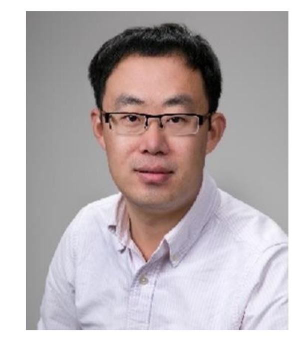
Lightweight, Backdrivable, and High-Bandwidth Knee Exoskeleton with Quasi-Direct Drive Actuation

BIOMECHATRONICS AND INTELLIGENT ROBOTICS

The City University of New York



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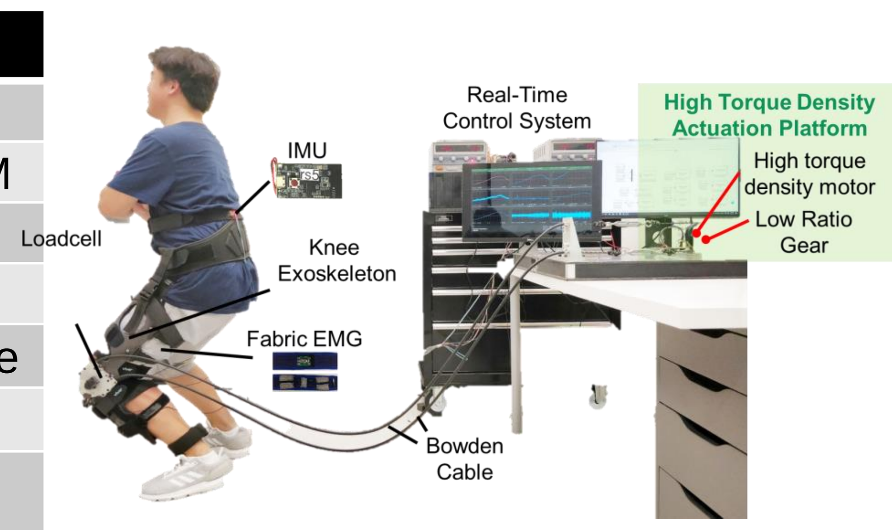
Motivation/Introduction

- More than $15 billion yearly due to physical overexertion of workers
- Stooping, kneeling and squatting increase the risk of developing bursitis, tendinitis, or osteoarthritis of the knee
- Exoskeletons have potential to mitigate the injury incidence and augment human
- Goal: lightweight, compliant, versatile devices to reduce musculoskeletal injuries

