Bio-inspired Design of Robotic Shoulder Exoskeleton for Musculoskeletal Injury Prevention

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***Abstract*—Assistive shoulder exoskeletons can reduce musculoskeletal loading, but typically suffer form joint misalignment and physical interference with natural shoulder movement. To solve these two issues, we created a shoulder exoskeleton design with two mechanisms: 1) a bio-inspired self-aligning mechanism that mimicked scapular rotation/protraction to align with the shoulder's shifting center of rotation during motion, and 2) a compact variable lever-arm transmission that increased the effective moment arm with elevation while minimizing the physical interference. Our experiment results showed that ROM has a minimized reduction of <8%; muscle activations were significantly reduced across major muscles during functional tasks; endurance increased by 73% (flexion) and 54% (abduction), which indicated effective assistance with preserved natural shoulder movement.**

I. Introduction

Lower limb exoskeletons can reduce musculoskeletal loading [1], [2], [3]. The unique anatomy of shoulder joint presents two design design challenges 1) delivering effective torque assistance without human–robot joint misalignment, and 2) providing assistance while not interfering with natural shoulder motions. To address these needs, we proposed a bio-inspired design that mimics scapular rotation and protraction to preserve alignment during abduction and flexion. Second, we designed a compact variable lever-arm transmission that minimizes the structure moving with the upper arm to mitigate its impairments to natural shoulder movement.

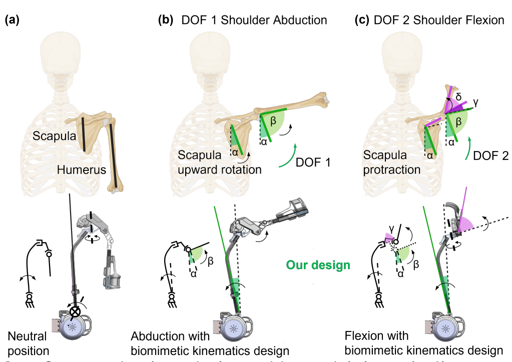

Fig. 1. Our first mechanism design addressed joint misalignment by mimicking scapular motion. Two passive planar revolute joints enabled self-alignment: during abduction, the first joint allows inward rotation in the frontal plane, mimicking upward scapular rotation; the second joint permits horizontal ad/abduction during elevation, mimicking scapular protraction, enabling flexion assistance.

II. Methods

We designed two mechanisms to address the misalignment and physical interference, respectively. First, we designed a biomimetic self-aligning mechanism mimicking scapular kinematics using two passive planar revolute joints (Fig. 1): one is near the waist to emulate upward scapular rotation during abduction, and one is posterior to the shoulder to mimic scapular protraction/retraction for horizontal movements. These joints allow the exoskeleton to compensate the shoulder's shifting center of rotation, preventing human–robot joint misalignment.

Second, we designed a variable lever-arm mechanism, where a compact winch-like mechanism increased the effective moment arm as shoulder elevates, delivering larger assistance when biologically needed. Our design effectively shrunk the structure size moving with the upper arm, achieving an equivalent lever arm up to 71 mm with a 68% reduction in the transmission volume on the arm, thus mitigating physical interference with natural motion.

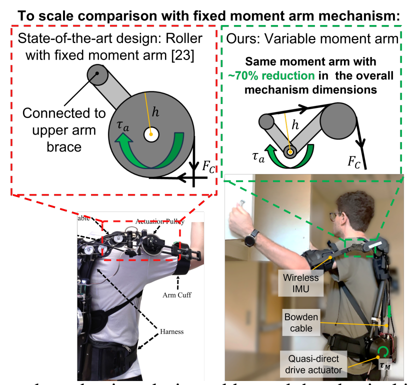

Fig. 2. Our second mechanism design addressed the physical interference with natural shoulder movements issue through a variable moment-arm mechanism that delivers an equivalent lever arm while shrinking on-arm transmission volume by 68% versus state-of-the-art designs.

III. Experimental Results

We evaluated our robot in randomized tests, including holding (endurance) at flexion and abduction, range of motion (ROM), and overhead assembly and lift-and-place. ROM results showed the our robot caused the lowest reduction (<8%), while state-of-the-art robots usually caused >30% ROM loss. In overhead work task, average sEMG significantly decreased from 17.3% to 65.2% for all the recorded major shoulder muscles. Endurance time in holding task increased by 73.2%, and 54.1% with assistance, alongside average EMG reductions range from 30.5% to 48.7% in flexion, 19% to 34% for abduction, for flexion and abduction.

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References

[1] S. Luo, M. Jiang, S. Zhang, J. Zhu, S. Yu, I. Dominguez Silva, T. Wang, E. Rouse, B. Zhou, H. Yuk, X. Zhou, and H. Su, "Experiment-free exoskeleton assistance via learning in simulation," *Nature*, vol. 630, no. 8016, pp. 353–359, 2024.

[2] S. Yu, T.-H. Huang, X. Yang, C. Jiao, J. Yang, Y. Chen, J. Yi, and H. Su, "Quasi-direct drive actuation for a lightweight hip exoskeleton with high backdrivability and high bandwidth," *IEEE/ASME Transactions On Mechatronics*, vol. 25, no. 4, pp. 1794–1802, 2020.

[3] T.-H. Huang, S. Zhang, S. Yu, M. K. MacLean, J. Zhu, A. Di Lallo, C. Jiao, T. C. Bulea, M. Zheng, and H. Su, "Modeling and stiffness-based continuous torque control of lightweight quasi-direct-drive knee exoskeletons for versatile walking assistance," *IEEE Transactions on Robotics*, vol. 38, no. 3, pp. 1442–1459, 2022.