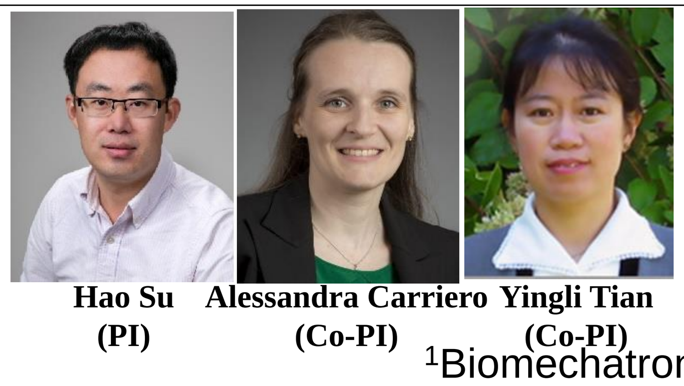
# Soft Wearable Robots for Injury Prevention and Performance Augmentation


The City University of New York

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## Motivation

- 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.

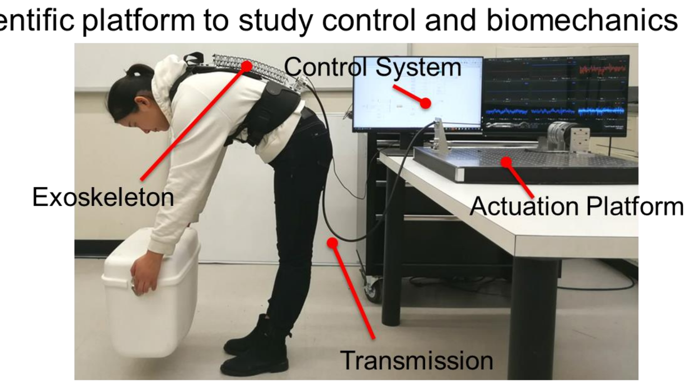
## Portable and Tethered Soft Exoskeleton Systems

