Human-Centered Exoskeleton: Upper Extremity Strength Augmentation in Occupational Settings - 17297

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ABSTRACT

Robotic exoskeletons have a wide variety of applications ranging from rehabilitation to military combat to strength- and performance-augmentation in occupational settings. Currently, the high-cost, complexity, and biomechanical limitations prevent these devices from introduction into specialized applications where low-cost and practicality are essential. Here, an initial prototype of Robotic Exoskeleton for Upper Extremity Strength Augmentation is introduced. Expanding upon previous three generations of robotic arms for muscle retraining, the new generation emphasizes high fidelity, low-cost, and practical strength-augmentation with focus on enhancing performance by muscle fatigue reduction and injury prevention. Simplified set up and configurability of the system make it suitable for highly dynamic environments, where time and safety are vital. This prototype demonstrates the feasibility of low-cost and practical exoskeletons; however, further improvements and investigations are necessary to improve and validate its function.

INTRODUCTION

Robotic augmentation of human function and performance is rapidly developing and involves new and emerging technologies in prosthetic limb and powered exoskeleton designs that will significantly enhance human capabilities. For example, powered exoskeleton designs have been developed for military applications that allow soldiers to carry increased loads and perform at higher-than-normal levels [1]; however, these devices are typically expensive, bulky, and require specialized training for use and maintenance which currently renders them impractical for use in simple occupational or rehabilitation settings. In most occupational settings, manpower is a major cost driver and can be influenced by the number of personnel able to reliably complete complex, repetitive, and laborious work tasks. In the environment where the alternative energy is becoming a cheaper option, the number of nuclear sites that are being decommissioned is increasing [2]. In addition to cost reduction, in Waste Management (WM) of radioactive materials, the traditional objectives are to minimize exposure of workers to hazardous environments and to improve safety [3]. Along with the use of fully autonomous robots outlined in [3,4], these objectives may be achieved by focusing on continuous development of generic or task-specific performance-augmenting, low-cost and human-centered exoskeletons.

METHODS AND RESULTS

In this work, an initial prototype of a practical, low-cost, robotic exoskeleton was designed to efficiently and safely augment biomechanical function, strength, and endurance of the upper extremities of workers. Called the Robotic Exoskeleton for

Upper Extremity Strength Augmentation (REUESA – pronounced “re-u-sah”), this high fidelity system can assist workers in slightly heavier-than-normal work tasks, such as materials handling and manipulation, while maintaining biomechanical stability and control during use. The REUESA system can be seen in Figures 2 and 3.

Previous Generations

REUESA’s design is an expansion upon three previous generations of low-cost, high fidelity robotic exoskeletons seen in Figure 1. While these generations focused on upper extremity neuromuscular rehabilitation as well as the promotion of cortical plasticity for hemiplegics, the REUESA system primarily targets strength and performance augmentation in occupational settings. Like the previous designs, the functionality of the new system can also be utilized as a rehabilitation tool for actuated muscle retraining.

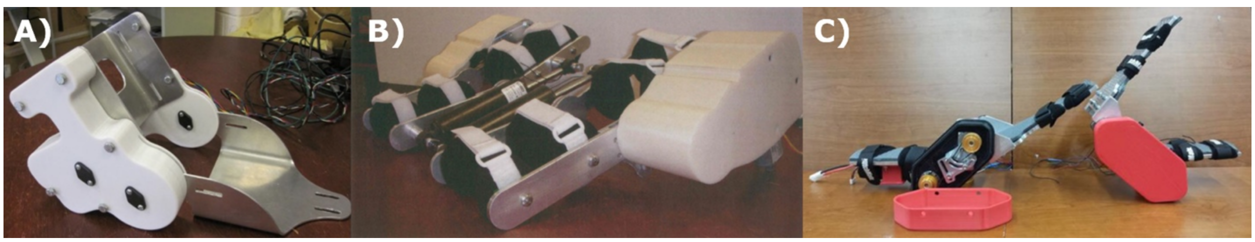

Figure 1. First three generations of rehabilitation exoskeletons

Low Cost

When compared to other commercially-available exoskeleton systems, REUESA represents a significant reduction in overall system cost by using quality low-cost actuators, materials, and 3D printed parts. The backbone of the device is constructed from metal components coupled together using low-cost 3D printed parts. The metal components are of low-weight aluminum alloy and the 3D printed parts are custom designed and produced using fused-deposition modeling (FDM) with a Replicator 2 (MakerBot Industries, Brooklyn, NY). Coupling the metal components with 3D printed parts minimizes machining requirements and allows for quick repairs and alterations that drive down the cost of the overall device. The actuators used in this design are low-cost high-torque DC motors.

