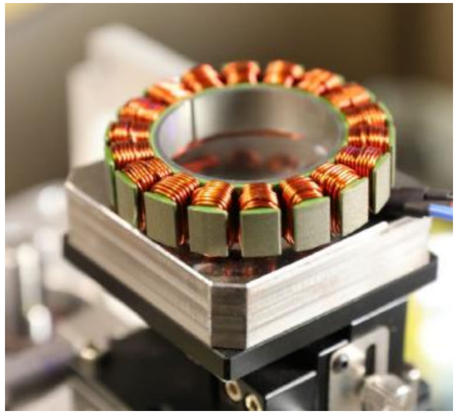
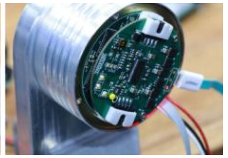
High-Performance Soft Robots for Human Augmentation

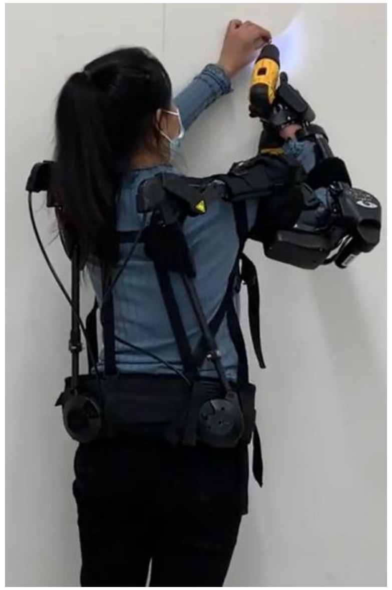
New Paradigm of Design and Control for Scientific Discovery

Israel Dominguez, Sainan (Selena) Zhang, Shuzhen (Susan) Luo, and Hao Su*

Lab of Biomechatronics and Intelligent Robotics, Mechanical and Aerospace Engineering, North Carolina State University (NCSU)





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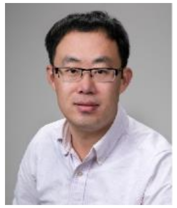
Israel Dominguez (Ph.D. student)

Sainan Zhang (Ph.D. student)

Shuzhen Luo (Postdoc)

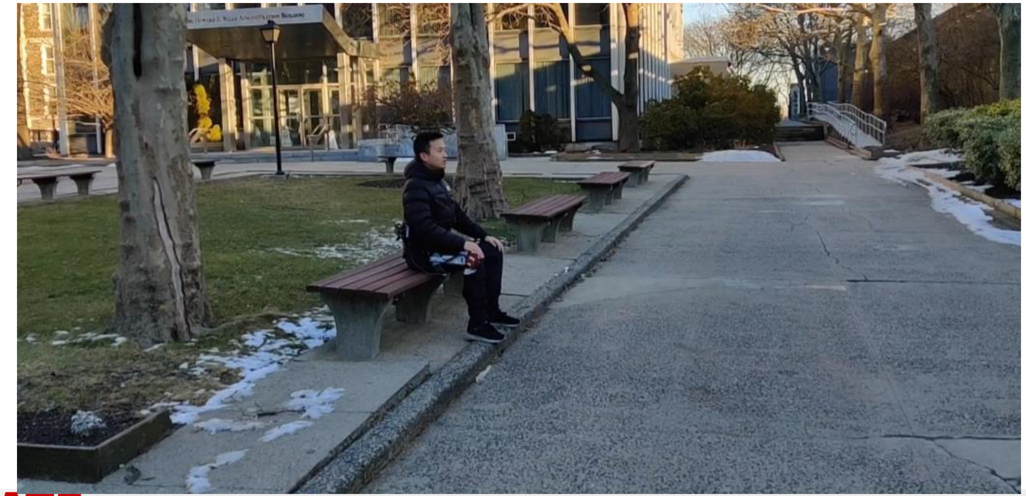


Hao Su (PI)

BIOMECHATRONICS AND INTELLIGENT ROBOTICS

Exoskeleton Assists Walking Outdoors

- Lightweight knee exoskeleton: unilateral 2.1 kg, bilateral 3.5 kg
- Compliant and high control bandwidth