**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 |

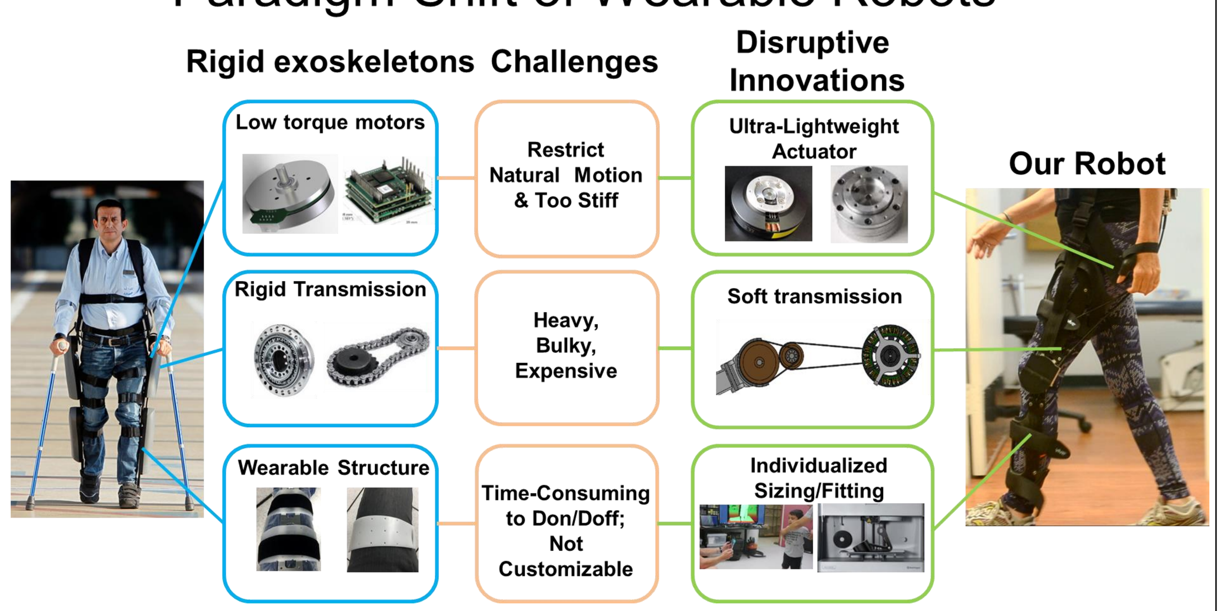

**Tethered System:** lightweight, scientific platform to study control and biomechanics

| 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 |

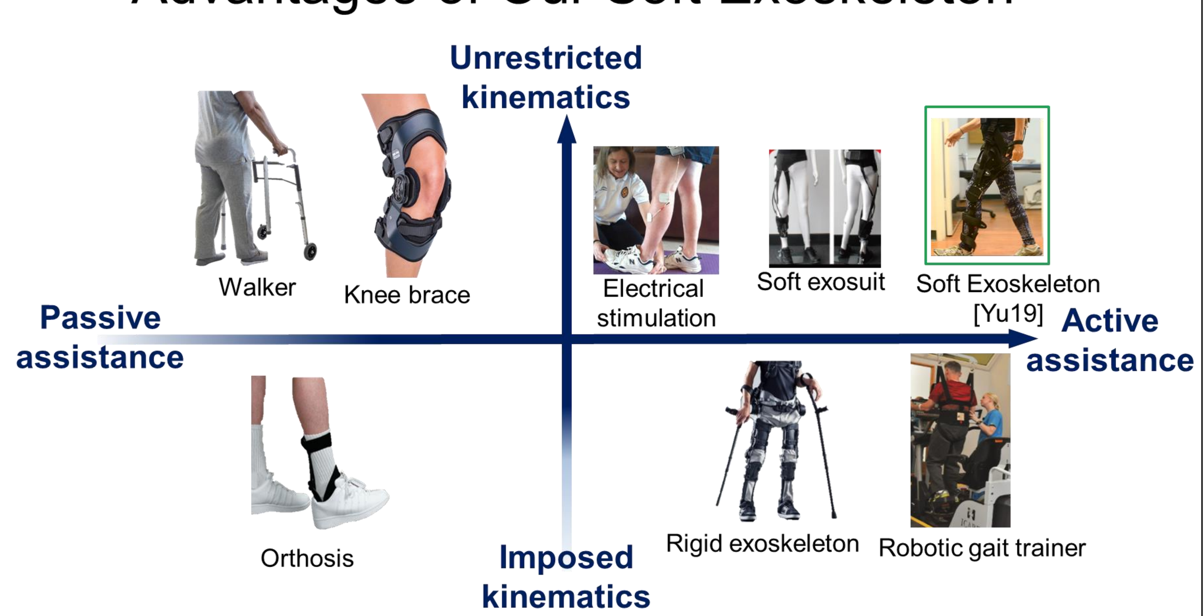



## Soft Exoskeleton Innovations

### Paradigm Shift of Wearable Robots




### Advantages of Our Soft Exoskeleton




## Published Journal


[1] Yang, Huang, Hu, Yu, Zhang, Carriero, Yue, Su. Spine-Inspired Continuum Soft Exoskeleton for Stoop Lifting Assistance. IEEE Robotics and Automation Letters, 2019

[2] Yu, Huang, Lynn, Sayd, Silivanov, 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 actuation for a lightweight hip exoskeleton with high backdrivability and high bandwidth. Trans. on Mechatronics (T-MECH), 2020. (Best student paper award finalists)

[4] Huang, Zhang, Yu, MacLean, Di Lallo, Bulea, Su, Modeling and Continuous Stiffness Torque Control of Quasi-Direct-Drive Knee Exoskeletons for Versatile Walking Assistance, Trans. on Robotics (T-RO), 2021 (in review)

[5] Yu, Huang, and Su. Artificial Neural Network-Based Activities Classification and Gait Phase Prediction: Application for Exoskeleton Control, Trans. on Biomedical Engineering (TBME) (in review)

