Collocated Impedance Control and High-fidelity Torque Estimation for a Lightweight Exoskeleton in Community Setting

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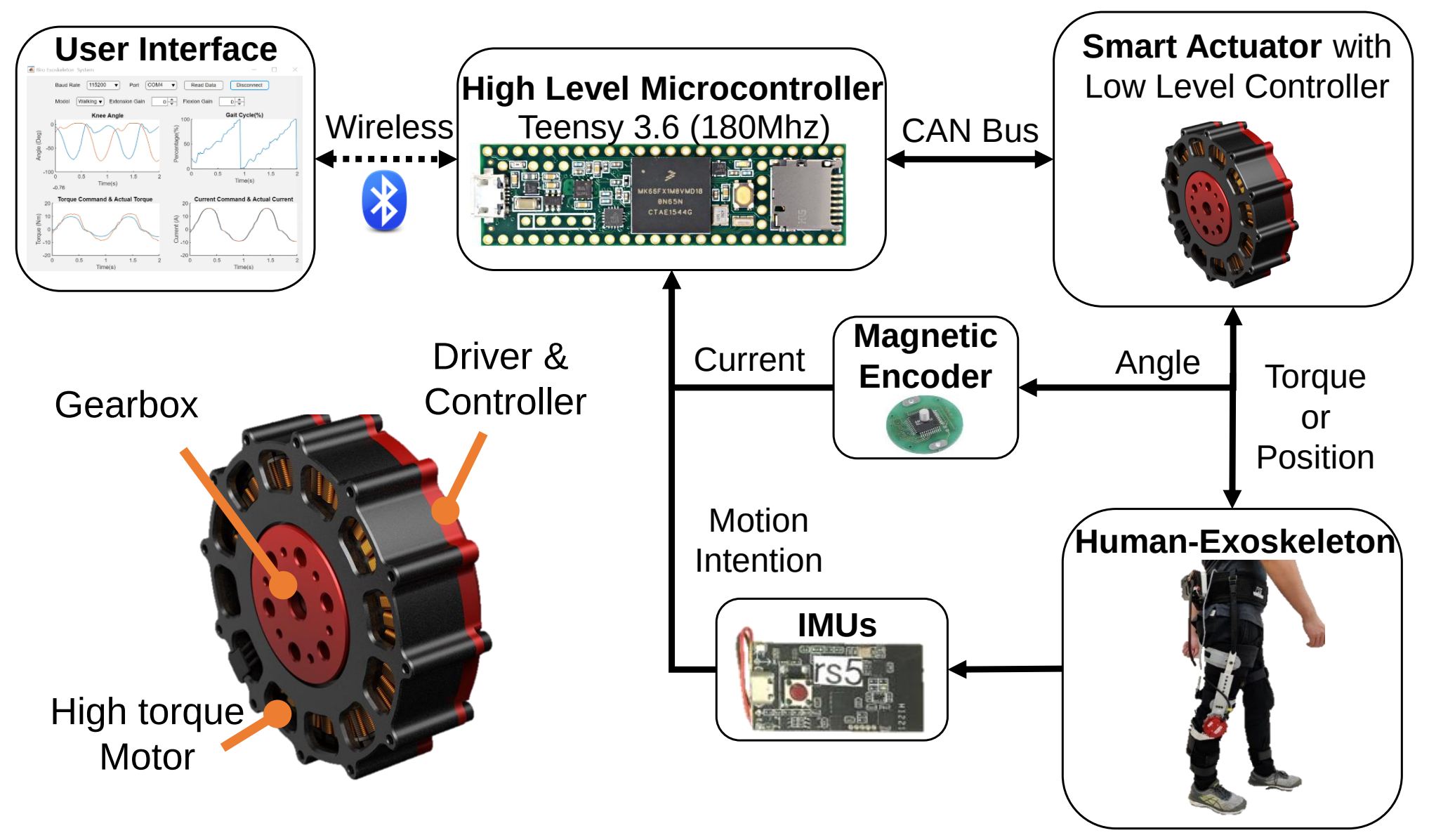
Objectives and Challenges

- 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.