Modeling of Human-Robot Interaction

- **Motor**: motor torque

$$L\frac{di}{dt} + RI + V = V_b \qquad \tau_m = k_t i$$

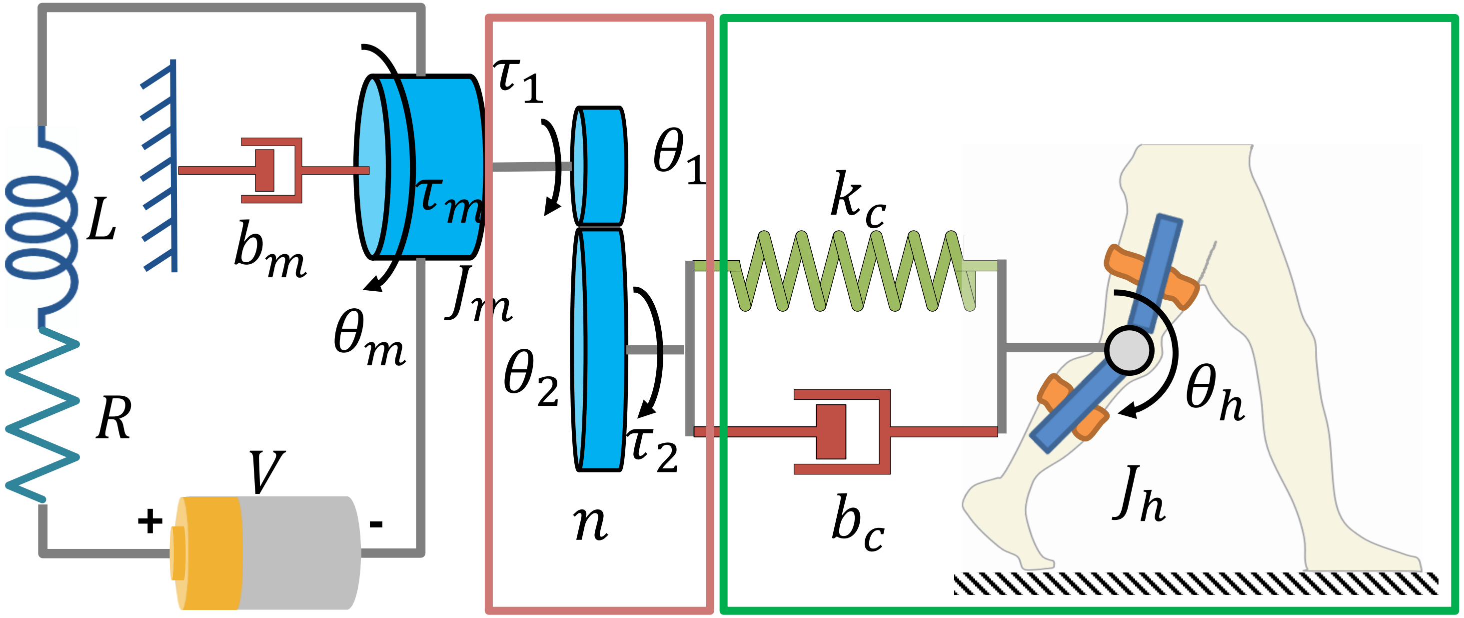
$$\tau_m = J_m\ddot{\theta}_m + b_m\dot{\theta}_m + \tau_1$$

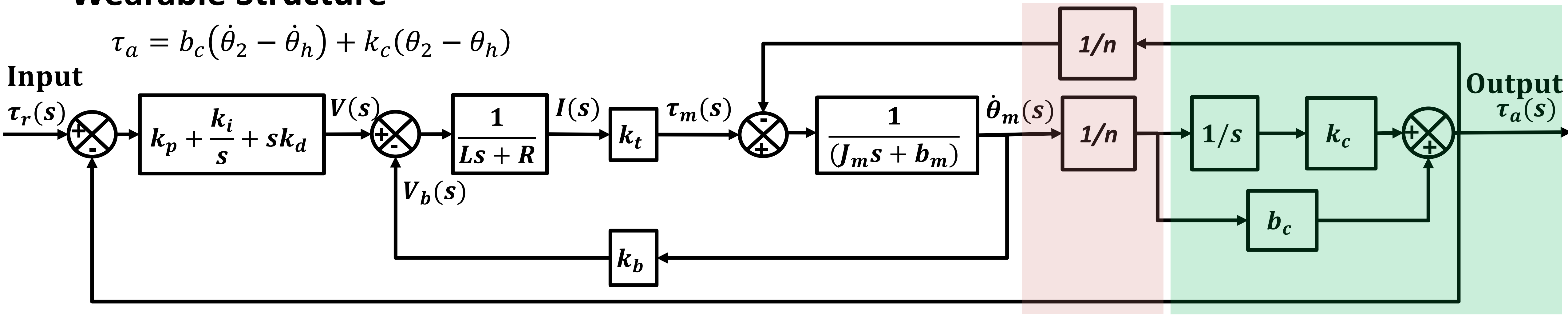
- **Transmission**: torque amplification