Tethered and Portable Soft Exoskeleton Systems

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

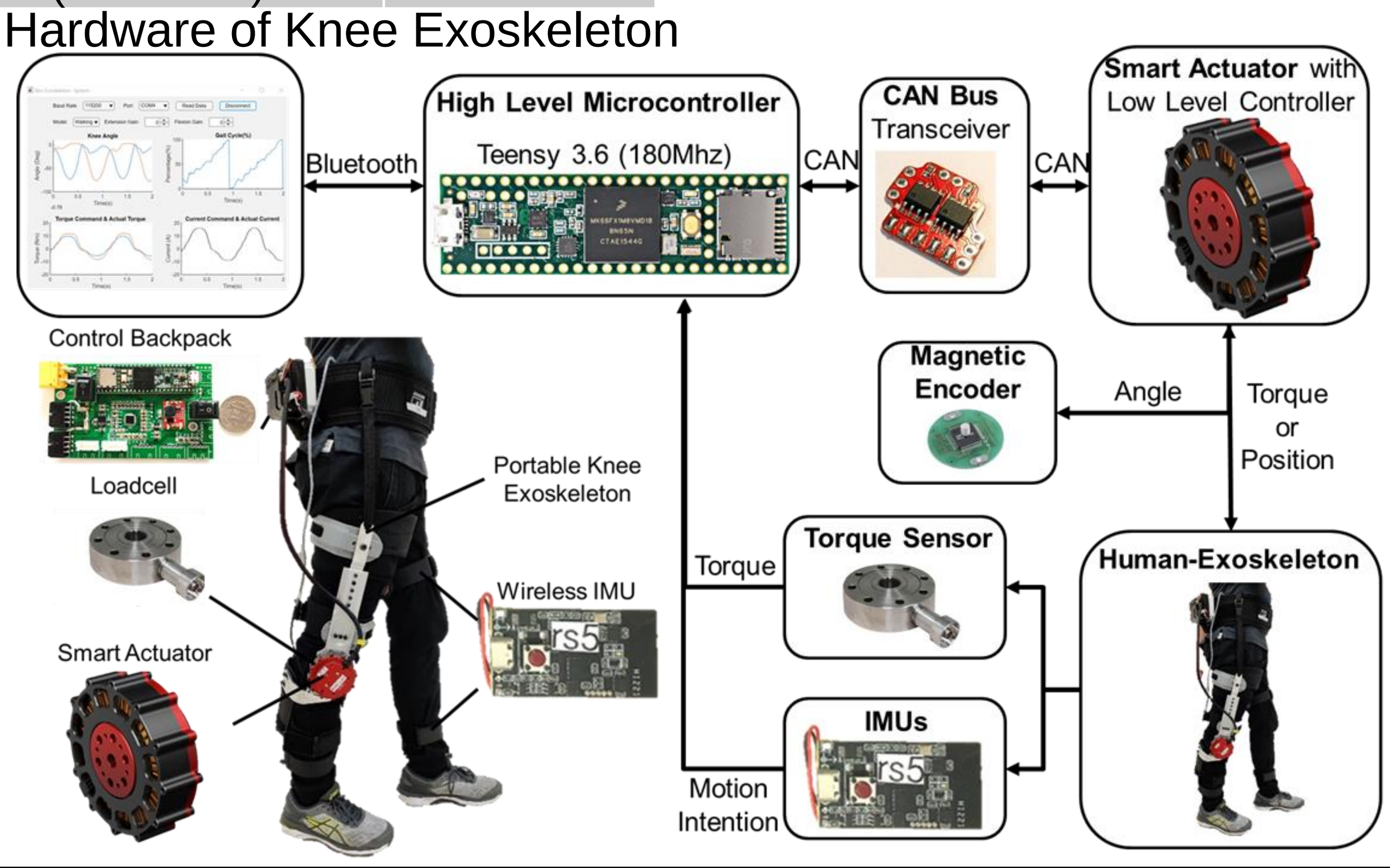
Specification Table	
Motor Torque	2Nm
Motor Speed	1500 RPM
Output Torque:	72 Nm
Output Speed:	4.4 rad/s
Range of Motion:	130 degree
Gear Ratio	36:1
Total Weight (Unilateral):	< 1 kg



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

Specification Table	
Motor Torque	1.1 Nm
Motor Speed	250 RPM
Output Torque:	20 Nm
Output Speed:	26.2 rad/s
Range of Motion:	160 degree
Gear Ratio	6:1
Total Weight (Unilateral):	2.5 kg