Range of Motion

The system has a total of twelve degrees of freedom with six degrees of freedom on each side (i.e. left and right upper extremity). On each side, there is one degree of freedom at the elbow joint to accommodate for elbow flexion/extension, three degrees of freedom for glenohumeral (i.e., shoulder) joint motion, and two degrees for motions of the shoulder-scapula complex (i.e., shoulder abduction/adduction, scapular elevation/depression). As demonstrated in the Figure 2 and 3, the mechanical configuration of REUESA system allows for close to a full range of motion with minimal limitation to shoulder abduction (Figure 2d) and external/internal rotation (Figure 3a and 3b). In the proof-of-concept testing where a subject was asked to perform basic tasks such as lifting and lowering wooden pallet, no significant limitations were observed that prevented the subject from finishing the task. Currently, ongoing testing is being conducted to further verify the functionality of the exoskeleton suit as described in latter sections in this paper.

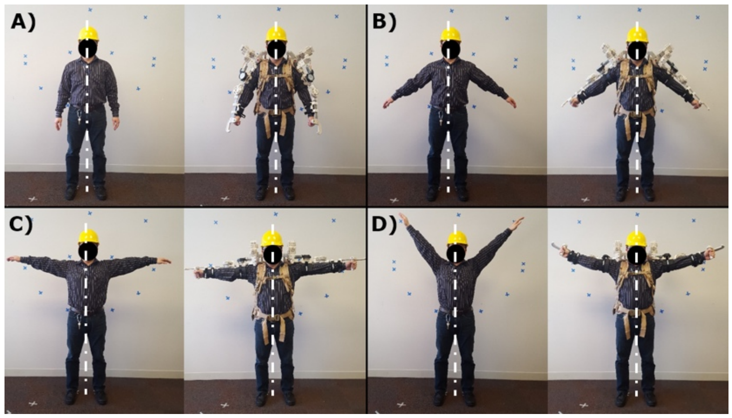

Figure 2. Comparison of range of motion with and without the exoskeleton suit for shoulder abduction at 0° (A), 45° (B), 90° (C), and 135° (D)

Figure 3. Comparison of range of motion with and without the exoskeleton suit for internal (A) and external (B) shoulder rotation, internal rotation (C) in combination with elbow flexion, neutral position with arms extended by the side(D), 90° elbow flexion (E), and 90° shoulder flexion (F)

Load Support

The elbow assembly of the exoskeleton is actuated by a DC motor-gear configuration, where the back and shoulder assemblies provide biomechanically passive support and non-actuated motion. The actuated motion of the system is capable of augmenting strength up to 40% and has multiple control modes available to the user as described below. The passive support is maintained with adjustable manual stops that set a limit to functional ranges of motion at each articulation joint. Once the limits are reached, the forces generated by the weight of the load distribute throughout the exoskeleton construct for support by larger muscle groups (e.g., lower extremity muscles) with intention of reducing the loading experienced by the upper extremities. The entire exoskeleton configuration is attached to a back frame with padding and adjustable straps that provide comfortable and stable support with a minimal interference to the range of motion or overall functional performance.

Attachment and User Set-up

The sizes of the individual exoskeleton structures are adjustable to account for anthropometric variability between users. Certain segments can be shortened or elongated by simply releasing a set screw and adjusting the length, while other segments can be easily and quickly replaced with an appropriately sized unit. The arm and forearm attachments are also configurable and can be adjusted for different lengths and geometries. An important characteristic of this design is the time required to don and operate the REUESA system. Currently, the actual set up of the design takes about 3 minutes and requires minimal assistance from a second person.

Control

To make REUESA compatible with various environments and various tasks, multiple control, or operation, modes are available, including free motion, manual, myographic, and brain wave modes. In the free motion, only a non-actuated passive support is provided where the load is lifted entirely by the user and a locking mechanism at the elbow joint secures the load at a desired elbow flexion/extension angle. In the manual control, flexion/extension at the elbow joint is controlled manually by switches integrated in the operator’s handles. Myographic control involves motor actuation of elbow flexion/extension when the mean absolute value (MAV) of conditioned electromyographic (EMG) signals from built-in sensors exceeds a pre-set MAV threshold. Currently, MAV thresholds are user specific and need to be normalized from maximum voluntary contractions (MVC) for each individual user prior to their use; however, further development of this control mode will eliminate the need for a normalization procedure and allow any individual to use the system with having to calibrate beforehand.