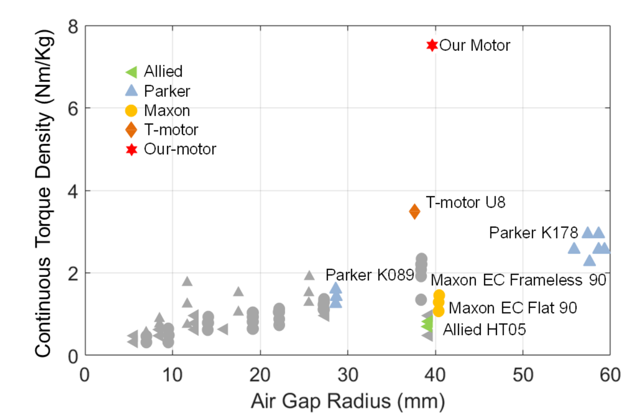

## New Actuation Paradigm for Co-Robots

| | Geared Motor with Force/Torque Sensor | Series Elastic Actuator | Quasi Direct Drive Actuator [Ours] |
|---|---|---|---|
| Compliance | Low | Medium | High |
| Bandwidth | High | Low | High |
| Efficiency | Low | Medium | High |
| Actuation Paradigm | High ratio gear; Conventional motor; Load | Conventional motor; Spring; Load | High torque density motor; Low ratio gear; Load |

### Motor Torque Density Comparison

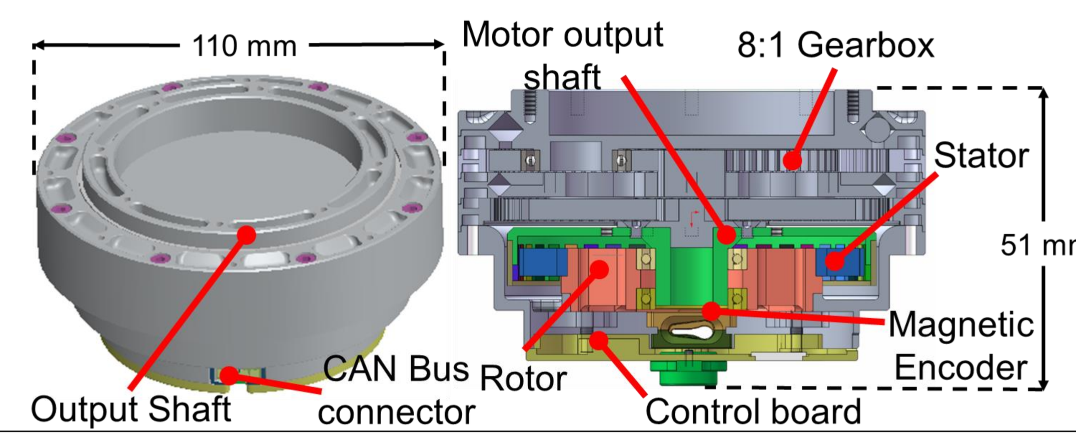
- Our custom-designed motor has the **highest torque density**

| Property | Our motor | EC-90 Flat |
|---|---|---|
| Motors: | | |
| Mass(g): | 244 | 648 |
| Nominal Power(W): | 314 | 107 |
| Nominal Voltage(V): | 42 | 48 |
| Nominal Current(A): | 7.47 | 2.12 |
| Nominal Torque(Nm): | 2 | 0.5 |
| Nominal Speed(RPM): | 1500 | 2080 |
| Nominal Speed(rad/s): | 157 | 217 |
| Power Density(W/Kg): | 1145 | 165 |
| Torque Density (Nm/Kg): | 7.29 | 0.76 |



