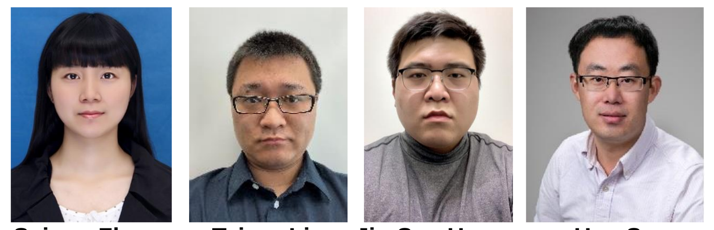
# Collocated Impedance Control of Proprioceptive Quasi-Direct Drive Actuators: High Fidelity Torque Estimation without A Torque Sensor

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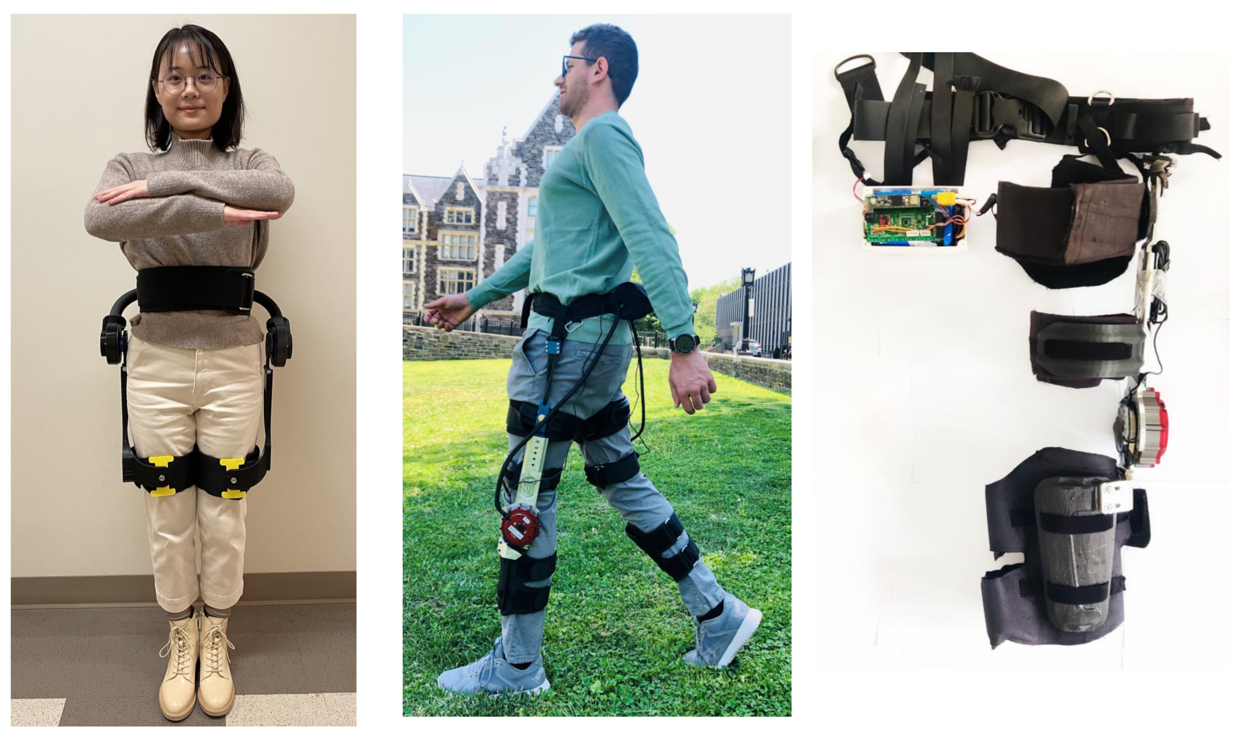
BIOMECHATRONICS AND INTELLIGENT ROBOTICS

