



Hao Su (PI) Alessandra Carriero (Co-PI) Yingli Tian (Co-PI)

Soft Wearable Robots for Injury Prevention and Performance Augmentation

Shuangyue Yu¹, Tzu-Hao Huang¹, Selena Zhang¹, Junxi Zhu¹, Alessandra Carriero², Yingli Tian³ and Hao Su¹

¹Biomechanics and Intelligent Robotics lab, Mechanical and Aerospace Engineering Department at the North Carolina State University, Raleigh, NC 27606 USA

²Department of Biomedical Engineering, City University of New York, New York, NY, 10031, USA

³Department of Electrical Engineering, City University of New York, New York, NY, 10031, USA



Website: <http://haosu-robotics.github.io>
Email: hsu4@ncsu.edu

Objectives and Challenges

- More than \$15 billion are paid yearly due to physical overexertion of workers
- Exoskeletons have potential to mitigate the injury incidence and augment human capabilities
- They are of high interest to occupational safety and health agencies and compensation insurers
- Current devices suffer from drawbacks: bulkiness, discomfort and inadaptability to different users

Portable and Tethered Soft Exoskeleton Systems

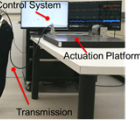
Portable System: high performance, versatile assistance in the field

Specification	
Motor Torque	2.2 Nm
Motor Speed	1500 RPM
Output Torque	40 Nm
Output Speed	16.2 rad/s
Range of Motion	130 degree
Gear Ratio	6:1
Total Weight	2.4 kg



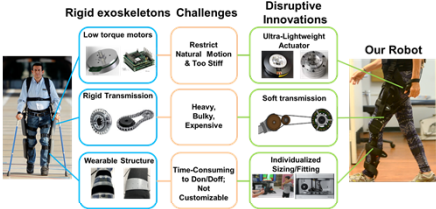
Tethered System: lightweight, scientific platform to study control and biomechanics

Specification	
Motor Torque	2Nm
Motor Speed	1500 RPM
Output Torque	72 Nm
Output Speed	4.4 rad/s
Range of Motion	130 degree
Gear Ratio	36:1
Total Weight	< 1 kg

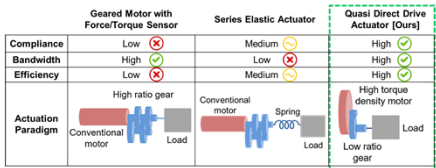


Soft Exoskeleton Innovations

Paradigm Shift of Wearable Robots



New Actuation Paradigm for Co-Robots

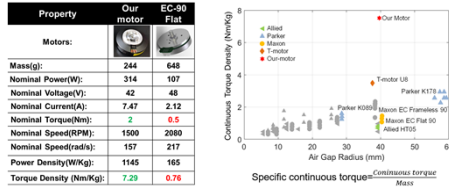


Published Journals

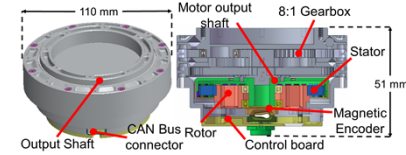
- [1] Yu, Huang, Hu, Yu, Zhang, Carriero, Yau, Su, Spine-Inspired Continuum Soft Exoskeleton for Stoop Lifting Assistance. IEEE Robotics and Automation Letters, 2019
- [2] Yu, Huang, Lynn, Sayd, Silvanov, Park, Tian, Su, Design and Control of a High-Torque and Highly-Backdrivable Hybrid Soft Exoskeleton for Knee Injury Prevention during Squatting. IEEE Robotics and Automation Letters (RA-L), 2019
- [3] Yu, Huang, Yang, Jiao, Yang, Chen, Yi, Su, Quasi-direct drive actuator for a lightweight hip exoskeleton with high backdrivability and high bandwidth. Trans. on Mechatronics (T-MECH), 2020 (Best Student Paper in Mechatronics by the ASME Mechatronics TC)
- [4] Huang, Zhang, Yu, MacLean, Di Lallo, Bules, Su, Modeling and Continuous Stiffness Torque Control of Quasi-Direct-Drive Knee Exoskeletons for Versatile Walking Assistance. Trans. on Robotics (T-RO), 2022 (conditionally accepted)
- [5] Yu, Huang, and Su, Artificial Neural Network-Based Activities Classification and Gait Phase Prediction: Application for Exoskeleton Control. Annals of Biomedical Engineering (ASME), 2022. (in review)
- [6] Yu, Huang, Zhang, Di Lallo, Fu, Su, Bio-Inspired Design and Torque Control of a Cable-Driven Knee Exoskeleton with High-Torque Actuators, Bioinspiration & Biomimetics, (in review)

Motor Torque Density Comparison

- Our custom-designed motor has the **highest torque density**

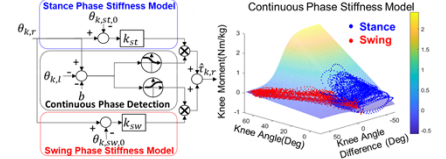


Customized High Torque Density Actuator



Versatile Knee Exoskeleton Controller

- Discrete control → continuous control (stiffness-inspired)
- Simple, analytical, adaptive to varying walking speed