$$\tau_2 = n\tau_1 \qquad \theta_2 = \theta_1/n$$

- **Wearable Structure**

$$\tau_a = b_c(\dot{\theta}_2 - \dot{\theta}_h) + k_c(\theta_2 - \theta_h)$$



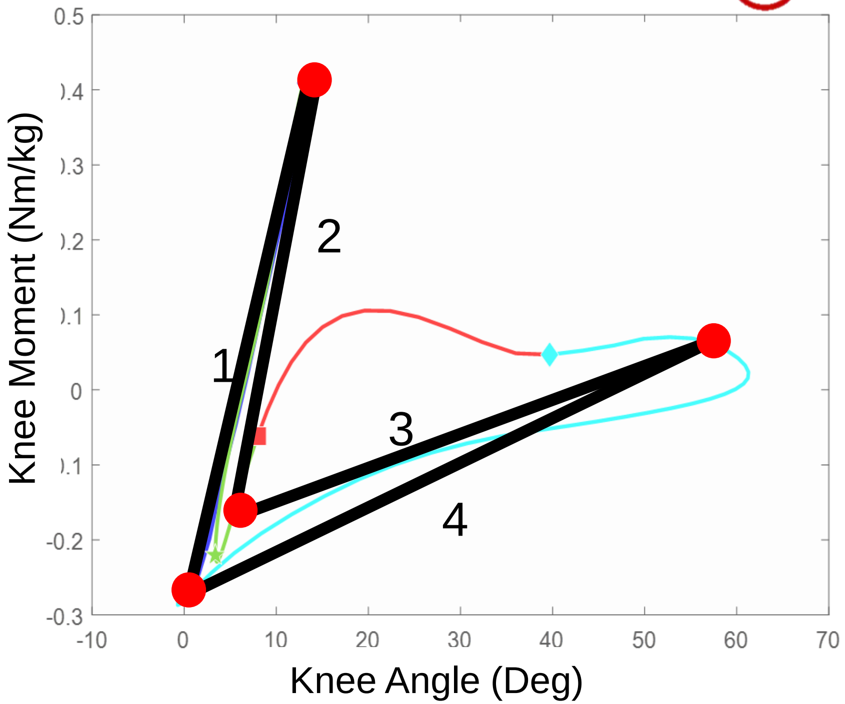


Huang TH, **Zhang S**, Yu S, MacLean MK, Zhu J, Di Lallo A, Jiao C, Bulea TC, Zheng M, **Su H**. Modeling and Stiffness-Based Continuous Torque Control of Lightweight Quasi-Direct-Drive Knee Exoskeletons for Versatile Walking Assistance. IEEE Transactions on Robotics. 2022 Jun 3.

Stiffness Model Based Continuous Torque Control

State-of-the-Art [Zhang 17]