## Objectives and Challenges

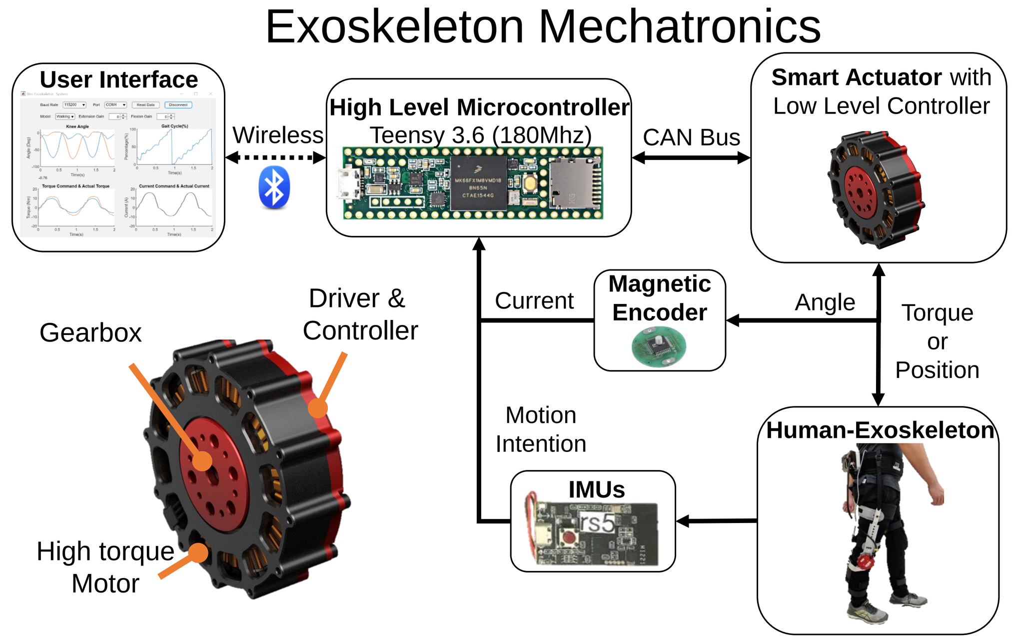
- Conventional actuators typically needs torque sensors while series elastic actuators (SEA) can estimate output torque via the deflection of an elastic element, but both require torque sensing to ensure a stable and accurate performance.
- Torque sensors are heavy and expensive, and additional elastic components (like springs) adds size, mass, and complexity.
- The two popularized actuator paradigms often use exteroceptive sensory feedback that is known to cause non-collocated sensing problems upon collision, which results in human-robot-interaction instability.

## Lightweight Modular Exoskeletons

### Hip and Knee Exoskeleton Schematic



### Exoskeleton Mechatronics




### Advantages of Our Exoskeleton

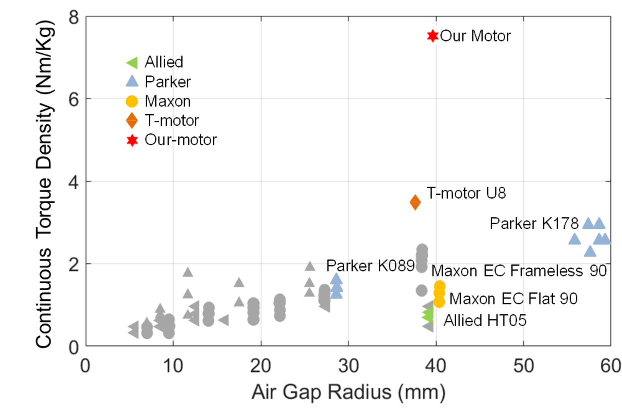

## Actuator Innovation: Design for Control

| | 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; Load; Low ratio gear |

## Motor Torque Density Comparison

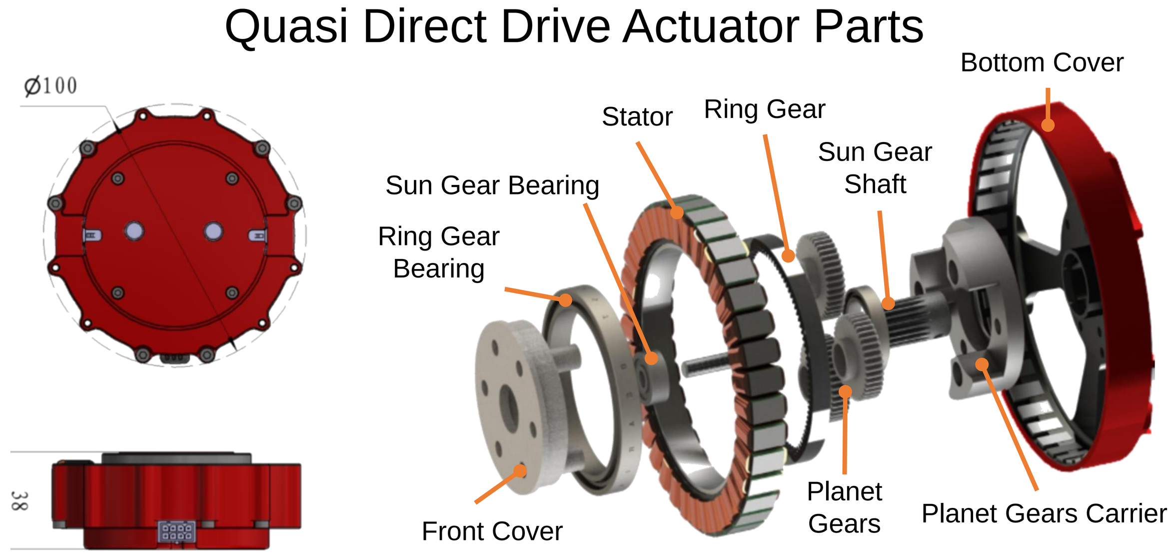
- Our custom-designed motor has the highest torque density

