Soft Upper Limb Exosuit for Musculoskeletal Injury Prevention of Firefighters

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***Abstract*— Firefighting can place extreme physical demands on the upper body. It often requires sustained arm elevation and handling heavy loads under hazardous conditions. These actions generate high torque requirements at the shoulder, causing rapid muscle fatigue and increasing the risk of musculoskeletal injury in the shoulder area. While exoskeletons can be used to reduce muscle activation during lifting, conventional designs for industrial or rehabilitation use often employ bulky, rigid linkages and heavy mechanisms or require tethers that would interfere with the mobility and personal protective equipment of a firefighter. In contrast, this work presents a soft, untethered upper-limb exosuit that provides targeted shoulder abduction and extension assistance for high-load firefighting tasks such as hose handling and overhead tool use. The system utilizes an inflatable actuator, compact pneumatic pump, flexible tubing, and embedded electronics to form an exoskeleton that preserves mobility, conforms to natural shoulder motion, and interfaces seamlessly with standard PPE. A single actuator is configured to assist two degrees of freedom—shoulder abduction and extension—reducing both muscular effort and fatigue without introducing rigid, restrictive components. This represents a potential advancement in assistive devices for firefighters, which may eventually help to reduce musculoskeletal injuries.**

I. Introduction

Firefighting is one of the most physically demanding professions, with firefighters routinely lifting and controlling hoses that, when charged, can weigh around 130 pounds and generate strong nozzle reaction forces [1]. Overhead tool operations require holding the arms at large elevation or abduction angles for extended periods. These postures have been shown to significantly increase activation in shoulder musculature and are associated with higher risk of fatigue and injury [2], [3]. Traditional training and equipment cannot mitigate these acute loads. However, a shoulder exoskeleton that provides support for dynamic motions [4] and sustained arm raises has the potential to reduce the torque load on the shoulder, thus reducing muscular effort and delaying fatigue, ultimately enhancing safety and endurance. Existing shoulder exoskeletons typically rely on heavy, rigid parts that compromise mobility and range of motion [5]. Their stiff structures can cause misalignment with the natural shoulder motions, resulting in discomfort and reduced task performance [6]. The excessive mass and rigid parts also lead to incompatibility with firefighter gear [7] [8].. The objective of our work is to design a soft exosuit that is lightweight, unobtrusive to human movements, untethered, and compatible with firefighting uniforms. We also aim to describe the necessary electronics and sensors needed to provide electrical communication and control of soft actuators.

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II. Method

Two very common tasks for firefighters are hose handling and overhead tool use. When a house is on fire, firefighters may need to control the flames with heavy hoses. In addition, firefighters often need to use overhead tools to create openings in roofs to ensure proper ventilation, reducing smoke and toxic gases. Examples of these tasks are shown in Fig. 1.

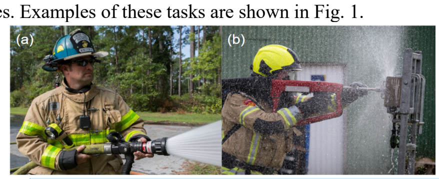

Fig. 1. Hose handling (a) and overhead tool use (b) poses. Firefighters need to be precise and steady when making overhead cuts and may handle hoses for multiple hours during fires, potentially causing muscle strain.

By attaching IMU sensors to a person and having them mimic different poses a digital human avatar can be created. Seven IMU sensors were used, including three per arm on the wrist, forearm and upper arm, and one on the lower spine. These sensors provide an accurate model of the upper body position.

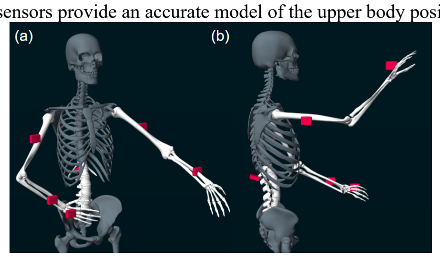

Fig. 2. Human avatar created with seven upper-body IMU sensors. The avatar is shown in (a) hose handling posture and (b) overhead tool use posture.