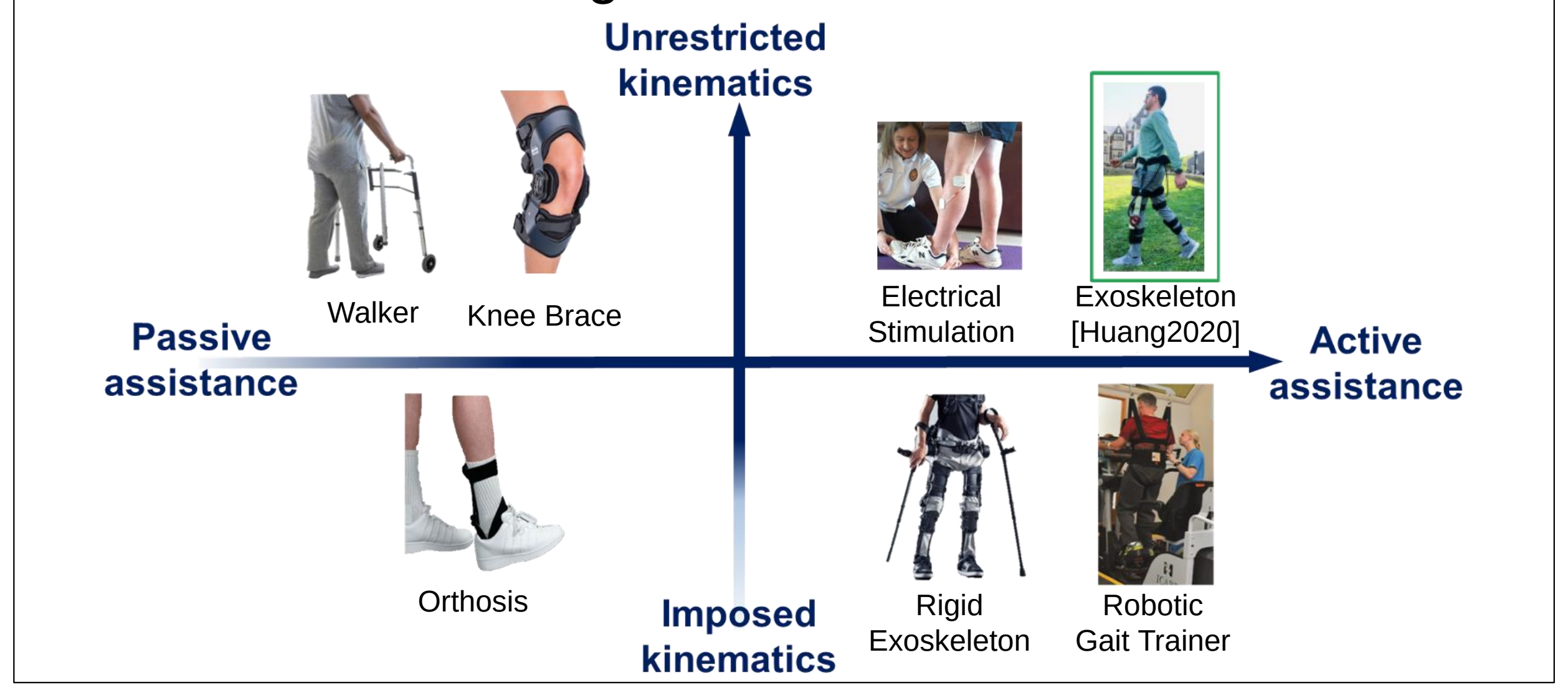
Lightweight Modular Exoskeletons

Hip and Knee Exoskeleton Schematic

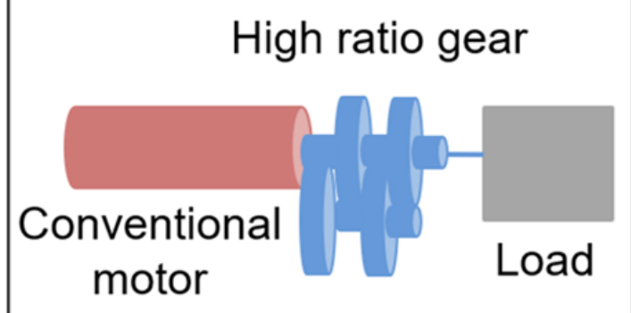
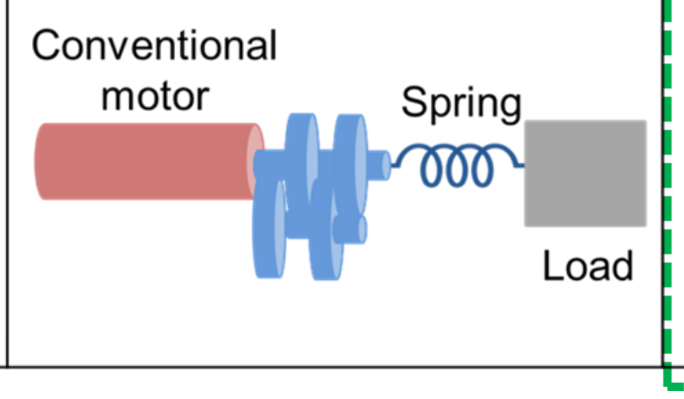
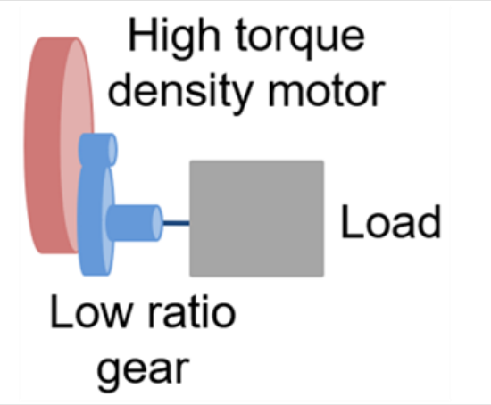
Exoskeleton Mechatronics



Advantages of Our Exoskeleton

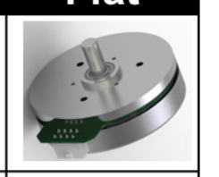


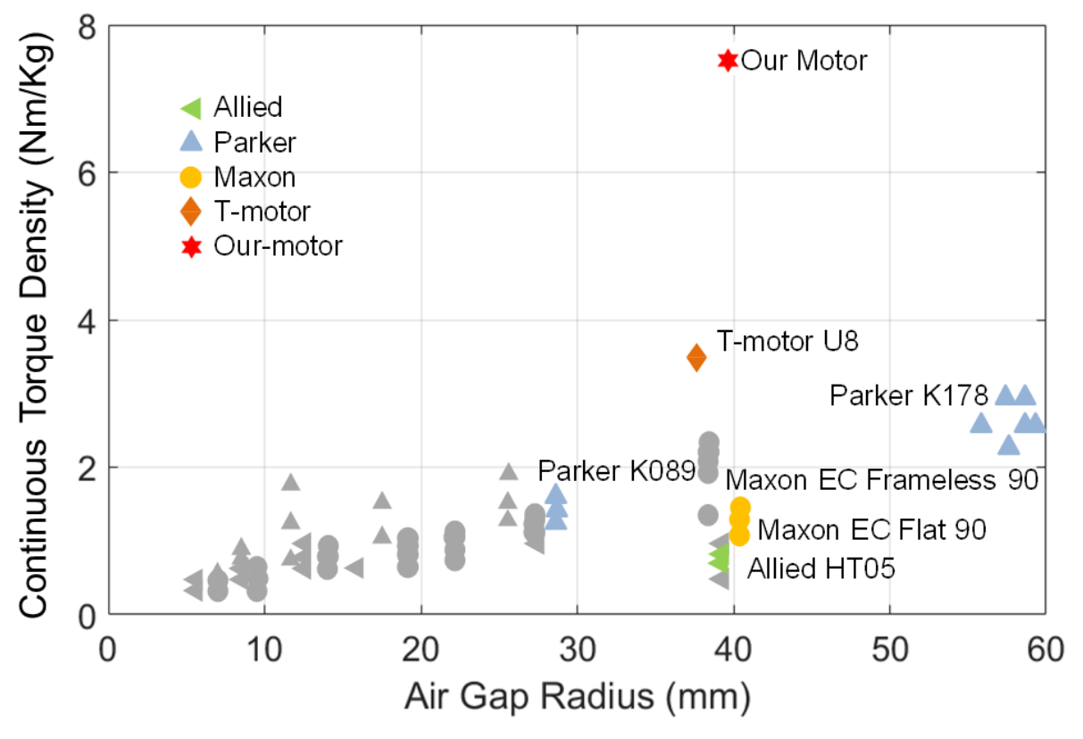
Actuator Innovation: Design for Control

	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

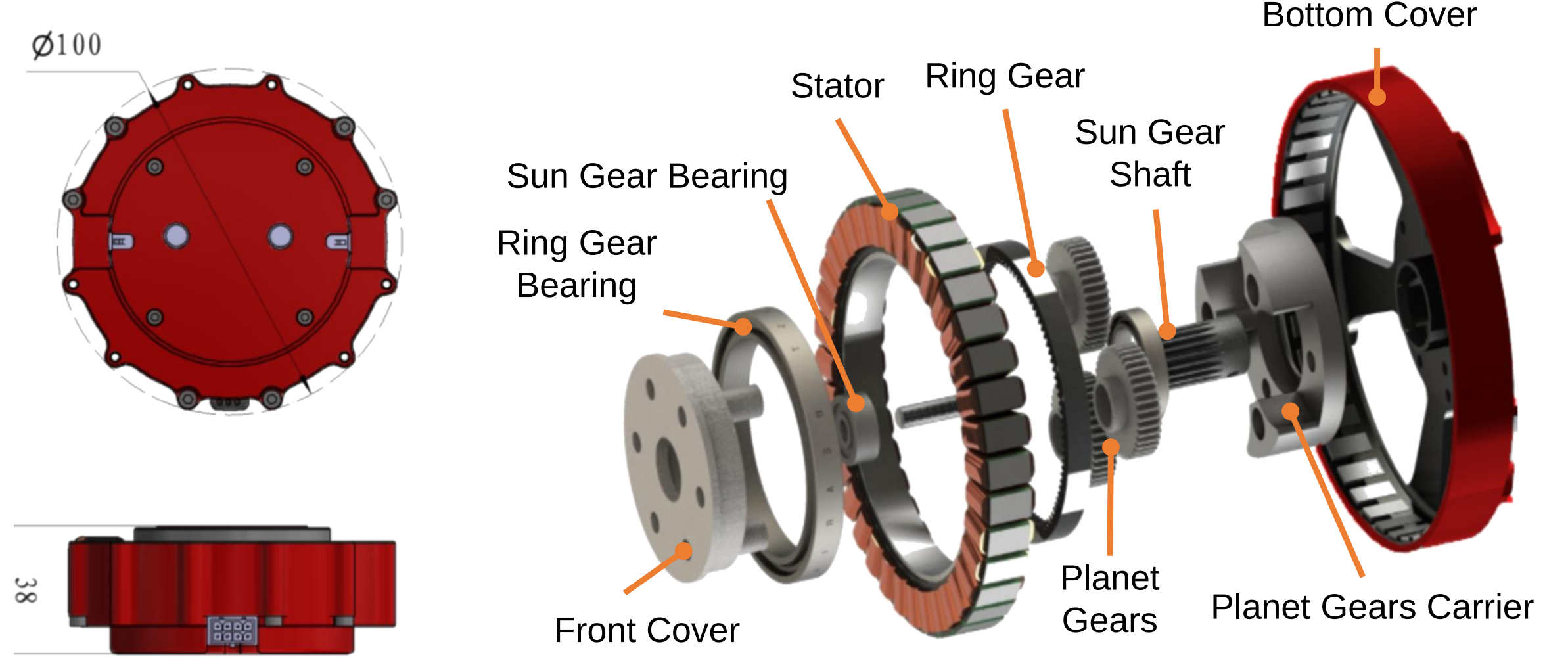
- Our custom-designed motor has the highest torque density