- Hardware of Knee Exoskeleton



Exoskeleton Innovations

- Advantages of Our Soft Exoskeleton

Acknowledgment

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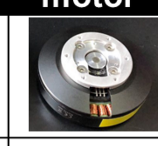
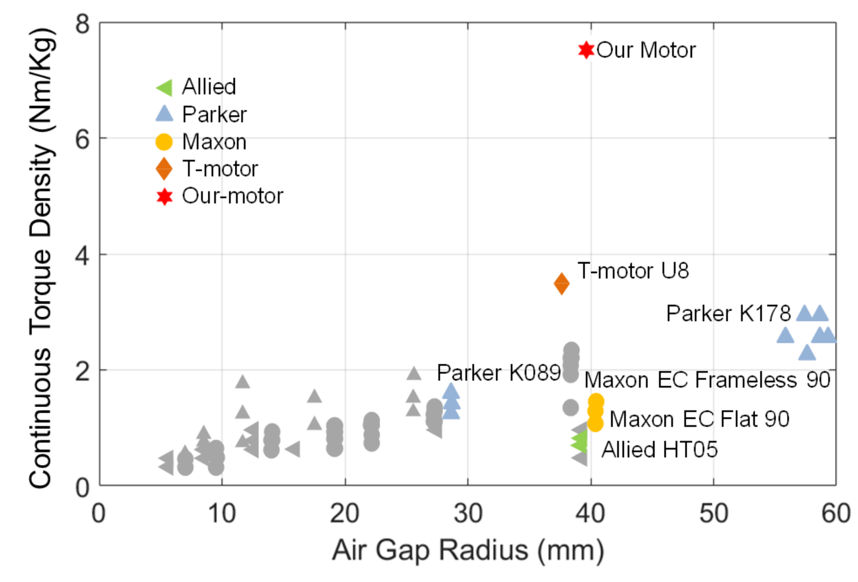
Reference

[1] S. Yu, etc. Design and Control of a High-Torque and Highly Backdrivable Hybrid Soft Exoskeleton for Knee Injury Prevention During Squatting. IEEE Robotics and Automation Letters, 2019
[2] J. Yang, etc. Machine Learning Based Adaptive Gait Phase Estimation Using Inertial Measurement Sensors. Design of Medical Devices Conference. American Society of Mechanical Engineers Digital Collection, 2019

- High Torque Density Motor

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

Versatile Dynamic Model Based Control

- Human Quasi-Static Model Based Control for Squatting and Stooping
  - A versatile biomechanics model for both squatting and stooping

Inertia matrix — Centrifugal and Coriolis loading

Knee joint torque ⟵ $\tau_k = I(\theta)\ddot{\theta} + C(\theta,\dot{\theta}) + G(\theta)$

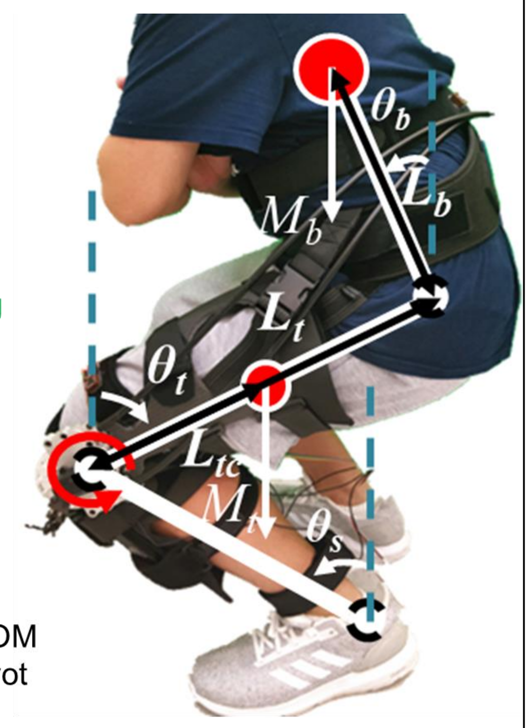
Joint angle acceleration — Gravitational loading