- Predefined piecewise torque ✗
- Discrete stiffness ✗

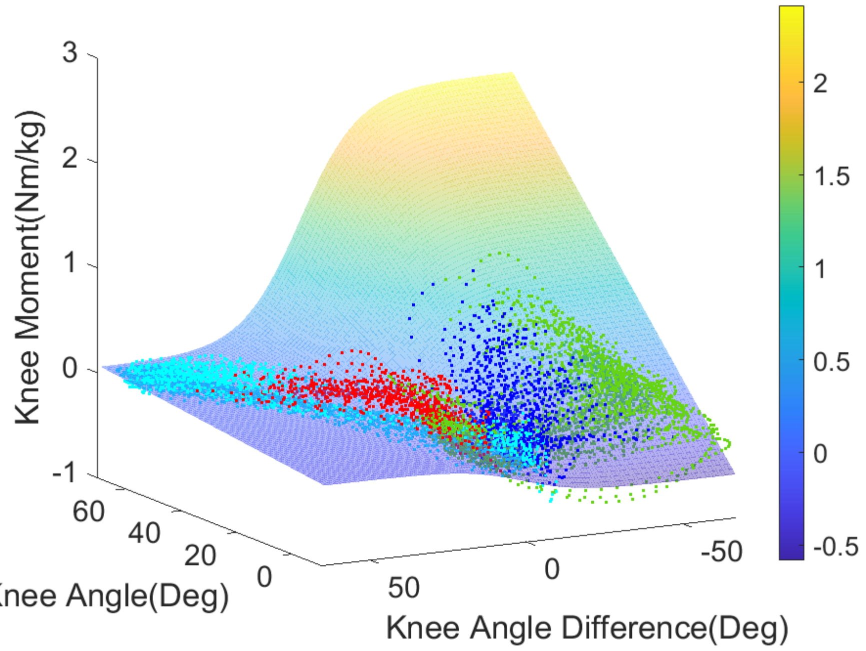


Smooth

Robust

Our Solution

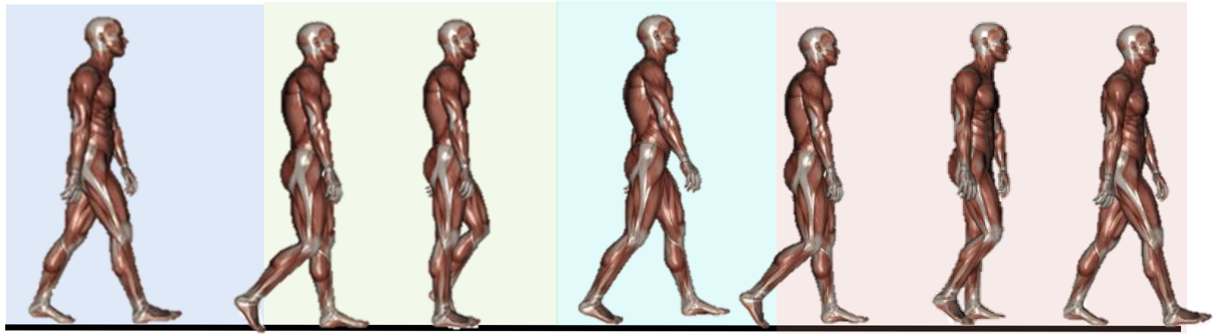
- Model based continuous torque ✓
- Unique correspondence between torque and kinematics ✓



- Zhang, J., & Collins, S. H. (2017). The passive series stiffness that optimizes torque tracking for a lower-limb exoskeleton in human walking. Frontiers in neurorobotics, 11, 68.
- Huang, T. H., Zhang, S., Yu, S., MacLean, M., Di Lallo, A., Bulea, C. T., Su, H., Modeling and Continuous Stiffness Torque Control of Quasi-Direct-Drive Knee Exoskeletons for Versatile Walking Assistance, IEEE Transaction on Robotics, 2021 (accepted)