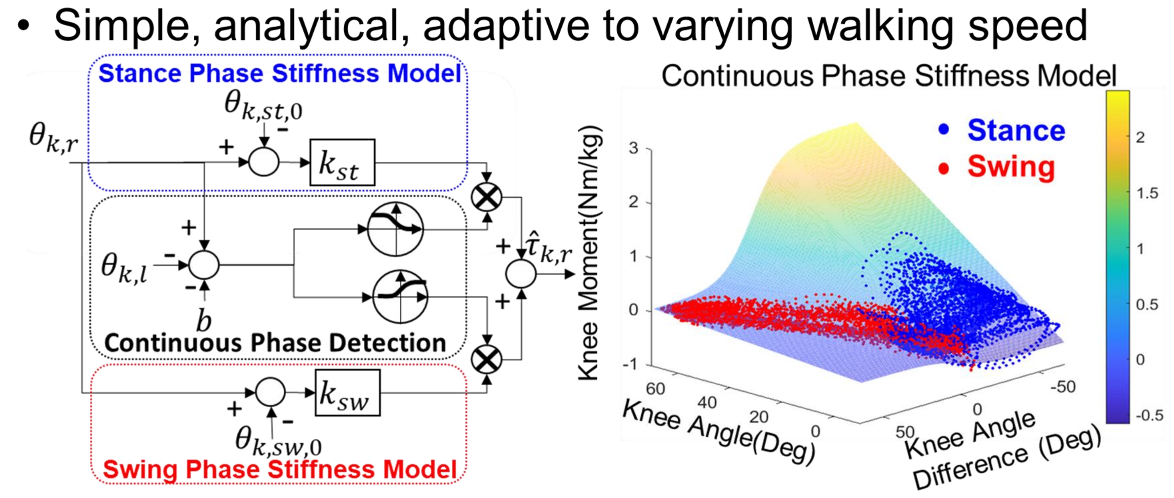

Specific continuous torque=$\frac{\text{Continuous torque}}{\text{Mass}}$

### Customized High Torque Density Actuator




## Versatile Knee Exoskeleton Controller

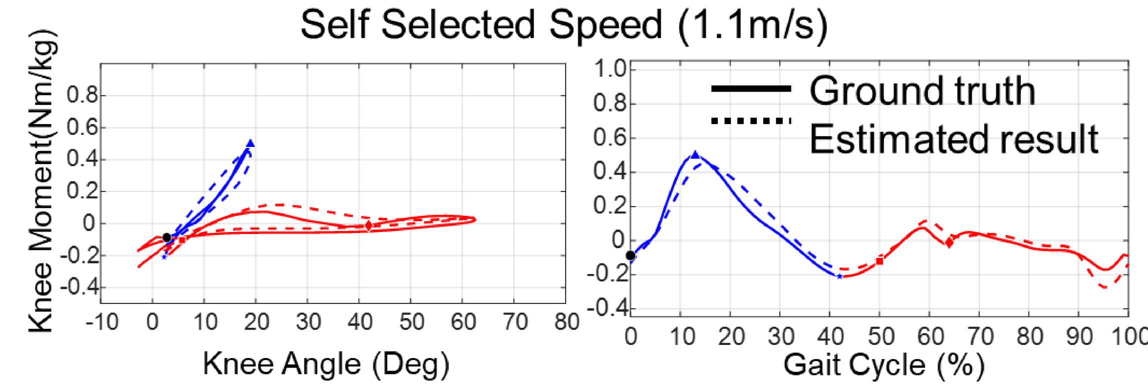
- Discrete control → continuous control (stiffness-inspired)
- Simple, analytical, adaptive to varying walking speed



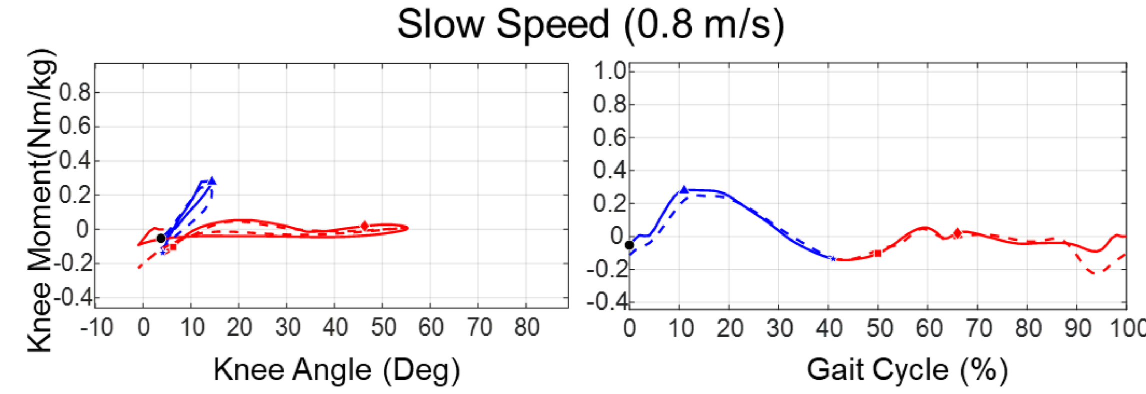

Estimated biological torque:

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

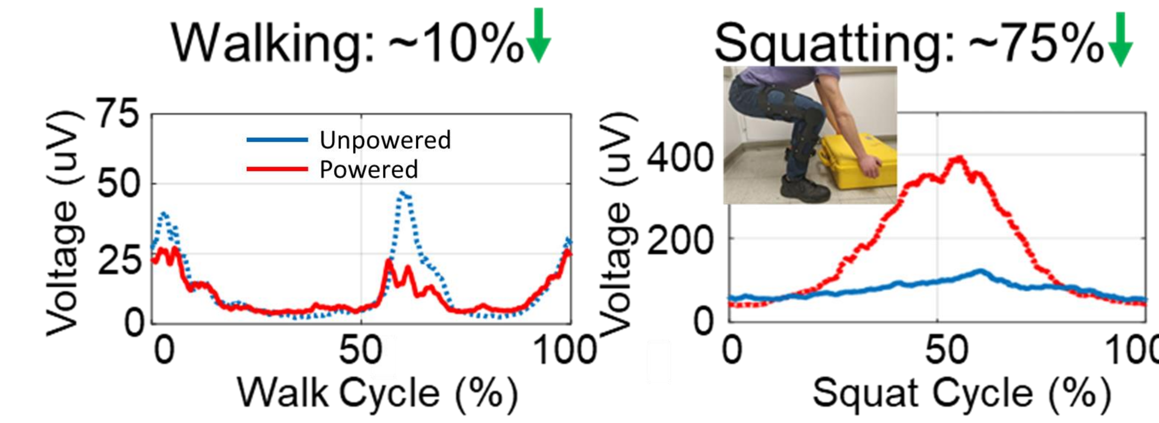
Self Selected Speed (1.1m/s)



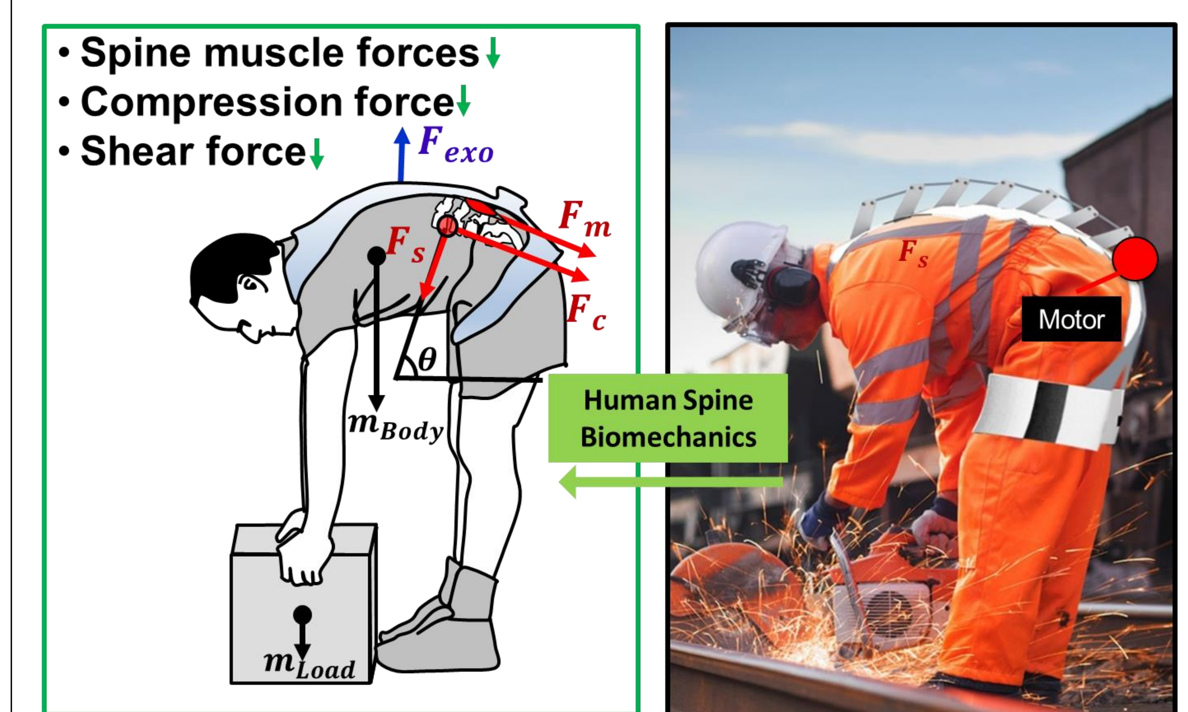

Slow Speed (0.8 m/s)