  - Since the lifting motions are typically relatively slow

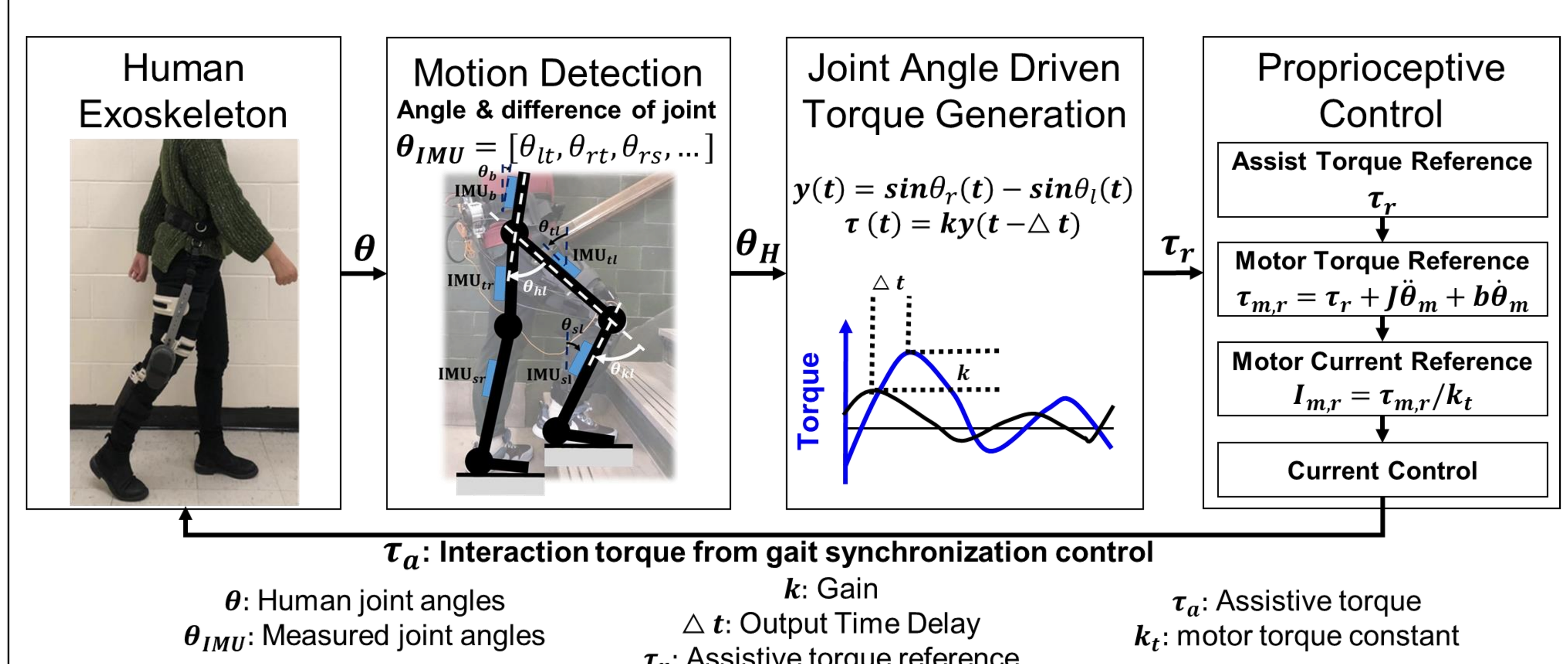
Length between COM of M_b and hip pivot — length of thigh — Mass of thigh

$\hat{\tau}_k = G(\theta) = -0.5 \cdot [M_b \cdot g \cdot (L_b \cdot sin\theta_b + L_t \cdot sin\theta_t) + M_t \cdot g \cdot L_{tc} \cdot sin\theta_t]$

Total mass of upper part of the body — Trunk angle — Thigh angle — Length between COM of M_t and knee pivot