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



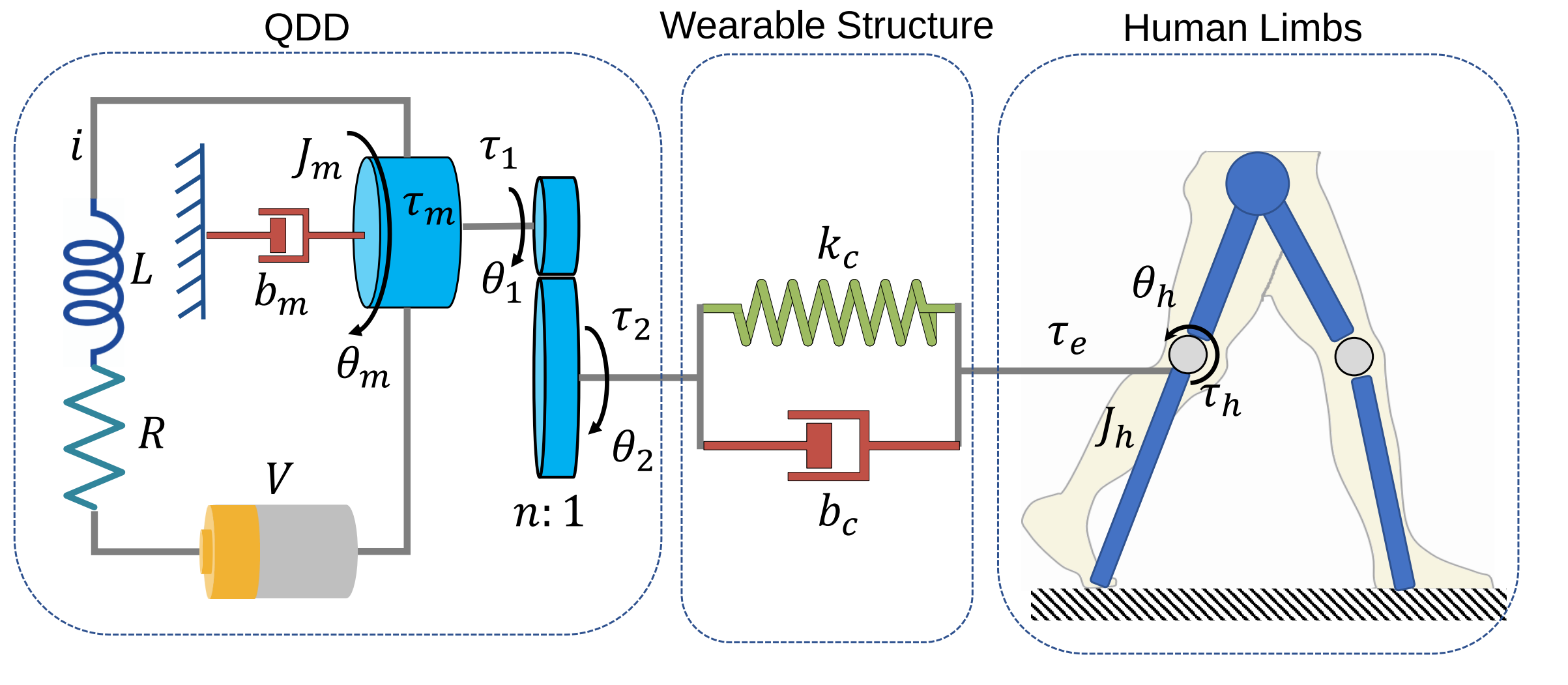
Specific continuous torque=$\frac{Coninuous\ torque}{Mass}$

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
θ_m: motor angle

τ_m: motor torque
τ_1: motor output torque
b_m: motor damping
n: gear ratio
τ_2: gear output torque

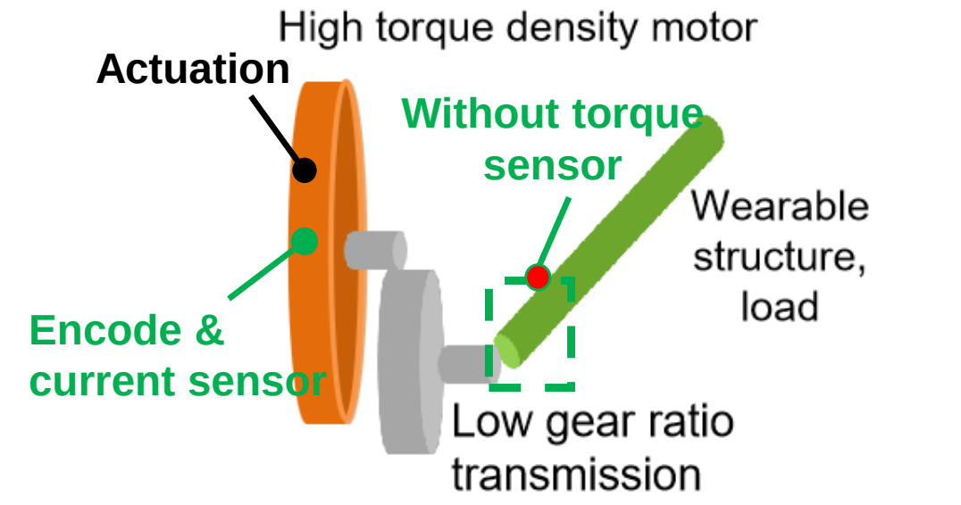
k_c: stiffness of human-exoskeleton interface
b_c: damping of human-exoskeleton interface
τ_e: exoskeleton output torque

J_t: thigh inertia
J_s: shank inertia
m_t: thigh mass
m_s: shank mass
τ_h: human knee torque

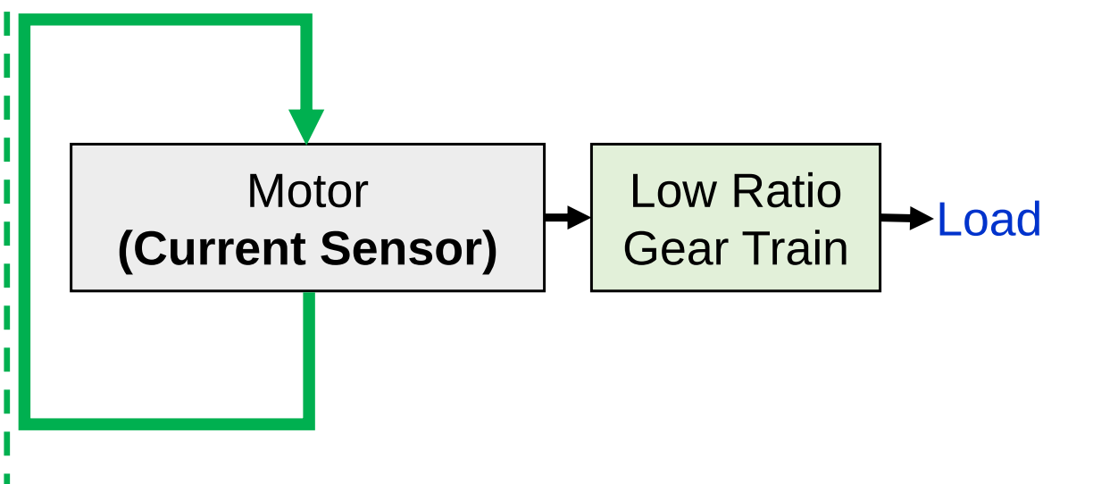
θ_t: thigh angle
θ_s: shank angle
F_G: ground reaction force