Overall Function

REUESA is intended to improve worker performance by assisting with slightly higher-than-normal loads. It lowers muscle activity levels and overall fatigue by redistributing forces generated by the weight of a load into larger muscle groups and for load support and transportation. While lifting in manual or mygoraphic mode, the actuated elbow joint can assist in lifting and sustaining up to 40 % of the load. Once the load or cargo is fully lifted and ready to be transported, it allows the user to transfer the entire weight to the exoskeleton structure by relaxing the upper extremity muscles. This is demonstrated in Figure 4, where the noticeable difference in the EMG muscle activity is shown while lifting a 40 lb. shipping pallet without and with the assistance of the exoskeleton suit. To further reduce the risk of an occupational injury, the user has an option to use a wide variety of forearm extensions or attachments. These extensions were designed to be easily exchangeable and were targeted to minimize wrist recruitment while lifting. Since wrist recruitment is very task dependent, the attachments can be designed with or without a handle attachment and/or fitted to fit a specific task.

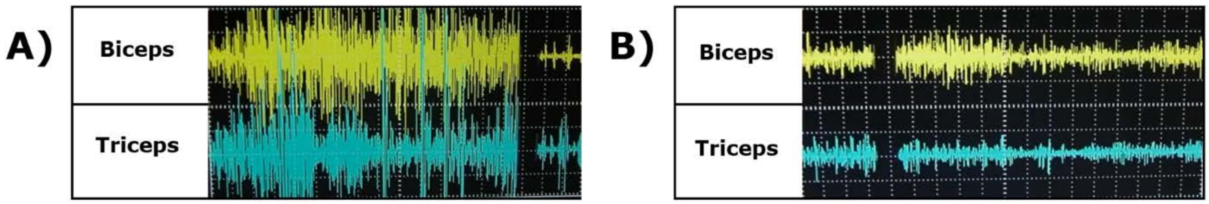

Figure 4. Surface electromyography (sEMG) measurement of biceps and triceps muscle activity during a lifting and holding task of a 40 lb. wooden shipping pallet (without exoskeleton suit (A) and with the exoskeleton suit (B))

DISCUSSION AND CONCLUSION

With the exoskeleton system providing strength augmentation exclusively for the upper extremities, it is not intended for lifting extremely heavy loads where an application of a full body exoskeleton might be more suitable. As demonstrated in Figures 2 and 3, the exoskeleton provides close to a full range of motion with minimal interference; however, newer modifications to the back and shoulder assemblies under development will eliminate these current limitations and will decrease the overall size of the system.

The restriction in shoulder external/internal rotation, shown in Figure 3a and 3b, is attributed to the current mechanical configuration, where the center of rotation of the exoskeleton armature is slightly offset from the actual center of rotation of the shoulder. This causes a shearing-like motion between the forearm and the exoskeleton forearm link, which is particularly emphasized during this rotation. It is partially solved by allowing the forearm attachment to move up and down along the armature, where, if it was fixed in place, then the limitation to the motion would be more severe. An additional degree of freedom is being incorporated into the exoskeleton forearm link and will improve the limited range of motion for wrist supination/pronation and will also improve external rotation typically accompanied by wrist supination. The ease of object grasping and handling is also in development and will improve the use and real-time inter-changeability of handle attachments.

The 3D printed parts were designed to emphasize the importance of structural strength, including optimal ribbing, edging, filleting, etc. and high internal densities greater than 85%. Each 3D printed component undergoes Finite Element Analysis (FEA) modeling, as well as a series of material tensile and compression tests, in order to optimize between strength and internal density for each printed part. This allows for the design of the strongest configuration using the minimum amount of material, which also minimizes material cost and manufacturing time.

The design of REUESA targets a plug-and-play-like approach with minimal need for maintenance and minimal requirement to get the system to a functional ready-to-go state, especially following any repairs. In the current design iteration, set-up requires an additional person to assist with strapping on and adjusting the device, where, in the future iterations, a docking station will be implemented to allow any user to don and self-deploy the system.

Further development involves power supply and distribution as well as reducing the weight of the overall exoskeleton system. Further development also involves modifying the myographic control to implement a more sophisticated muscle activity monitoring algorithm that will eliminate the need for EMG calibration. Since managing EMG sensitivities among varied users is an extremely challenging task, complementing the EMG monitoring system with pressure-sensitive padding is under investigation. As seen in Figure 4, a clear reduction in muscle activity was demonstrated throughout the entire task of lifting, transporting, and lowering a wooden pallet. Here, only two EMG electrodes were used to compare muscle activity levels of the biceps and triceps, while ongoing work targets more comprehensive EMG modeling of the upper and lower extremities, torso, and lower back. In addition, current work also involves the use of opto-electronic motion capture and force plates to study and validate biomechanical performance, including human motion and efficiency, especially to ensure that the risks associated with occupational injuries are truly reduced. Outcomes from this work will determine the level of impact robotic strength augmentation has on the prevention of work related injuries associated with lifting and maneuvering heavy objects.

In conclusion, REUESA will improve worker performance and increase worker productivity by facilitating more significant engagement of larger muscle groups, which will be beneficial for the prevention of occupational related injuries and lead to an increase in quality of work.

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