| 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 |



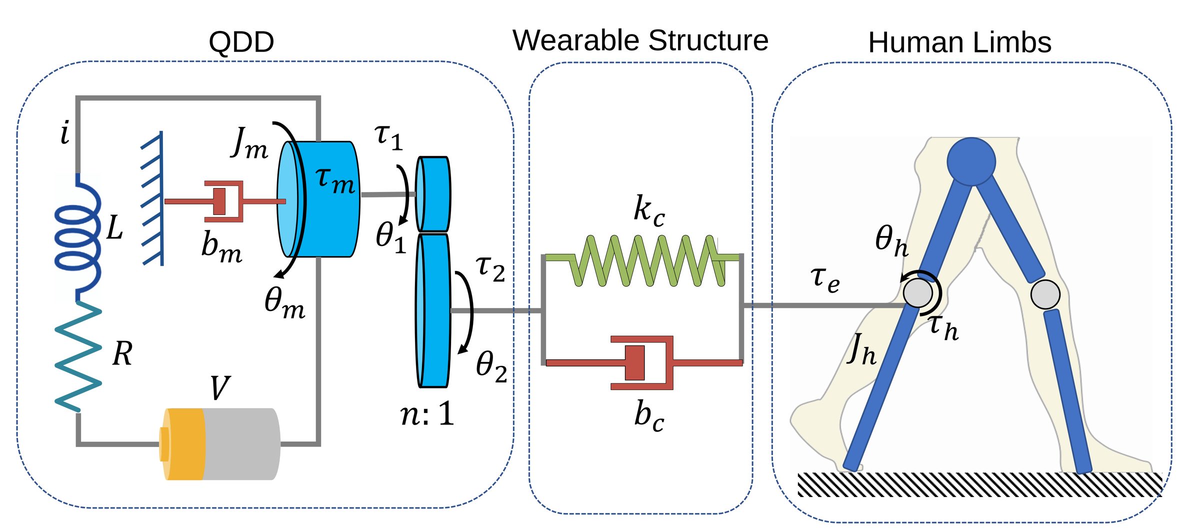

Specific continuous torque=$\frac{Continuous\ torque}{Mass}$

### Quasi Direct Drive Actuator Parts




## Versatile Knee Exoskeleton Controller

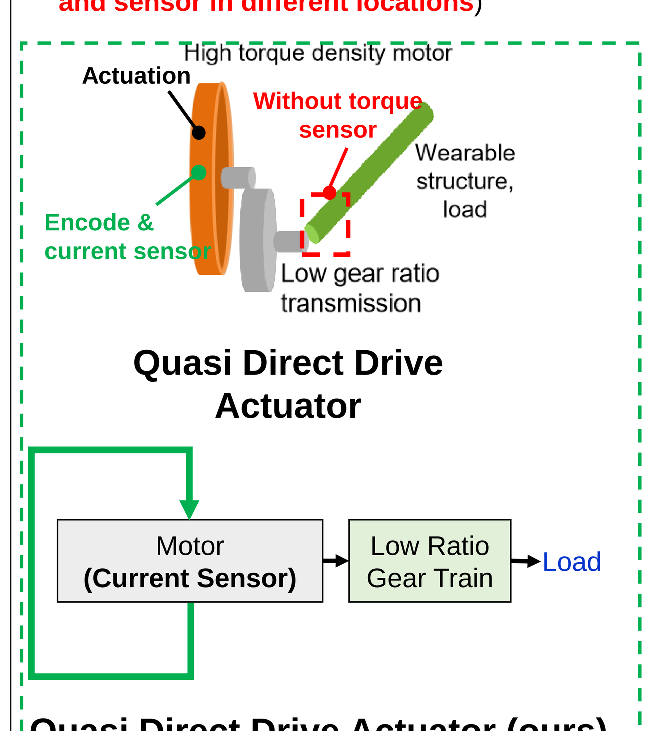
### Exoskeleton Model

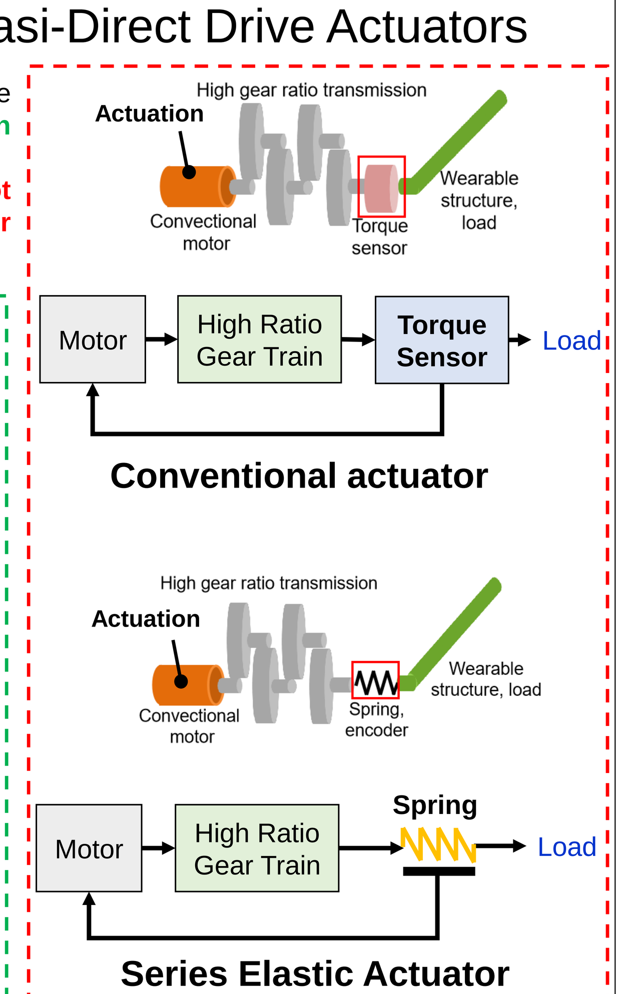



$V$: winding voltage
$L$: winding inductance
$R$: winding resistance
$i_m$: motor current
$J_m$: motor rotor inertia
$\theta_m$: motor angle
$\tau_m$: motor torque
$\tau_1$: motor output torque
$b_m$: motor damping
$n$: gear ratio
$\tau_2$: gear output torque
$k_c$: stiffness of human-exoskeleton interface