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**)

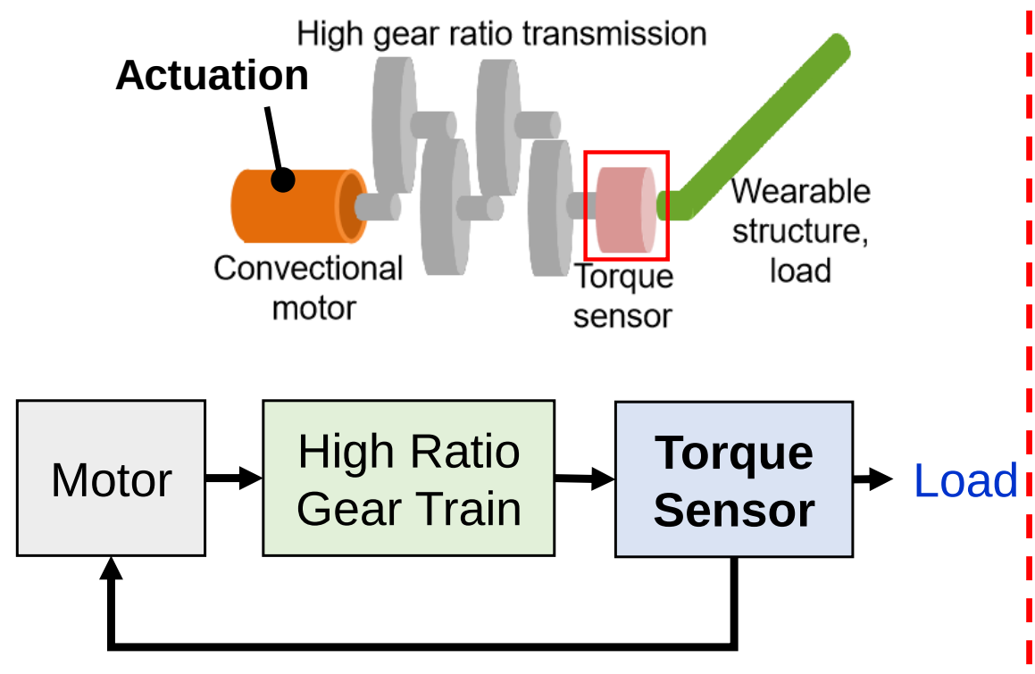


Quasi Direct Drive Actuator

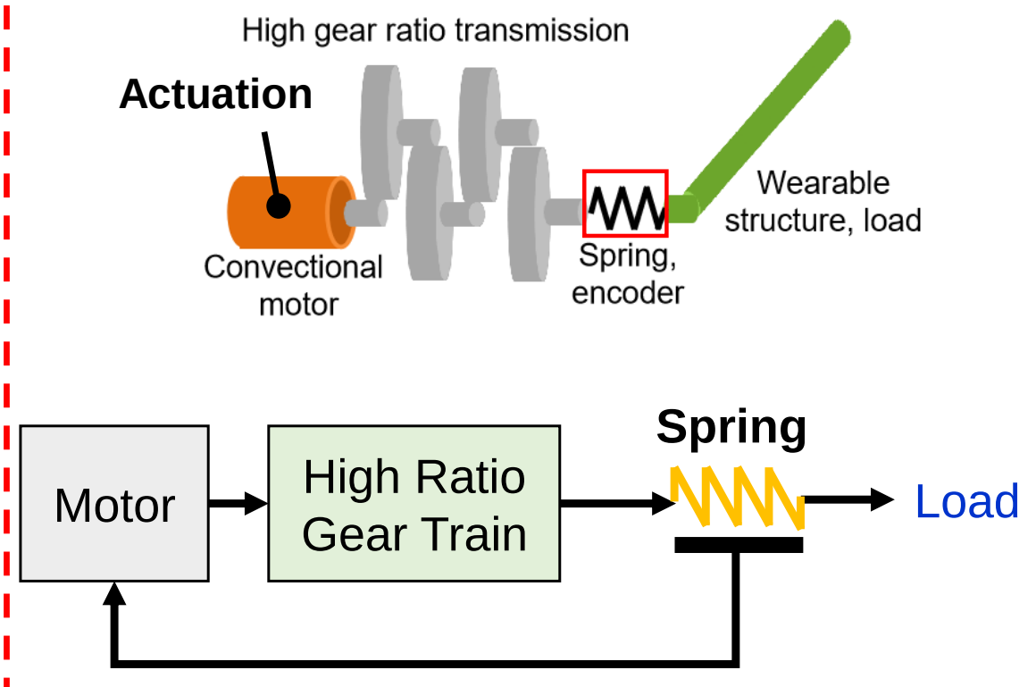


Quasi Direct Drive Actuator (ours)