By simulating firefighting postures, the avatar highlights the muscles and joints that are most heavily engaged, such as the shoulder during hose handling and tool use. This makes it easier to visualize where fatigue and strain are likely to occur and shows how support from the exosuit can reduce it. In the hose-handling pose (Fig. 2a), the arm is lifted out to the side at the shoulder. This posture puts a heavy load on the shoulder muscles, especially the deltoid, which must constantly work to hold the arm up against the weight of the hose. Over time, this can lead to fatigue and strain in the shoulder. The exosuit helps by providing lift under the arm, reducing the effort required from the shoulder muscles to keep the hose steady.

批注 [1]: This needs to be supported somewhere in the text of the paper. Say something in the methods/results about it fitting over clothes and being adjustable to accommodate bulky firefighter jackets

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In the overhead tool-use pose (Fig. 2b), the arms are raised forward to about head level. This position engages the front shoulder muscles to keep the arms stable while operating heavy tools. The exosuit supports the arms in this position by reducing the amount of effort needed to keep them raised, allowing firefighters to use tools more effectively and with less strain. In both poses, the avatar helps to show exactly which joint would benefit the most from assistance; in this case, the shoulder.

III. RESULT

To solve the problem of firefighter muscle fatigue, we designed an untethered soft pneumatic shoulder exosuit and its control box (Figs. 3 and 4, respectively). This actuator was designed to inflate to assist with both shoulder abduction and flexion, conforming to natural shoulder motion. In addition, the exosuit fits over clothes and is adjustable to accommodate bulky firefighter gear. This design minimizes weight and stiffness, compared to rigid exoskeletons, which enhances comfort and mobility, while allowing seamless integration with firefighting gear.

The exosuit can assist firefighters in lifting and maneuvering heavy equipment by providing targeted shoulder support. For overhead tool use tasks, as shown in Fig. 1a, the exosuit stabilizes the weight of the saw during overhead cutting, improving precision and extending endurance. During hose operations, as shown in Fig. 1b, it can help to support the shoulder elevation and control the hose line, minimizing muscle strain and reducing fatigue over extended periods of time.

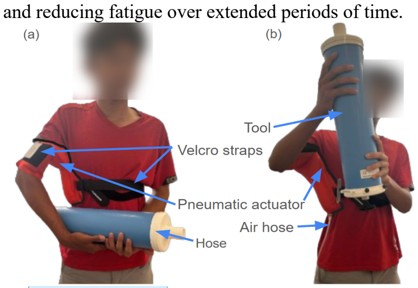

Fig. 3. Example poses for hose handling (a) and overhead tool use (b). These poses resemble the ones in (Fig. 2) and they show how a firefighter would wear the exosuit. The exosuit is attached under the user's right armpit, and velcro straps are used to secure it to the user. The air hose connects to the air accumulator and control box.

IV. CONCLUSION

We presented an untethered soft upper-limb exosuit designed for firefighter shoulder assistance, especially for hose hand We presented an untethered soft upper-limb exosuit designed for firefighter shoulder assistance, especially for hose handling and extension. We used IMU sensors to track human posture and

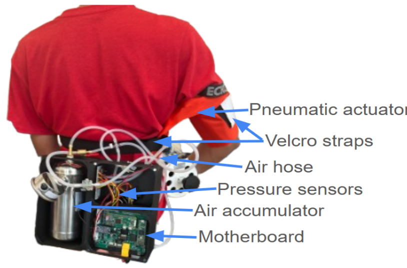

Fig. 4. Control box for exosuit. It connects to the actuator using an air hose and is powered using a 22V Li-Po battery[8]. When turned on, it inflates the actuator using an air accumulator.

generated a skeletal avatar to highlight the musculoskeletal demands of firefighting tasks. This avatar demonstrated that the exosuit can support shoulder flexion and abduction. Future plans include fully integrating the entire system to improve portability and comfort by designing a wearable backpack. This backpack will store the control box for the exosuit, making it more robust and practical. Additionally, minimizing the noise produced by the air pump is also a priority, as excessive noise can be distracting.