$b_c$: damping of human-exoskeleton interface
$\tau_e$: exoskeleton output torque
$J_t$: thigh inertia
$J_s$: shank inertia
$m_t$: thigh mass
$m_s$: shank mass
$\tau_h$: human knee torque
$\theta_t$: thigh angle
$\theta_s$: shank angle
$F_G$: ground reaction force

### Collocated Control of Quasi-Direct Drive Actuators

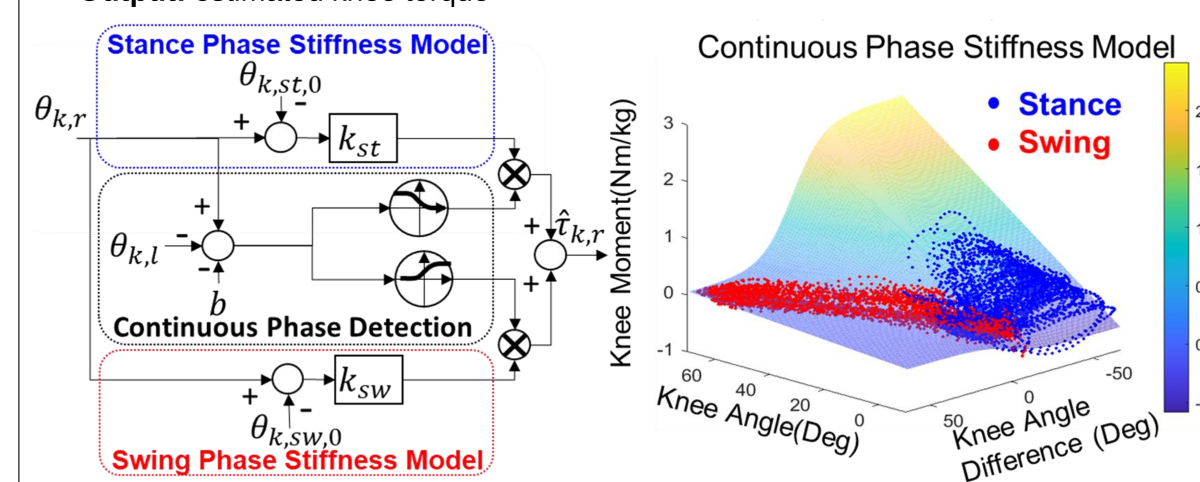
- **Collocated system:** The sensor is placed at the location of the actuation (**motor and sensor in the location**)
- **Non-collocated system:** The sensor is **not** placed at the location of the actuation (**motor and sensor in different locations**)