Collocated control



Conventional actuator

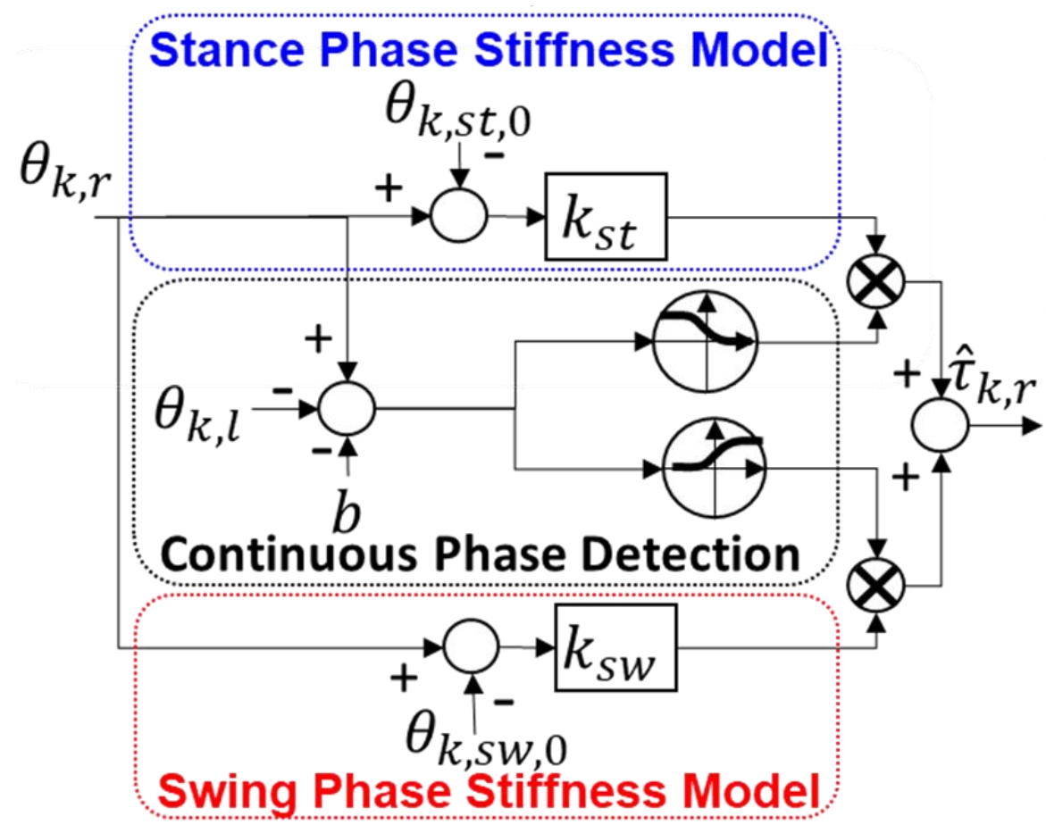


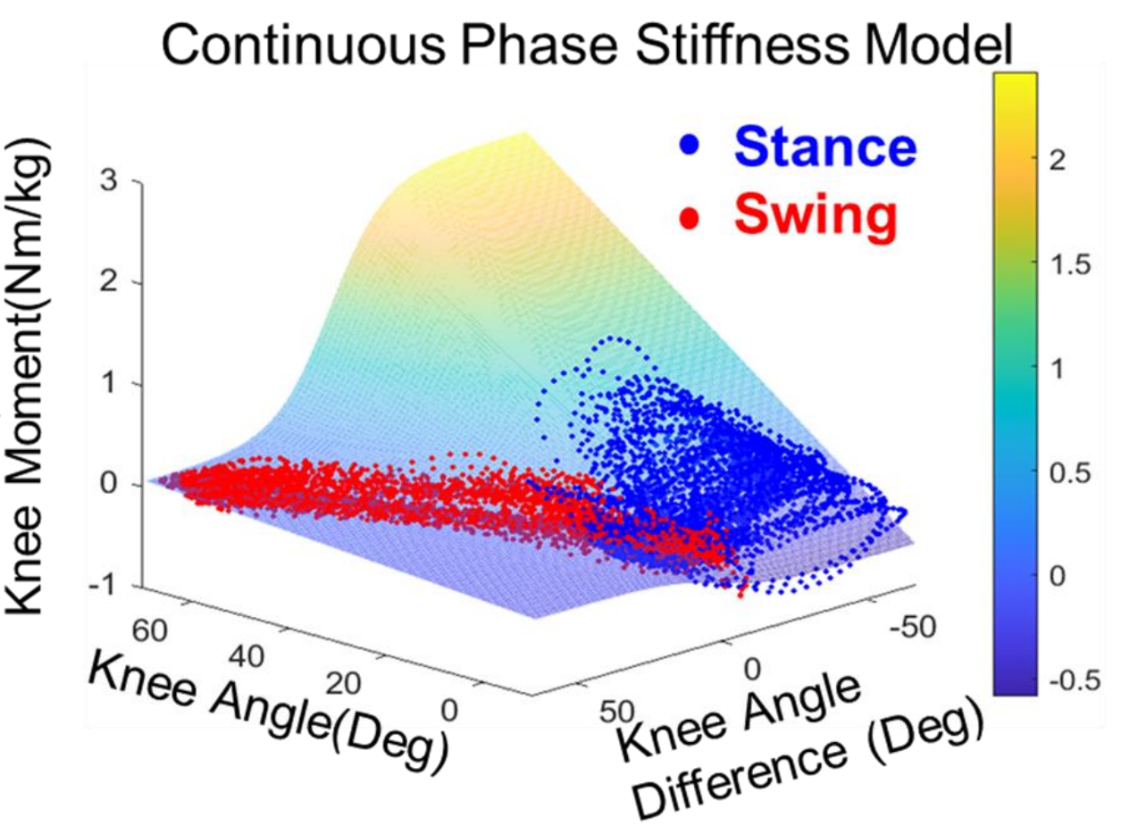
Series Elastic Actuator

Non-collocated control

Discrete Control ⟶ Continuous Control (Stiffness-inspired)

