements in subgoals of comfort and practicality. The belt design did not pose the same prolonged discomfort as heavy backpacks can have on shoulders, and the pouches could be repositioned, allowing the wearer to adjust for comfort and freely sit without needing to take anything off. Furthermore, it was possible to conceal the majority of the exosuit underneath the wearer's clothing and remain operable in the same way with no negative effects on performance, though this made it more cumbersome to put on. Only the belt and side pouches of the exosuit were visible when maximally concealed as demonstrated in Fig. 3. The user could also put the device on without assistance, though it was inconvenient. The device could be worn over any garment and in all, weighed approximately 1.7kg, including power supply.

Figure 3. Final prototype. (a) Visible. (b) Maximally Concealed

B. *Analysis of Functionality*

Fig. 4 below demonstrates how the exosuit functions when lifting a regular household item that weighed 2kg. Between the two parts, it can be seen how the cable shortens when the motor is engaged and how the motor pouch ascends slightly but was prevented from going higher by the leg strap caught by the ankle cuff, keeping the pouch in roughly the same position. Walking with it engaged did not slow the subject or cause significant discomfort nor awkward leg movement, which was the major hope of this design. It was also found that the system did not require much power. There were 30 tests performed using various weights, and the LiPo battery's voltage had dropped from 15.92V at the beginning to about 15.87V by the end. The maximum practical operating time was too difficult to measure accurately, but at maximum current draw (7A) the battery would last approximately 42 minutes.

The tests were performed with the subject holding weights concentrated in the palm and engaging the device until it was nearly at maximum height or became uncomfortable. Data from the motor's encoder was collected over 5 seconds at a sample rate of 2.5ms and plotted in Fig. 5. The exosuit behaved mostly as expected, where the slopes decreased as total load increased, with the only exception being +3kg which is the weight that stalled the motor. This is likely because the load was so much heavier than the true stall load that it behaved like a fixed point in the system, forcing all the power of the motor to go into deforming the exosuit, hence the parabolic nature of the transient behavior; unlike the other tests, where the elastic and stiffness elements in the exosuit had reached equilibrium with the load, allowing it to be pulled up nearly linearly. This meant that the true stall load of the exosuit was between 2.5-3kg which equated to 124.5-140kgcm or 12.21-13.66Nm of assistive torque; more than enough for most everyday objects.

Figure 4. Lifting object with exosuit[1]. (a) Start location. (b) End location.

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[1] To see the full demonstration: https://youtu.be/2SRdYaOEBB0

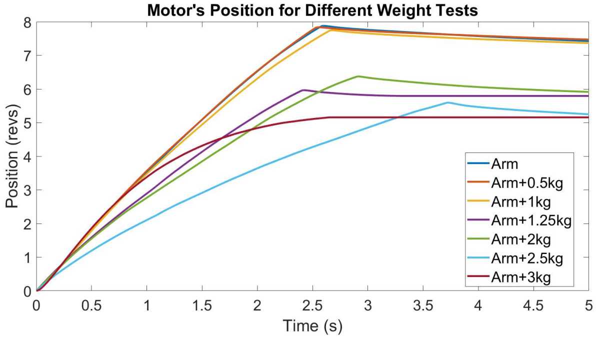

Figure 5. Plot of motor's position during operation for different loads.

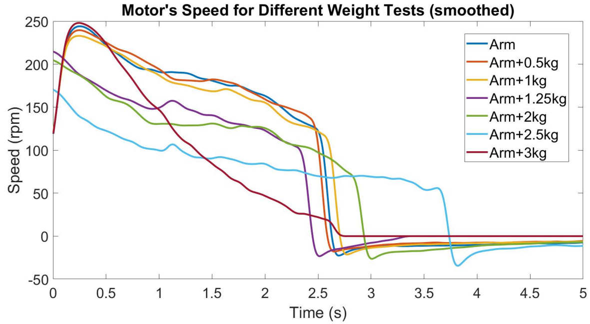

Figure 6. Plot of motor's speed during operation for different loads.

The crests on most of the plots in Fig. 5 occurred when the motor was turned off after the load was perceived to reach the desired location. The +3kg test did not contain a crest because it never reached the desired location as it had stalled. For the tests that did reach crests, there is a noticeable slope in the position after, which was caused by the load slowly unspooling the cable, though the inertia of the motor's shaft and the subject's arm were enough to slow that descent. The speed differences are made clearer in Fig. 6. In this figure, we see the speed characteristics of each test across time, smoothed out to find the underlying behavior. The maximum speed of the motor was 251rpm which is confirmed by the first three of the lightest loads. It is also confirmed by the stall load test, which is even closer to the maximum speed than the lighter tests despite stalling. The reason for this was that the heavy weight was enough that the motor's power output went into elastic deformation of the compliant arm components without moving the arm. There is also a noticeable jump just after 1 second for the +1.25kg and +2.5kg tests. In both cases, the leg strap was not properly tightened, or had loosened, and the extra slack meant that the spool was no longer perpendicular to the cables, allowing one of the lines to slip out from under the spool end before being wound back in. The implications of this are that the less slack in the leg strap the better, but for a trade-off with an increase in restrictiveness in the wearer's leg movement.

IV. CONCLUSIONS AND FUTURE WORK

In all, this proof-of-concept device was highly successful in demonstrating that a different and more practical form of exosuit portability exists that does not severely impact the wearability of the device. This research provides the foundation necessary for further development of a device that is relatively cheap to manufacture and has promising advantages that are desirable for commercial viability. It can be extended in a variety of ways with more advanced manufacturing and materials by improving comfort, safety, sleekness, and efficiency. There are obvious applications in medicine for sufferers of physical impairments who would greatly benefit from a take-home device that they can wear daily; even wearing it outside with concealment would be possible, without drawing unwanted attention. With this research, SWRs are closer to becoming accessible to more people with great potential to become integrated into society just like other useful technologies.

Future work should focus on developing an intention detecting control system to make the device as close to autonomous as possible and to redesign/optimize the arm sleeve and leg attachments to maximize efficiency and improve device quality if it is to be acceptable for clinical applications. Some important considerations include the following: employing electromyography (EMG) or tactile sensors; performing adequate material analyses to determine ideal textiles to be used in the frame and leg attachment that minimize inefficiencies, are durable, and comfortable; redeveloping the arm sleeve into a single unit and embedding the cable sheath inside it for compactness and safety; adding anti-slip padding to the shoulder section of the frame to prevent sliding off the wearer; optimizing the leg attachment to function under greater loads whilst being as unrestrictive for the wearer as is feasible; optimizing spool and motor bearings to handle greater radial forces. Extending the exosuit to both arms would be worthwhile, though it could require compromises with convenience and wearability. Future testing should be performed by potential end users to better gauge the restrictiveness of the leg attachment and find its limitations.

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