- Reduced muscle activities for walking squatting

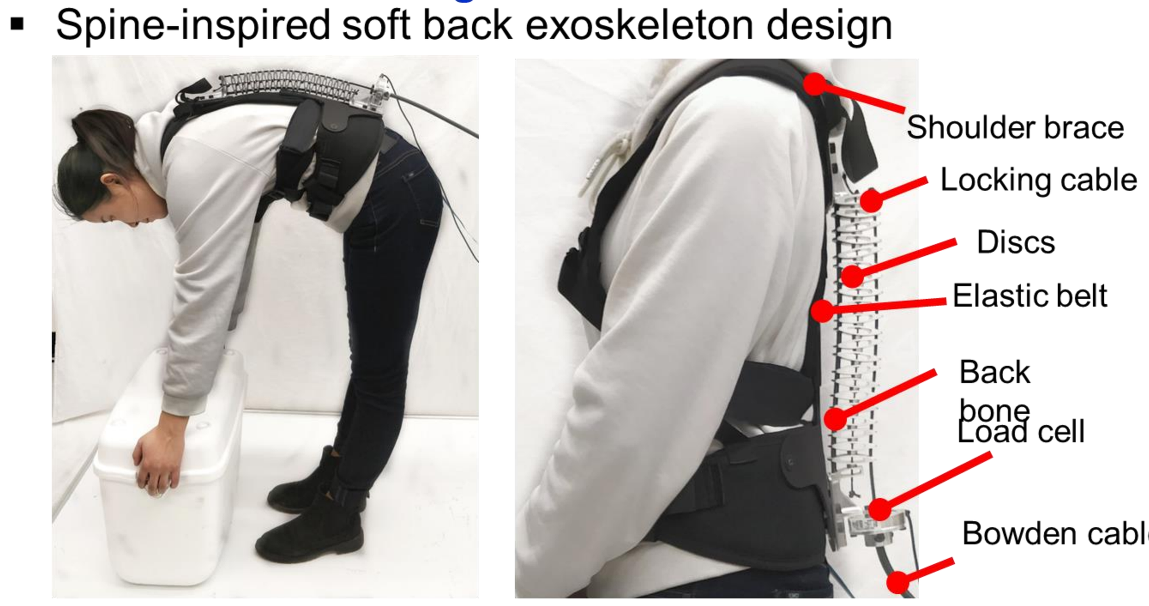



## Spine-Inspired Continuum Back Exoskeleton

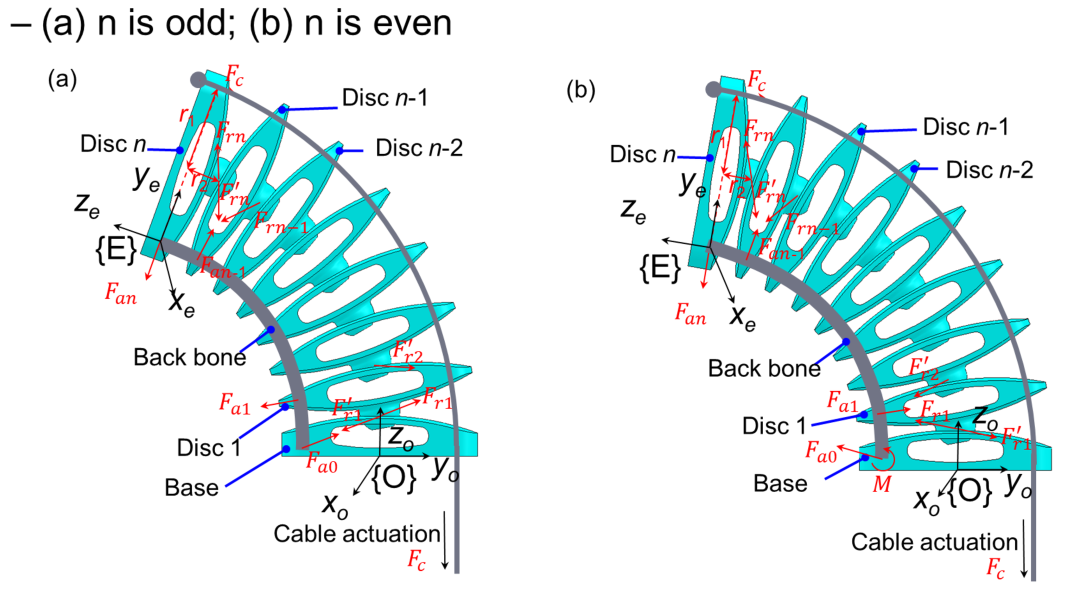