## Discrete Control→Continuous Control (Stiffness-inspired)

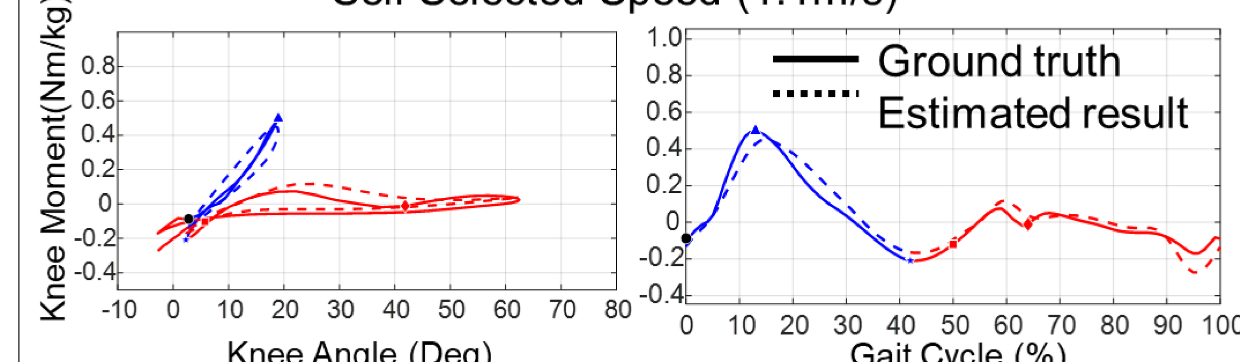
- **Input:** knee angles $\theta_{k,r}, \theta_{k,l}$ and their difference
- **Output:** estimated knee torque



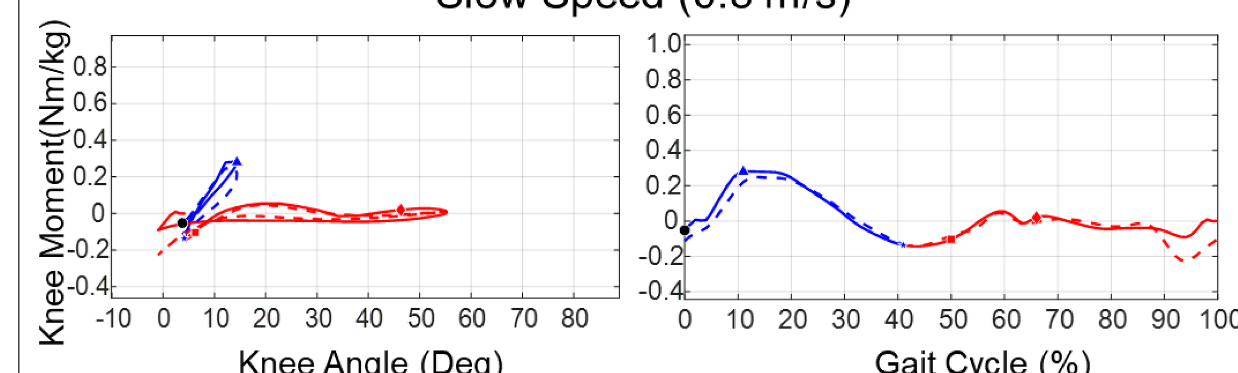

| Estimated Biological Torque | Sigmoid Function: Discrete to Continuous |
|---|---|