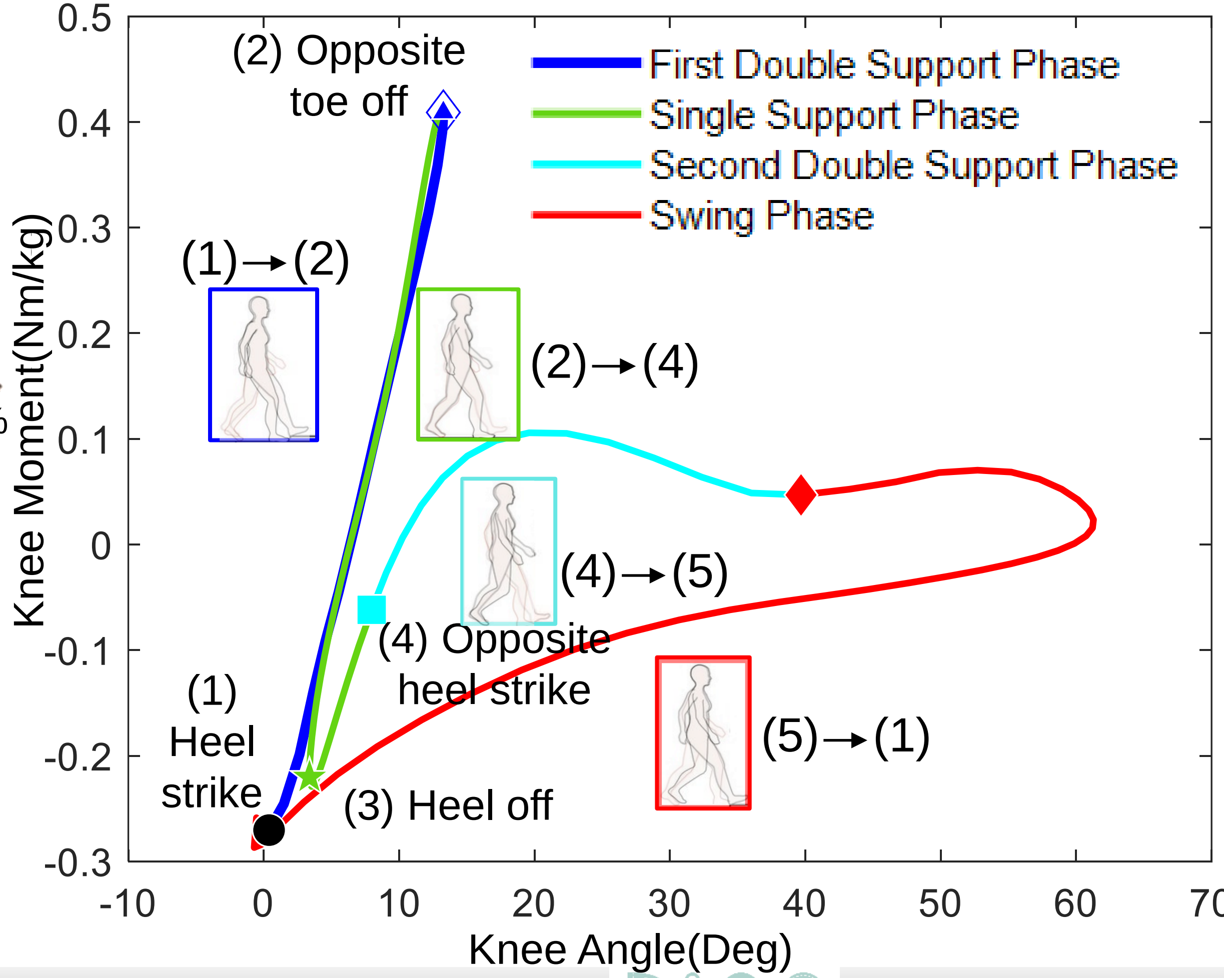
Biomechanics-inspired Continuous Torque Estimation

Can we identify methods for simple and adaptive torque control to sync with human?



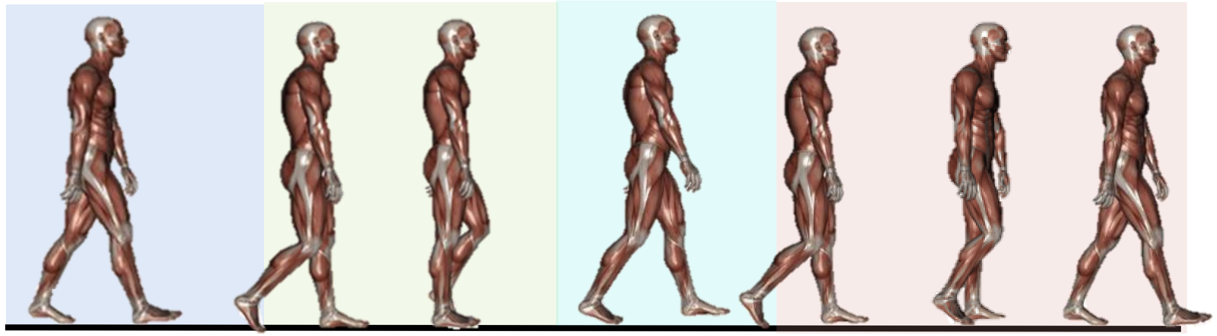
0% 100%

Events	Heel strike	Opposite toe off	Heel off	Opposite heel strike	Toe off	Mid swing	Next heel strike
Tasks	Weight Acceptance	Single-limb Support		Limb Advancement			
Phases	1st Double Support	Single Support		2nd Double Support	Swing		
Moments	Flexion	Extension		Flexion	Extension		