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





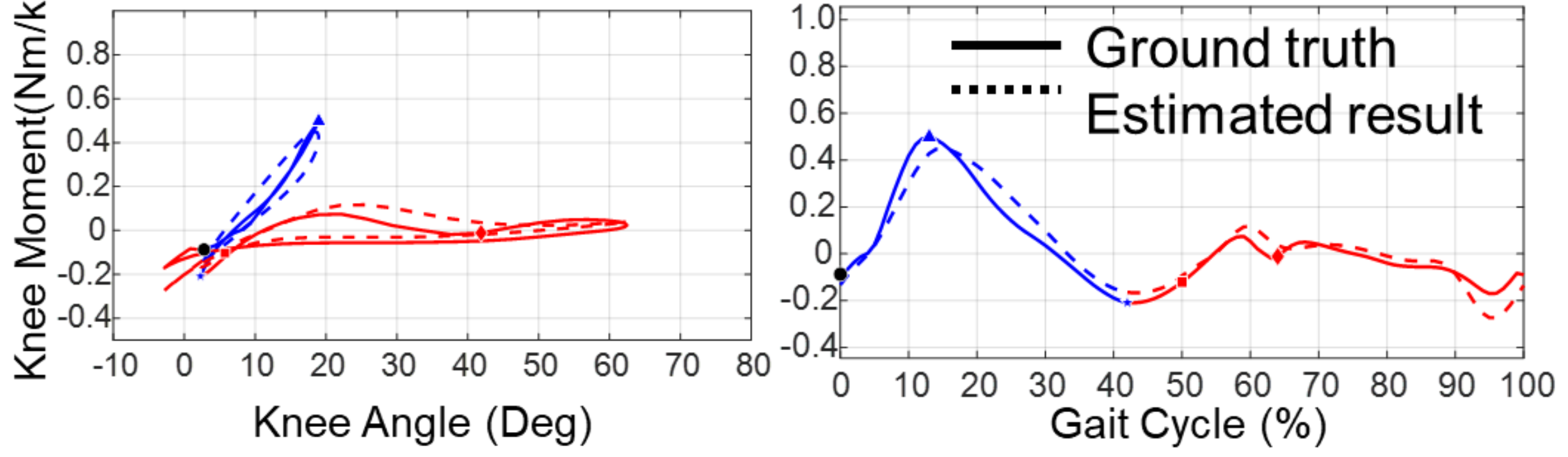
Estimated Biological Torque

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

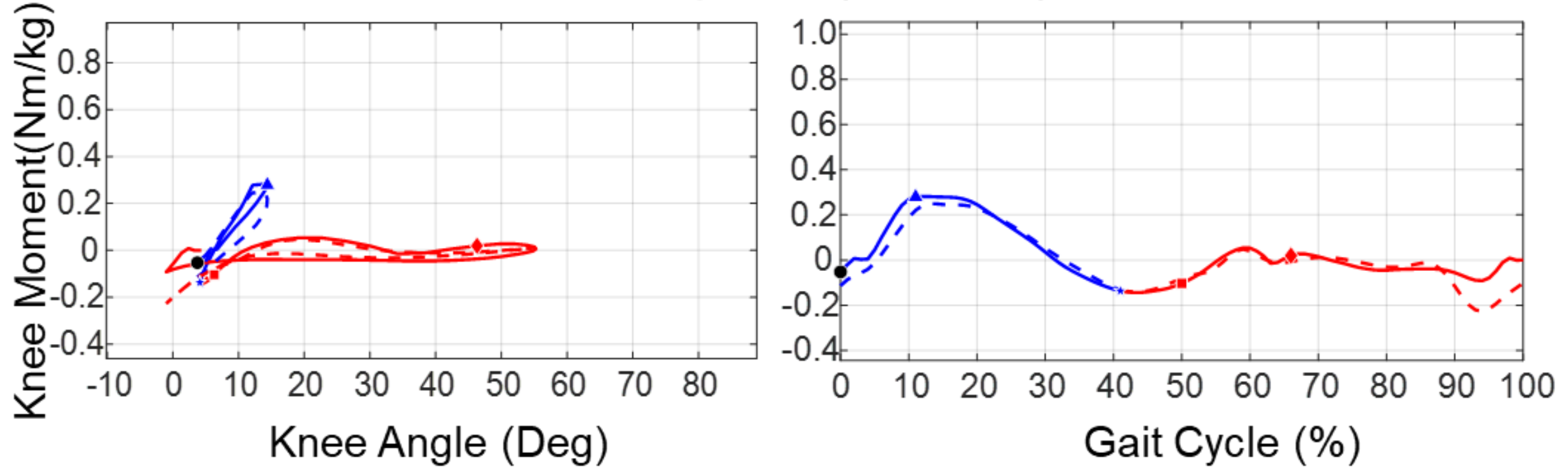
Sigmoid Function: Discrete to Continuous

$$f(\theta_{k,r}, \theta_{k,r}) = (\theta_{k,r} - \theta_{k,l}) - b$$

Self Selected Speed (1.1m/s)



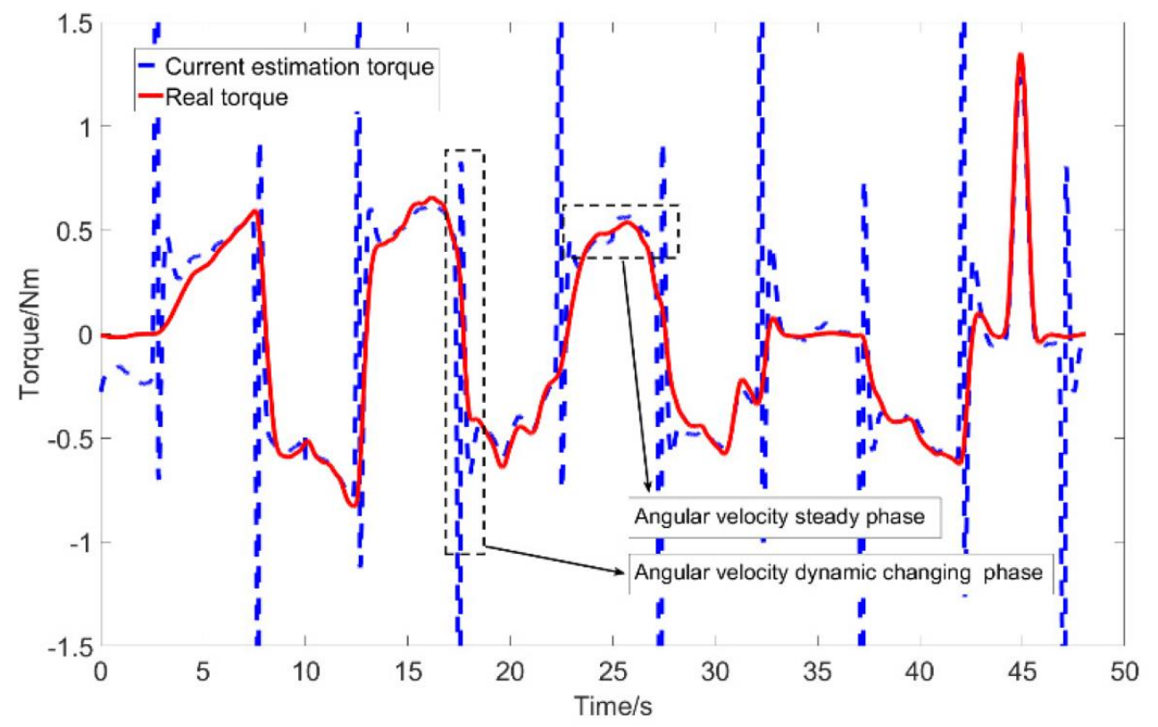
Slow Speed (0.8 m/s)



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

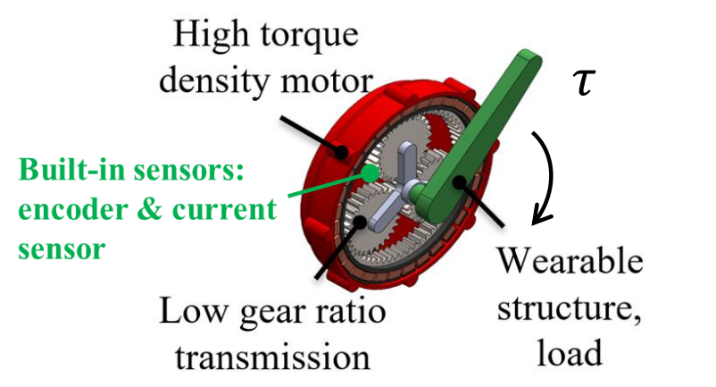


- When the motor commutates or the angular acceleration is large, the output torque measured by the motor current has a large deviation from the real torque

Our Torque Estimation with Built-in Sensors

- Advantages of our estimation method
  - No torque sensor: cost-effective and lightweight
  - Simpler mechanical design, more compact
  - High-fidelity torque estimation for versatile activities

Sensing torque using built-in sensors



Use the human-robot angle information in real-time

Our torque estimation method:

$$\hat{\tau}(s) = n(\tau_m - \hat{J}_m\ddot{\theta}_m - \hat{b}_m\dot{\theta}_m) = \frac{\hat{k}}{\hat{k} - k_d}(k_d + b_d s) * \left[\theta_{h,r}(s) - \frac{1}{n}\theta_m(s)\right]$$

Estimate torque for activities with different frequency

$\frac{\text{Transmission stiffness}}{\text{Transmission stiffness} - \text{Desired stiffness}}$