- Delayed Output Feedback Control Algorithm for Walking



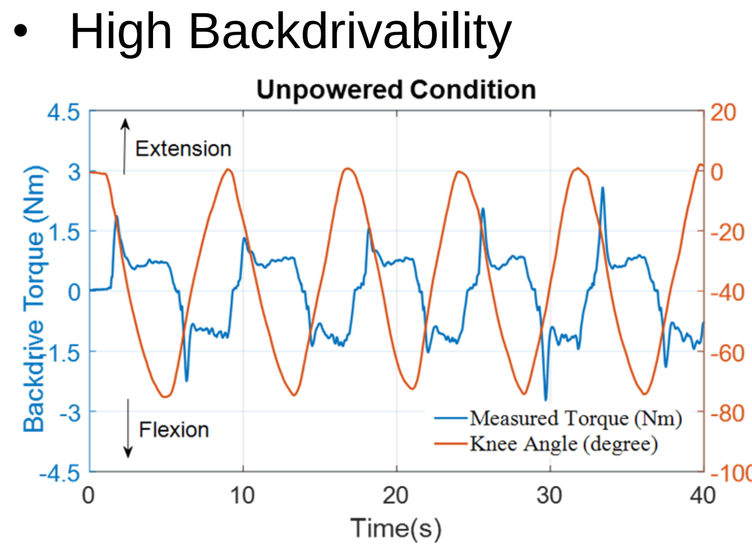
$\theta_{IMU} = [\theta_{lt}, \theta_{rt}, \theta_{rs}, \dots]$; $y(t) = sin\theta_r(t) - sin\theta_l(t)$; $\tau(t) = ky(t - \triangle t)$; $\tau_{m,r} = \tau_r + J\ddot{\theta}_m + b\dot{\theta}_m$; $I_{m,r} = \tau_{m,r}/k_t$

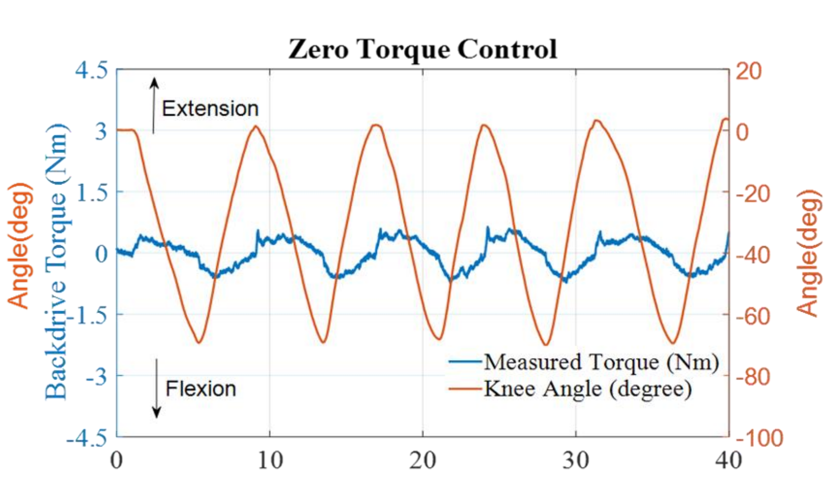
τ_a: Interaction torque from gait synchronization control

θ: Human joint angles
θ_{IMU}: Measured joint angles
k: Gain
$\triangle t$: Output Time Delay
τ_r: Assistive torque reference
τ_a: Assistive torque
k_t: motor torque constant