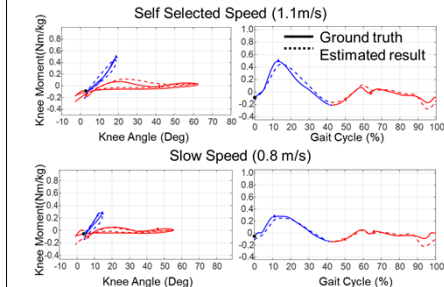
Input: knee angles $\theta_{k,r}$, $\theta_{k,l}$ and their difference; Output: estimated knee torque

Estimated biological torque:

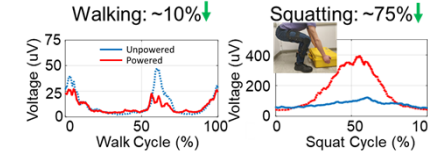
$$\hat{\tau}_{k,r} = [1 - S(\theta_{k,r}, \theta_{k,l})]k_{st}(\theta_{k,r} - \theta_{k,st,0}) + S(\theta_{k,r}, \theta_{k,l})k_{sw}(\theta_{k,r} - \theta_{k,sw,0})$$

Sigmoid function: discrete to continuous

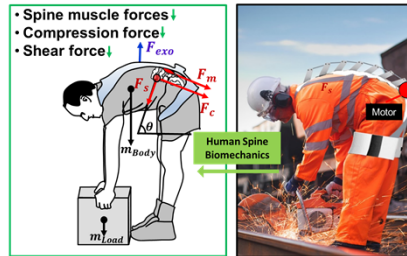
$$S(\theta_{k,r}, \theta_{k,l}) = \frac{1}{1 + e^{-a f(\theta_{k,r}, \theta_{k,l})}} \quad f(\theta_{k,r}, \theta_{k,l}) = (\theta_{k,r} - \theta_{k,l}) - b$$



Reduced muscle activities for walking squatting



Spine-Inspired Continuum Back Exoskeleton



Advantages of Our Back Exoskeleton

Unlimited range of motion

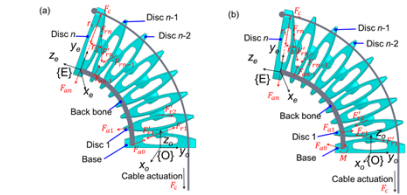


Spine-inspired soft back exoskeleton design

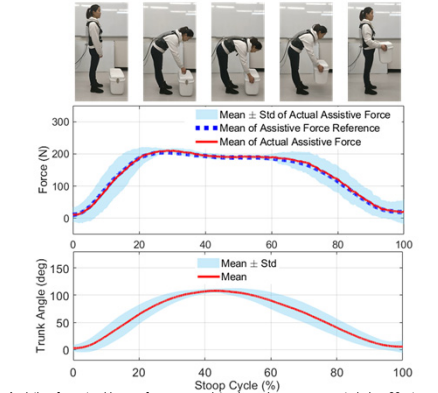


Kinetics of back exoskeleton in bending configuration

– (a) n is odd; (b) n is even

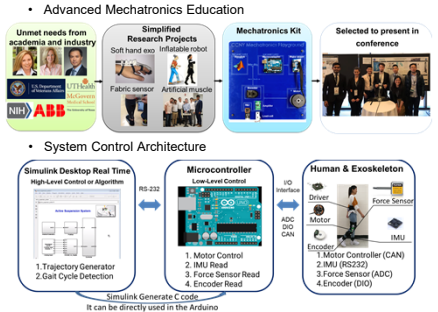


- Assistive force tracking performance and trunk angle measurement during stoop lifting



Assistive force tracking performance and trunk angle measurement during 30 stoop cycles. The actual assistive force (red line) tracked assistive force reference (blue line) with good accuracy (RMS error in 30 stoop cycles was 6.63 N, that is 3.3 % of the peak force).

Lowering Barriers To Learn Robotics



- International conferences (2 awards) + 18 undergrad student projects

- Salmeron, Juca, Mahadeo, Yu, and Su, International Conference of Wearable Robotics Association (WearRicon), 2020 (2nd prize, Innovation Challenge)
- Salmeron, Juca, Ma, Yu, Su, "Un tethered Electro-Pneumatic Exosuit for Gait Assistance of People with Foot Drop", Design of Medical Devices Conferences, 2020 (2nd prize, Three-in-One Competition)
- Yuan, Nogatz, Chi, Ferdous, Yu, Su, "Omniscient Back-Support Exoskeleton: Soft, Active Suit to Reduce Spinal Loading", Design of Medical Devices Conferences, 2019
- Yu, Perez, Barkas, Mohamed, Eldady, Su, "Soft Force Hand Exoskeleton for Assistance of Stroke Individuals", Design of Medical Devices Conferences, 2019
- Yang, Huang, Yu, Su, Spungen, Tsai, "Machine Learning Based Adaptive Gait Phase Estimation Using IMU Sensors", Design of Medical Devices Conferences, 2019