### Advantages of Our Back Exoskeleton

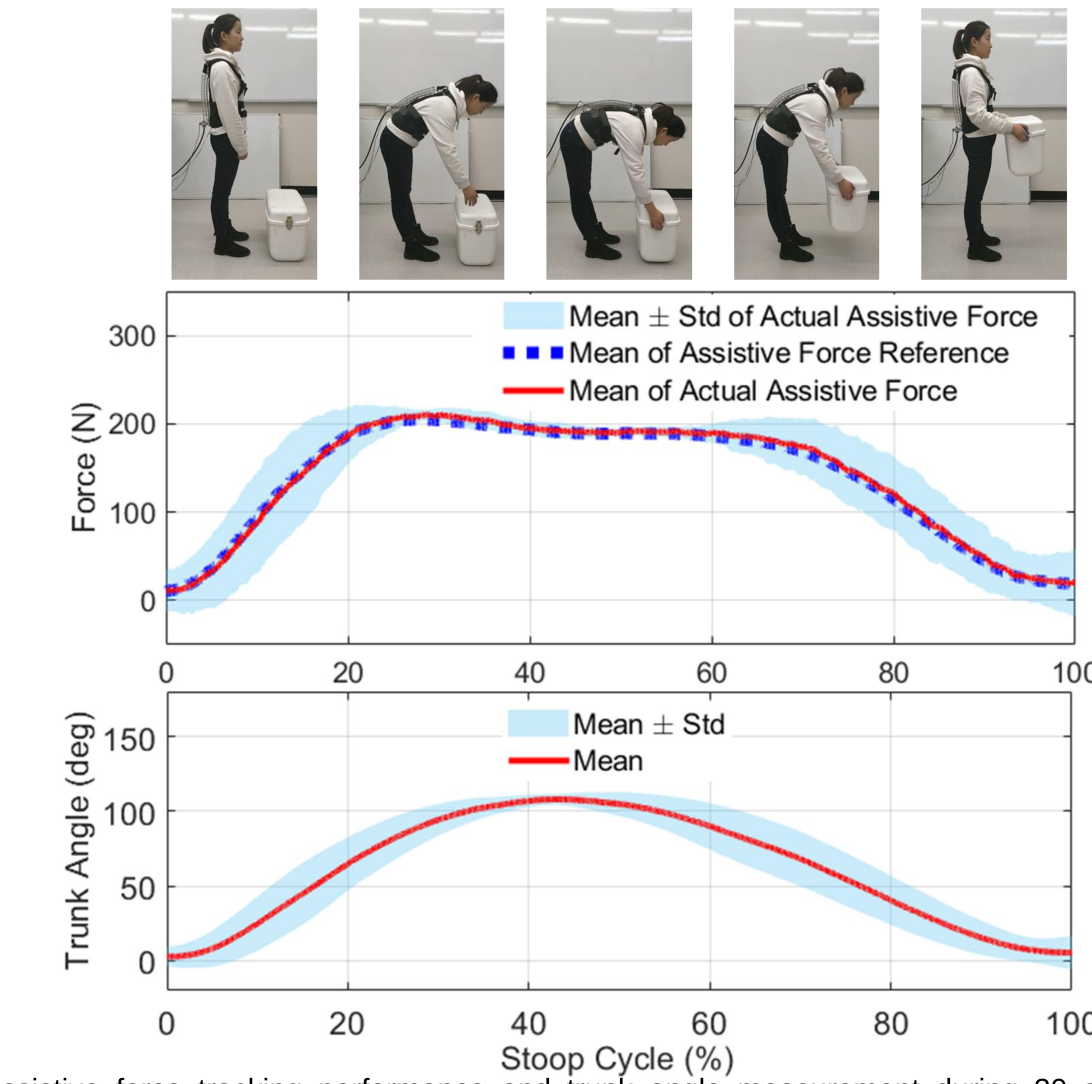

- Spine-inspired soft back exoskeleton design




- Kinetics of back exoskeleton in bending configuration
  - (a) n is odd; (b) n is even