Experimental Result

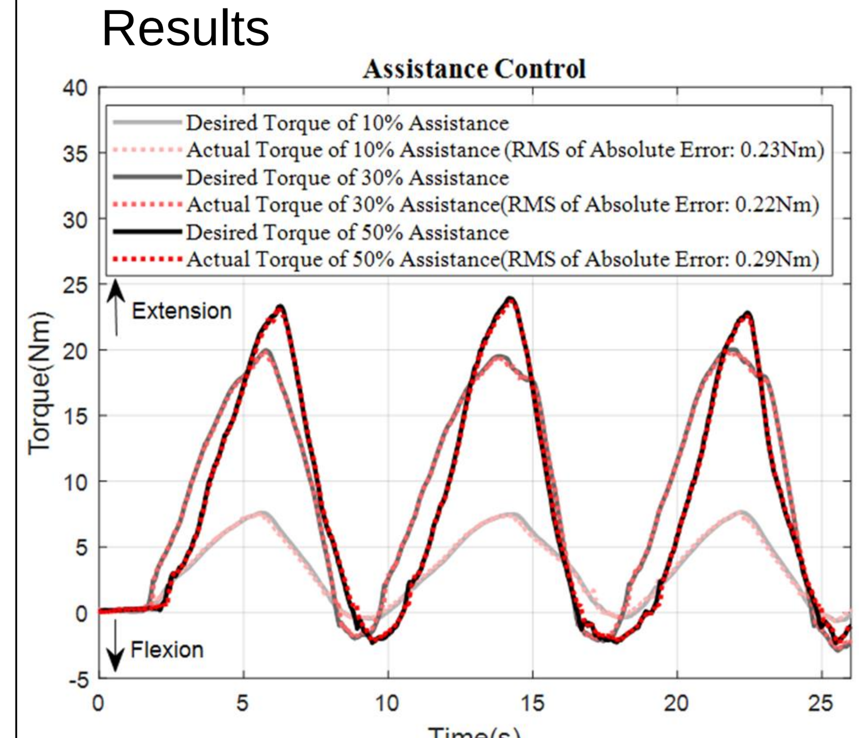
- High Backdrivability

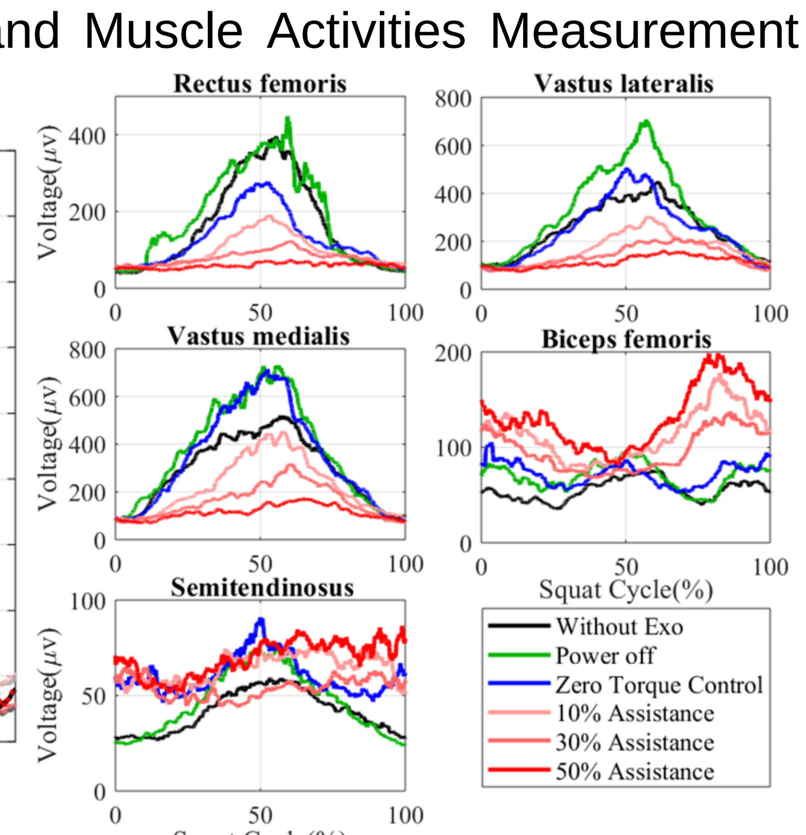




The backdrivability performance of the knee exoskeleton in the unpowered mode and zero torque tracking control. The average backdrive torque is 0.92 Nm and 0.34 Nm respectively

- Torque Tracking for Squatting and Muscle Activities Measurement Results





The tracking performance of the 10%, 30%, 50% of knee torque assistance in three squatting cycles. The RMS of the absolute error between the desired and actual torque trajectory was 0.3 Nm, 0.22 Nm, and 0.29 Nm in 10%, 30%, and 50% knee assistance respectively.

It shows the average of EMG in 15 squat cycles (three healthy subjects with 5 cycles each). The result shows that the exoskeleton effectively reduced activities of three knee extensor muscles.