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

### Self Selected Speed (1.1m/s)



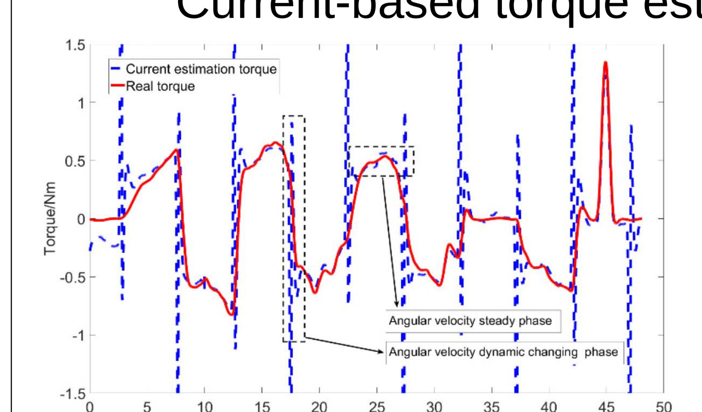

### Slow Speed (0.8 m/s)




## Results: Design for Sensing

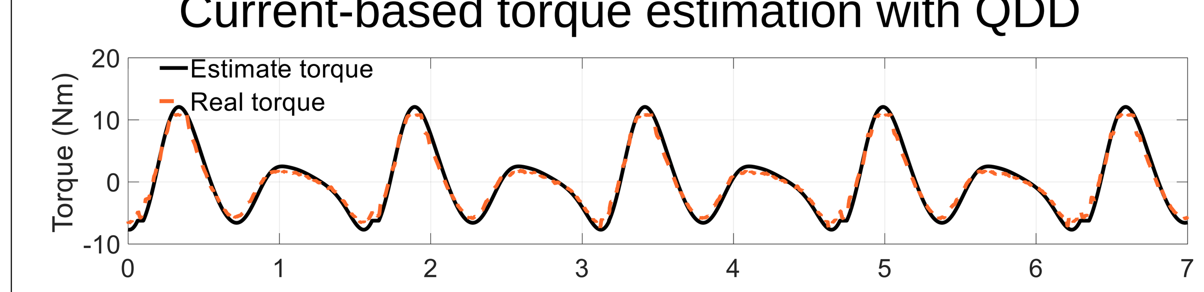
- Output torque estimation
  - Conventional actuator and SEA : output torque cannot be estimated by current.
  - QDD with current-based torque estimation: it can be estimated well (10.1% error).
  - QDD with our torque estimation method: high fidelity torque estimation (5.3% error)

### Current-based torque estimation of SEA [4]

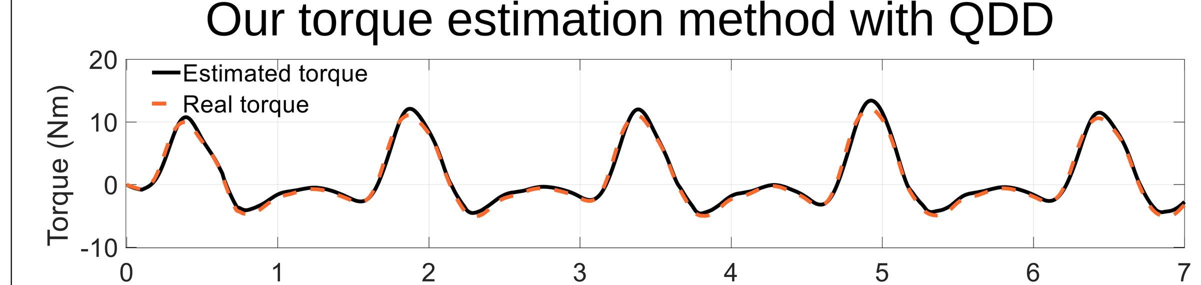



- When the motor commutates or the angular acceleration is large, the output torque measured by the motor current has a large deviation from the real torque