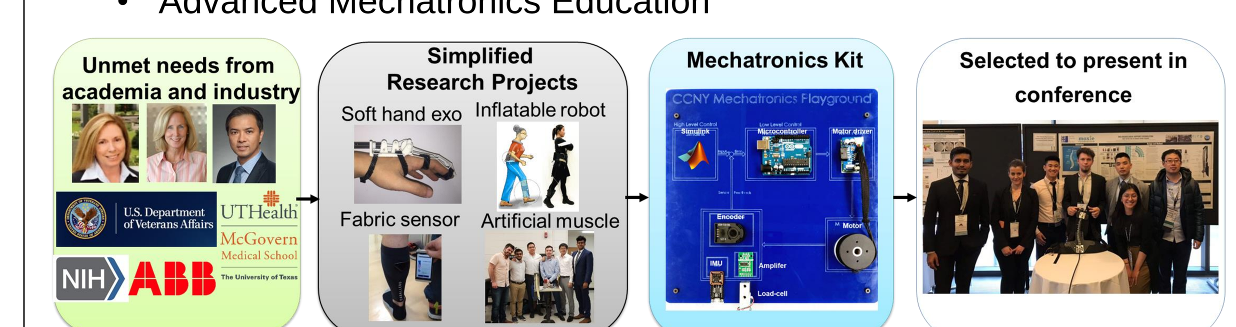

- Assistive force tracking performance and trunk angle measurement during stoop lifting



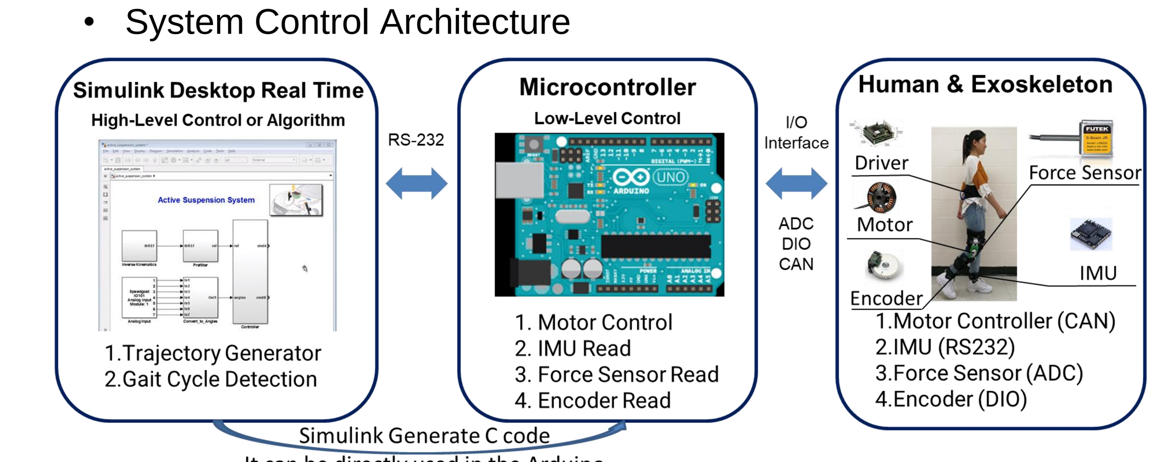

Assistive force tracking performance and trunk angle measurement during 30 stoop cycles. The actual assistive force (red line) tracked assistive force reference (blue dash line) with good accuracy (RMS error in 30 stoop cycles was 6.63 N, that is 3.3 % of the peak force).

## Lowering Barriers To Learn Robotics

- Advanced Mechatronics Education




- System Control Architecture




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


1. Salmeron, Juca, Mahadeo, Yu, and **Su**, International Conference of Wearable Robotics Association (WearRAcon), 2020 (2nd prize, Innovation Challenge)
2. Salmeron, Juca, Ma, Yu, **Su**, "Untethered Electro-Pneumatic Exosuit for Gait Assistance of People with Foot Drop", Design of Medical Devices Conferences, 2020 (2nd prize, Three-in-Five Competition)
3. Yuen, Nogacz, Chi, Ferdousi, Yu, **Su**, "Oxeous Back-Support Exoskeleton: Soft, Active Suit to Reduce Spinal Loading", Design of Medical Devices Conferences, 2019.
4. Yu, Perez, Barkas, Mohamed, Eldaly, **Su**, "Soft High Force Hand Exoskeleton for Assistance of Stroke Individuals," Design of Medical Devices Conferences, 2019
5. Yang, Huang, Yu, Su, Spungen, Tsai, "Machine Learning Based Adaptive Gait Phase Estimation Using IMU Sensors," Design of Medical Devices Conferences, 2019