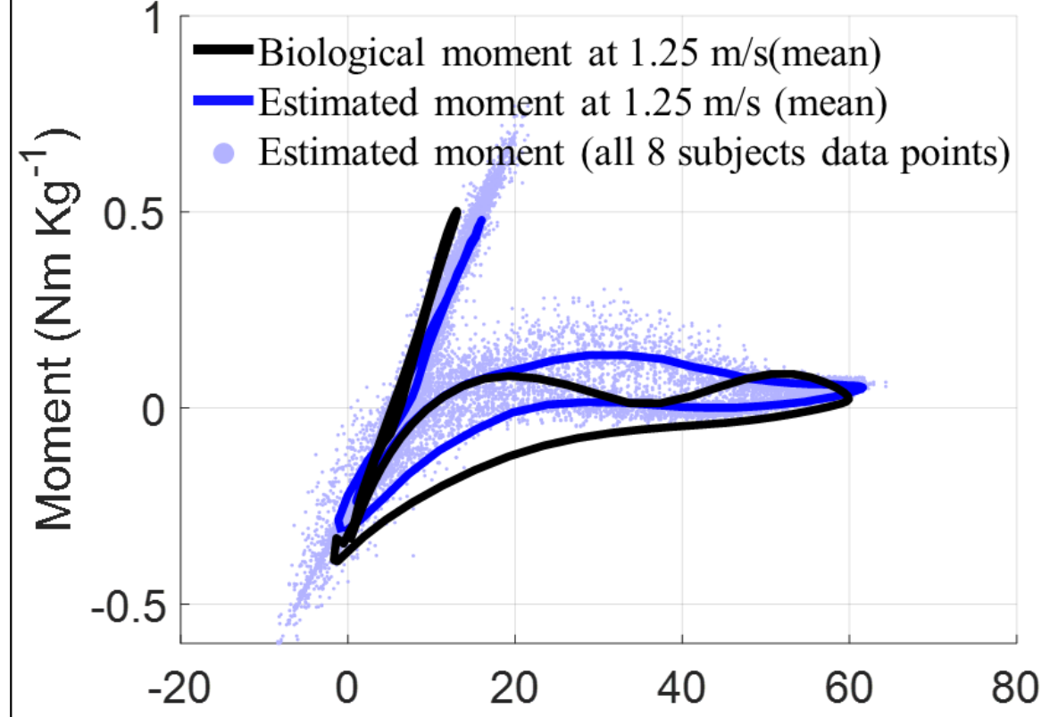
Desired impedance

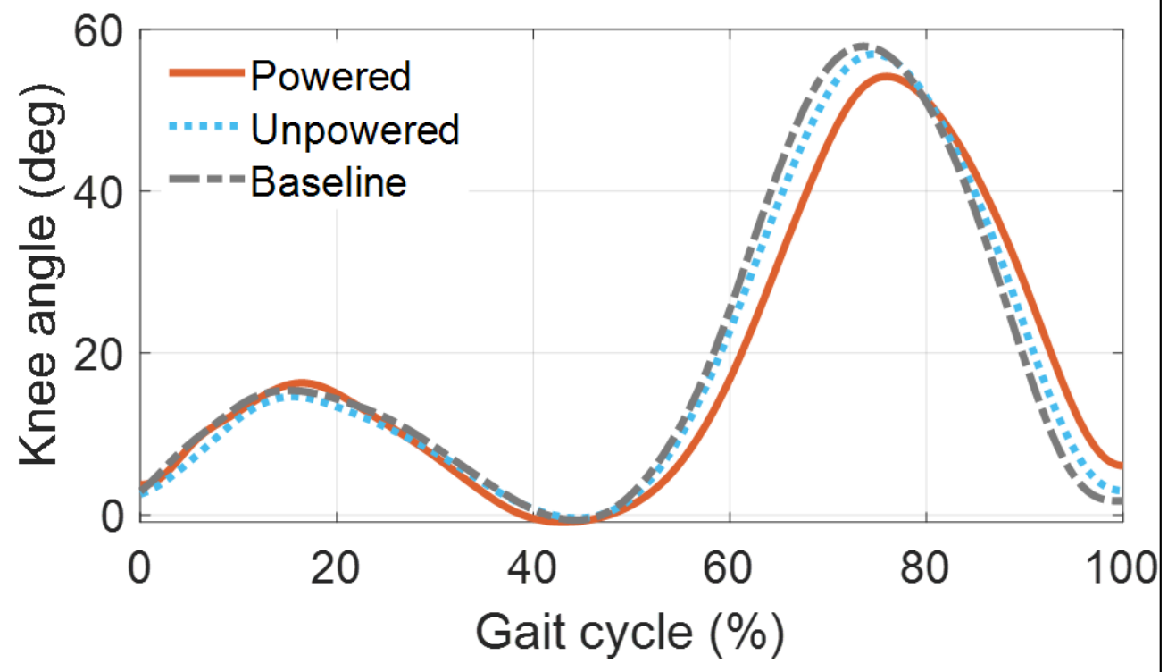
joint angles ref

Robot joint angles

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

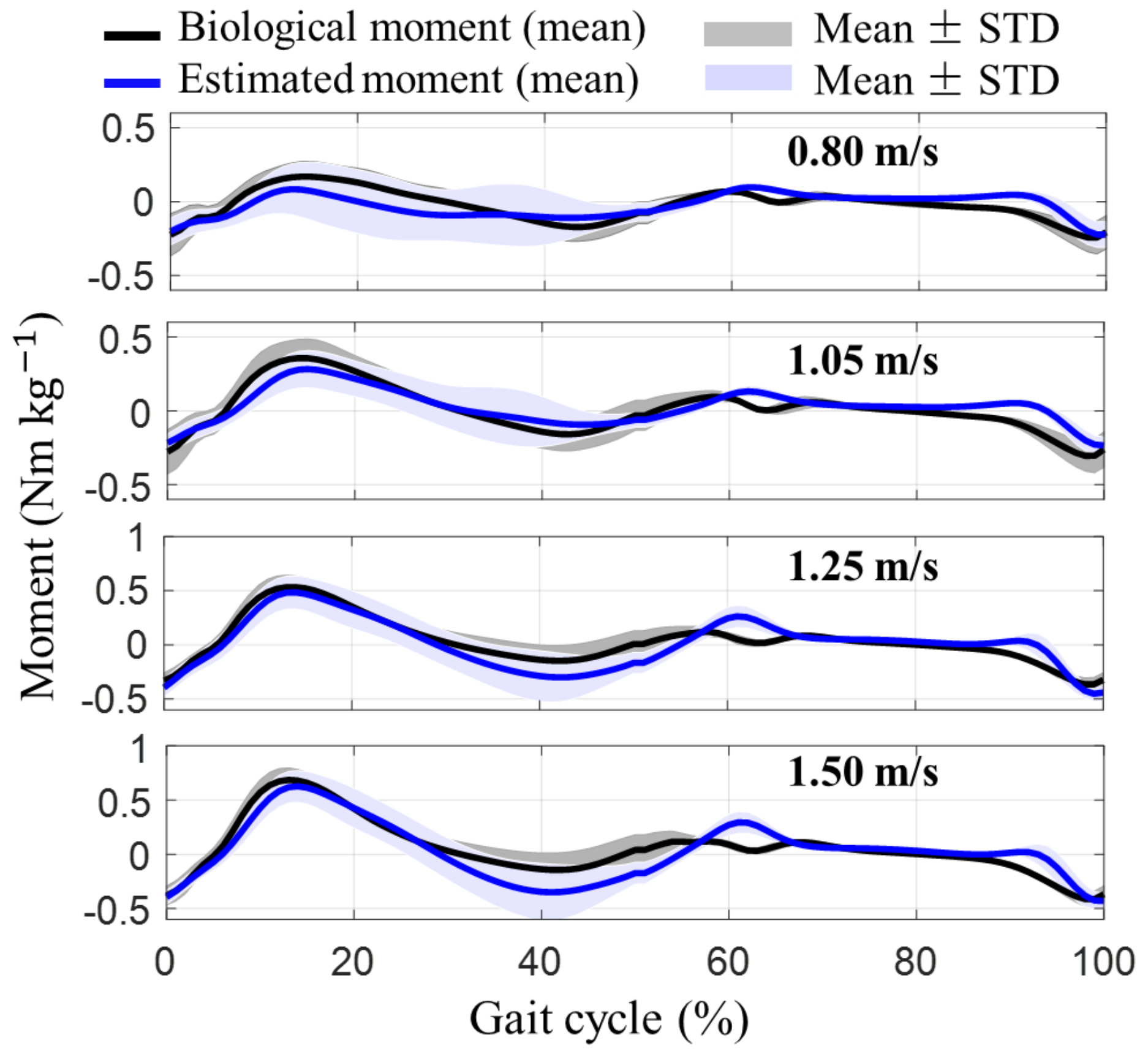
- The controller was able to adapt quickly and generate an accurate continuous knee moment by using the knee joint angle and not explicitly the estimated gait phase.