### Current-based torque estimation with QDD

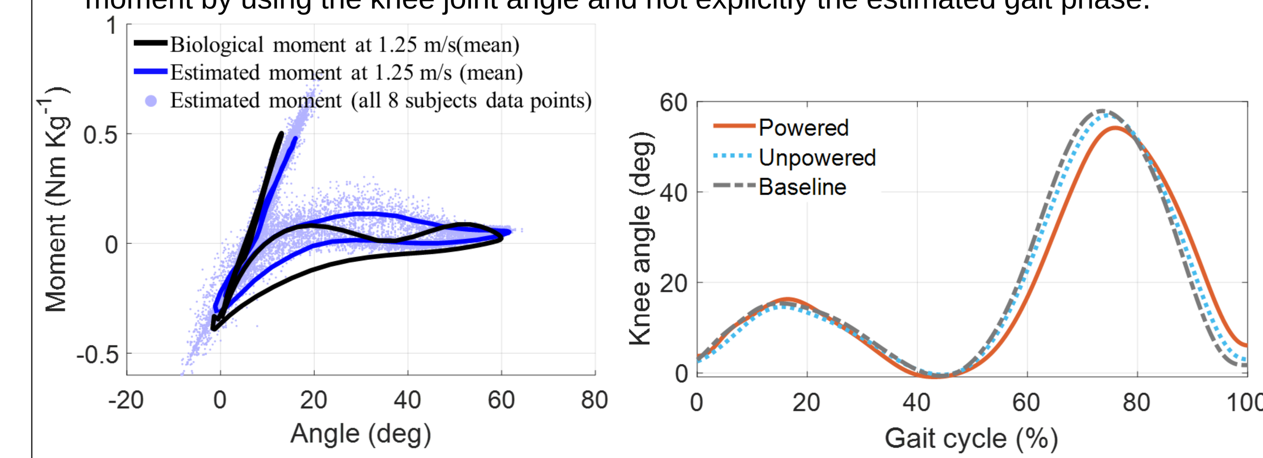



### Our torque estimation method with QDD



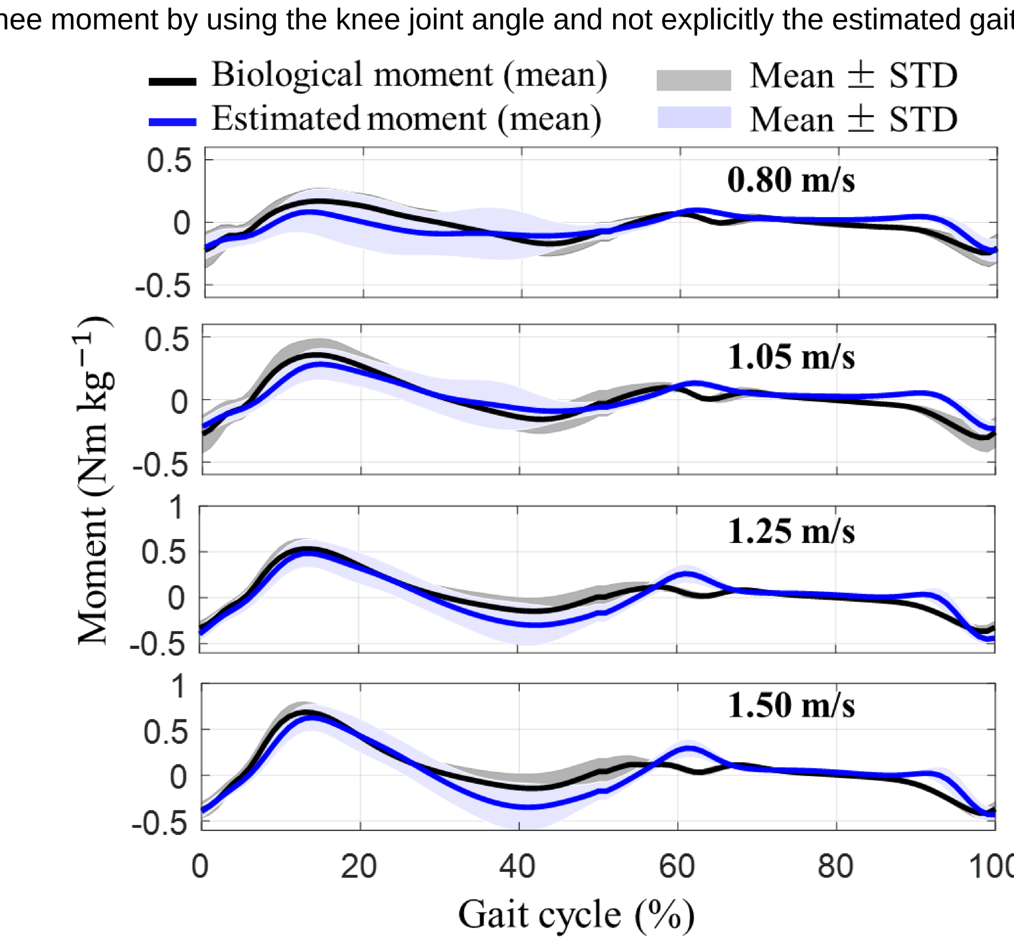

## Knee Angle vs. Joint Moment  Knee Angle vs. Gait Cycle

- The controller was able to adapt quickly and generate an accurate continuous knee moment by using the knee joint angle and not explicitly the estimated gait phase.