REFERENCES

[1] "5 Critical Factors: How Much Does a Fire Hose Weigh in 2025?", CNBaianFire.

[2] S. Ding et al., "A novel passive shoulder exoskeleton for assisting overhead work," PMC, 2023.

[3] C. Howard, A. Kahnt, J. L. Volberding, and J. Dawes, "Assessment of Bilateral Shoulder Range of Motion in Firefighter Trainees Using a Markerless Motion Capture System," International Journal of Athletic Therapy and Training, vol. 28, no. 5, pp. 263-268, 2023.

[4] J. G. Deshani, *MAE 586 – Final Report*, Dept. Mechanical and Aerospace Engineering, North Carolina State Univ., Raleigh, NC, USA, 2023.

[5] W. Gao, A. Lallo, and H. Su, "A Portable Powered Soft Exoskeleton for Shoulder Assistance During Functional Movements: Design and Evaluation," in Proc. Int. Symp. Med. Robot. (ISMR), Atlanta, GA, USA, May 2023.

[6] A. Lallo, S. Yu, J. E. Slightam, G. X. Gu, J. Yin, and H. Su, "Untethered Fluidic Engine for High-Force Soft Wearable Robots," *Adv. Intell. Syst.*, vol. 2400171, 2024.

[7] A. Coca, S. Williams-Bell, J. A. Gillis, D. A. Jamnik, and S. J. Shaw, "Effects of firefighter protective ensembles on mobility and performance," *Applied Ergonomics*, vol. 41, no. 4, pp. 636–641, Jul. 2010, doi: 10.1016/j.apergo.2009.12.009.

[8] W. Gao, J. Zhou, and H. Su, "Soft Pneumatic Exosuit for Shoulder Assistance in Individuals with Amyotrophic Lateral Sclerosis," in *Proc. North-East Bio-Eng. Conf. (NEBEC)*, 2025.

[9] X. Yang, T.H. Huang, H. Hu, S. Yu, S. Zhang, X. Zhou, A. Carriero, G. Yue, H. Su. "Spine-Inspired Continuum Soft Exoskeleton for Stoop Lifting Assistance." IEEE Robotics and Automation Letters, 14;4(4):4547-54. Aug. 2019

[10] L. J. Salmeron, G. V. Juca, S. M. Mahadeo, J. Ma, S. Yu, H. Su, "An Untethered Electro-Pneumatic Exosuit for Gait Assistance of People with Foot Drop", Design of Medical Devices Conferences (DMD), Minneapolis, 2020.

[11] S. Yu, T.H. Huang, D. Wang, B. Lynn, D. Sayd, V. Silivanov, Y.S. Park, Y. Tian, H. Su. "Design and Control of a High-Torque and Highly-Backdrivable Hybrid Soft Exoskeleton for Knee Injury Prevention during Squatting". IEEE Robotics and Automation Letters, Jul 26;4(4):4579-86., 2019

[12] Q. Xiao, M. Musa, I. Godage, H. Su, and Y. Chen. "Kinematics and Stiffness Modeling of Soft Robot With a Concentric Backbone." ASME Journal of Mechanisms and Robotics. Oct. 2023.

批注 [8]: Make sure when you rearrange figures that you update all references in text to the correct figure number

批注 [10]: All of these citations need to be referenced in the text. The format should be something like: "Firefighting causes muscle fatigue [1]" and then citation 1 is something that supports that claim. The order they appear in the bibliography should be the same as they appear in the text. Look at any of Prof. Su's other papers for an example of this or let me know if anything is unclear.

批注 [9]: A bit nit-picky here, but try not to have the velcro strap arrows cross the pneumatic actuator arrow. Also the font size is better, but I would go bigger with the line weight and arrow size. You want to make it as easy as possible to understand the figures.