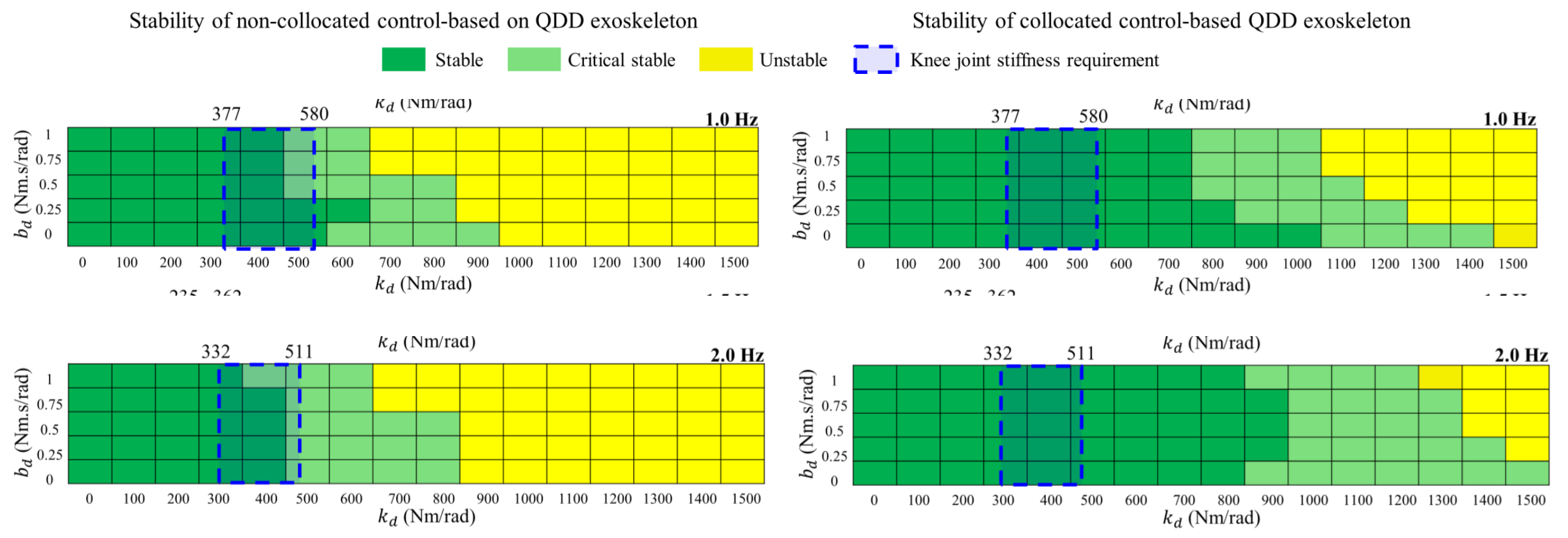
Moment Estimation at Different Speeds

- 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.



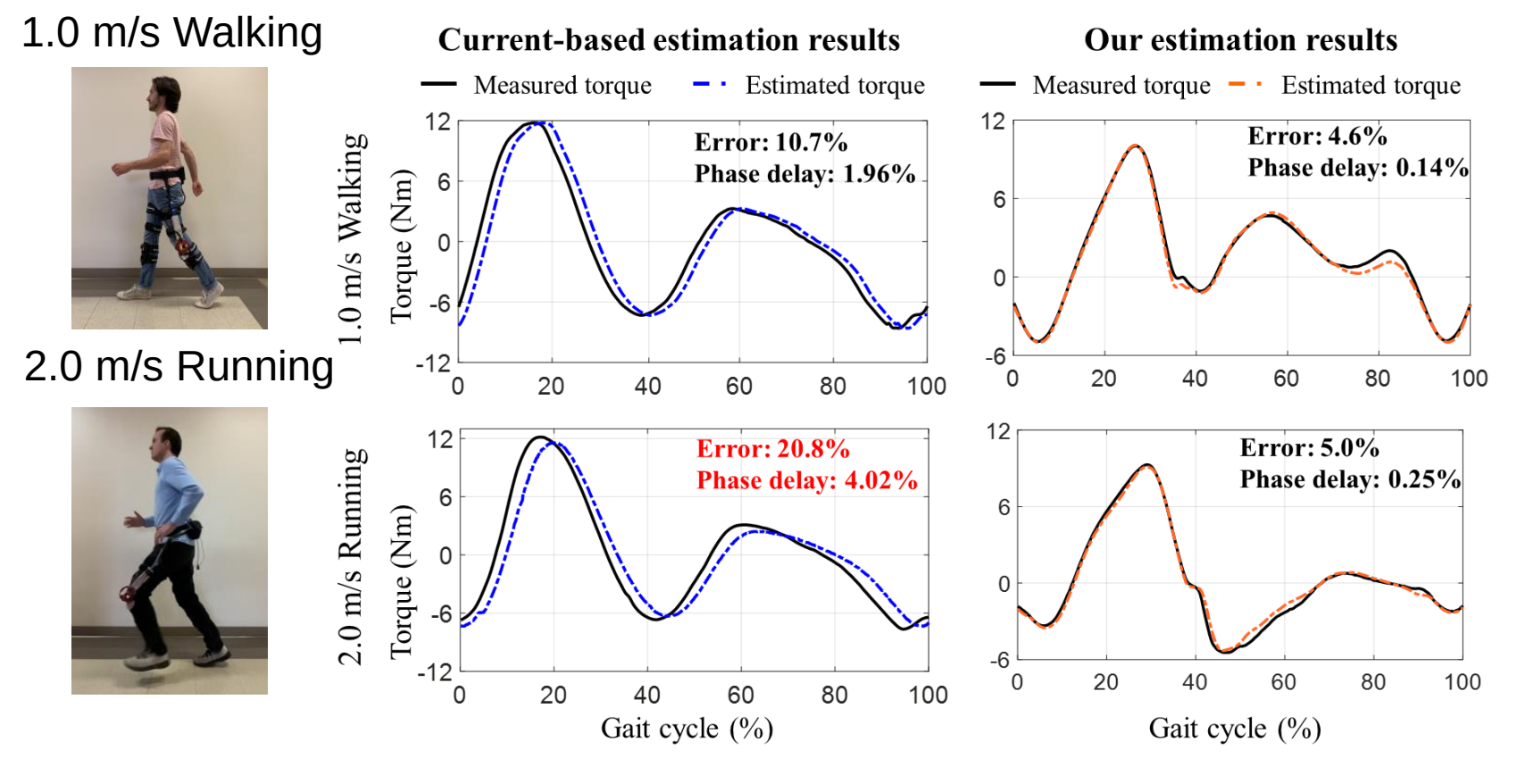
Stability Enhancement by Our Collocated Control

- Enhanced gain margin: increase stiffness rendering from 400 to 900 Nm/rad at 2.0 Hz
- Intrinsic stability of actuation for walking and running



Our High-fidelity Torque Estimator

- SEA: 25% error
- QDD current-based estimation: 10% - 20. 8% error, with 1.96% - 4.02% phase delay
- QDD our torque estimation: 4-5% error, without phase delay



Phase delay > 2.5%
- Huge error
- Increases Exo energetic penalty

References

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[2] S. Zhang, J. Huang, J. Zhu, T.H. Huang, H. Su, "Collocated Torque Control of Portable Exoskeleton Without Torque Sensors: Stability Enhancement and High-Fidelity Torque Estimation", IEEE Transactions on Robotics, 2024. (under review, major revision)
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[4] 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 **(2022 Best Paper in Mechatronics Award + 2023 ASME-DSCD Biosystems and Healthcare Technical Committee Best Paper Award)**
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