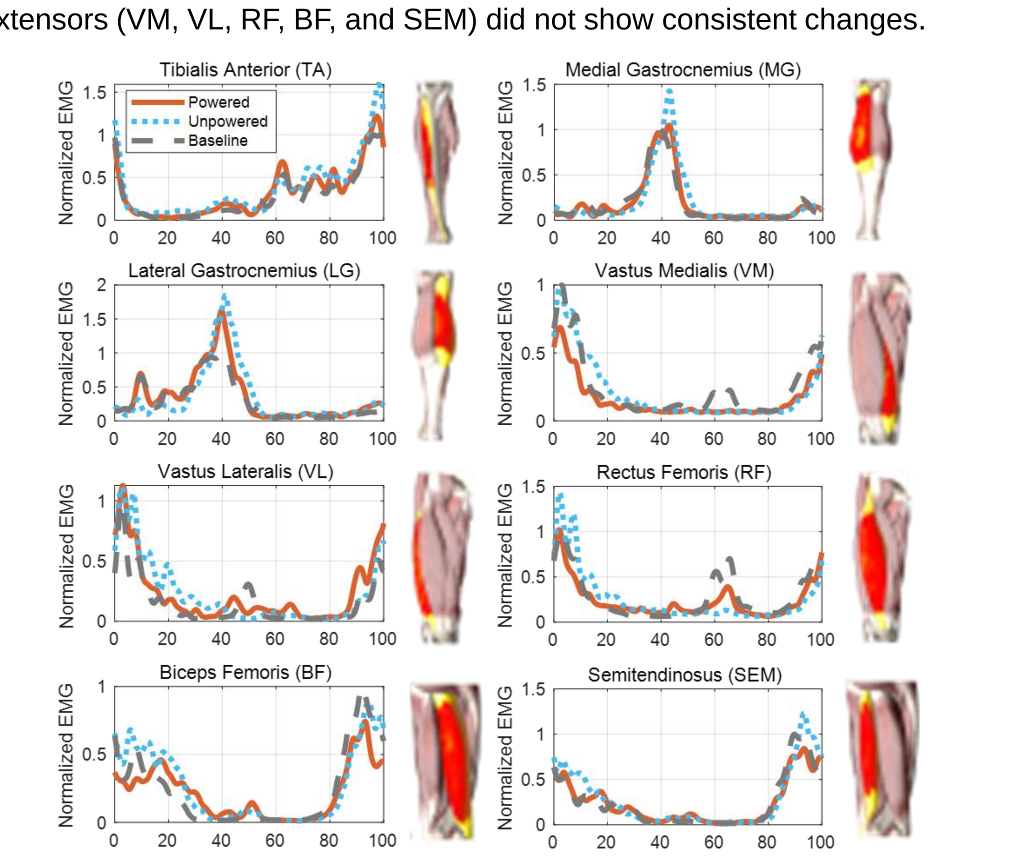

### Moment Estimation at Different Speeds

- The stiffness controller was able to adapt quickly and generate an accurate continuous knee moment by using the knee joint angle and not explicitly the estimated gait phase.




### EMG Results

- Powered vs unpowered conditions for 8 muscles
  - RMS EMG reduction by 7.45% - 15.22%, max EMG reduction by 6.85% - 10.24%
- Powered vs baseline conditions for 8 muscles
  - 3 flexors (TA, LG, and MG)
    - RMS EMG reduction by 7.45% - 15.22%, max EMG reduction by 6.85% - 10.24%
  - 5 extensors (VM, VL, RF, BF, and SEM) did not show consistent changes.




## References


[1] Huang, Zhang, Yu, MacLean, Zhu, Di Lallo, Jiao, Bulea, Zheng, & Su, Modeling and Stiffness-based Continuous Torque Control of Lightweight Quasi-Direct-Drive Knee Exoskeletons for Versatile Walking Assistance, Trans. on Robotics, 2022
[2] J. Zhu, C. Jiao, I. Dominguez, S. Yu, H. Su, "Design and Backdrivability Modeling of a Portable High Torque Robotic Knee Prosthesis With Intrinsic Compliance For Agile Activities", IEEE/ASME Transactions on Mechatronics, 2022
[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 , 2020. (Best student paper award finalists)
[4] Wei, H., Xiang, K., Chen, H., Tang, B., & Pang, M. (2021, October). Improvement of Torque Estimation for Series Viscoelastic Actuator Based on Dual Extended Kalman Filter. In Actuators (Vol. 10, No. 10, p. 258). Multidisciplinary Digital Publishing Institute.
[5] Lee, J., Lee, C., Tsagarakis, N., & Oh, S. (2018). Residual-based external torque estimation in series elastic actuators over a wide stiffness range: Frequency domain approach. IEEE Robotics and Automation Letters, 3(3), 1442-1449.
[6] Zhao, Y., Paine, N., Jorgensen, S. J., & Sentis, L. (2017). Impedance control and performance measure of series elastic actuators. IEEE Transactions on Industrial Electronics, 65(3), 2817-2827.