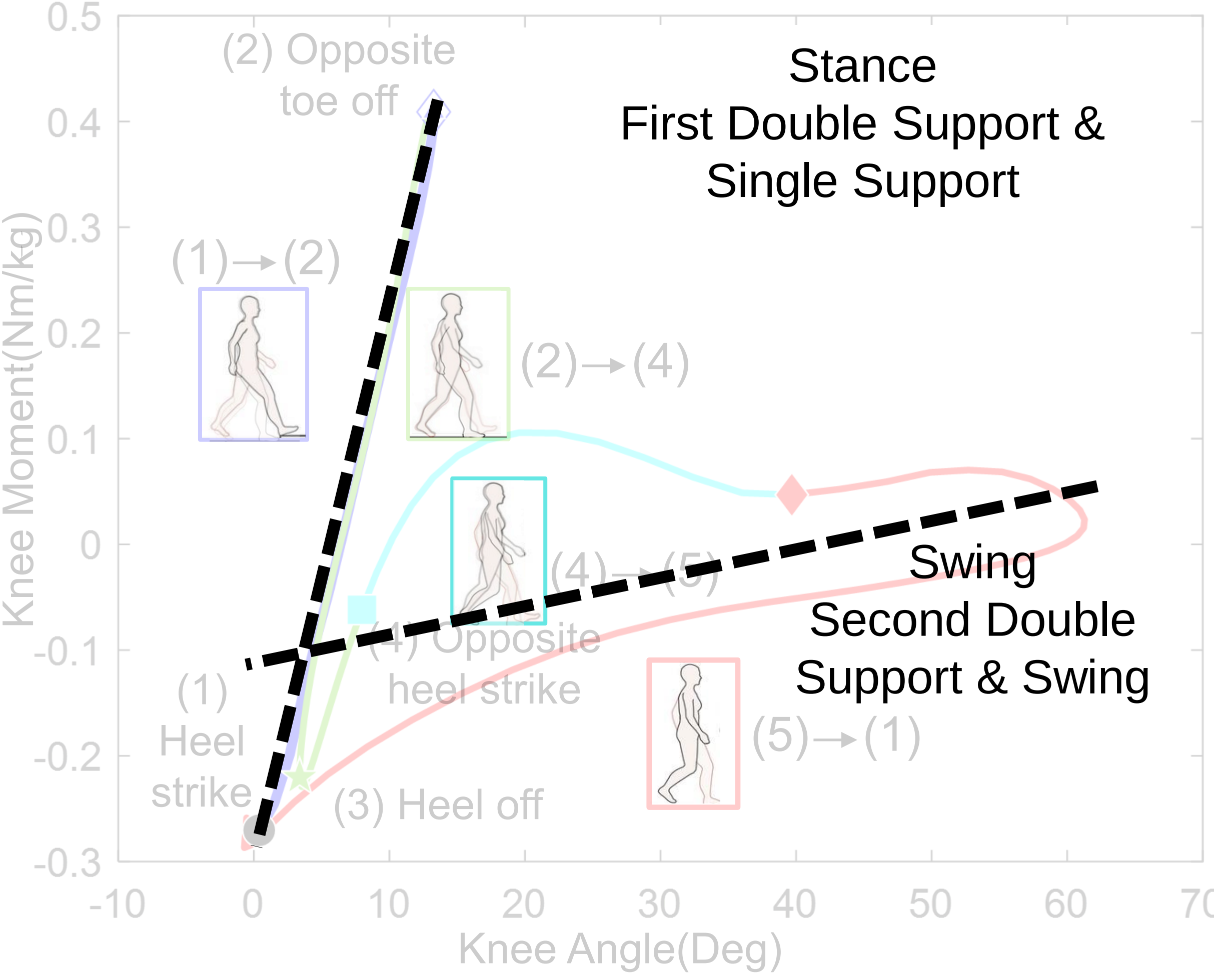
Biomechanics-inspired Continuous Torque Estimation

- Stance phase: high stiffness
- Swing phase: low stiffness



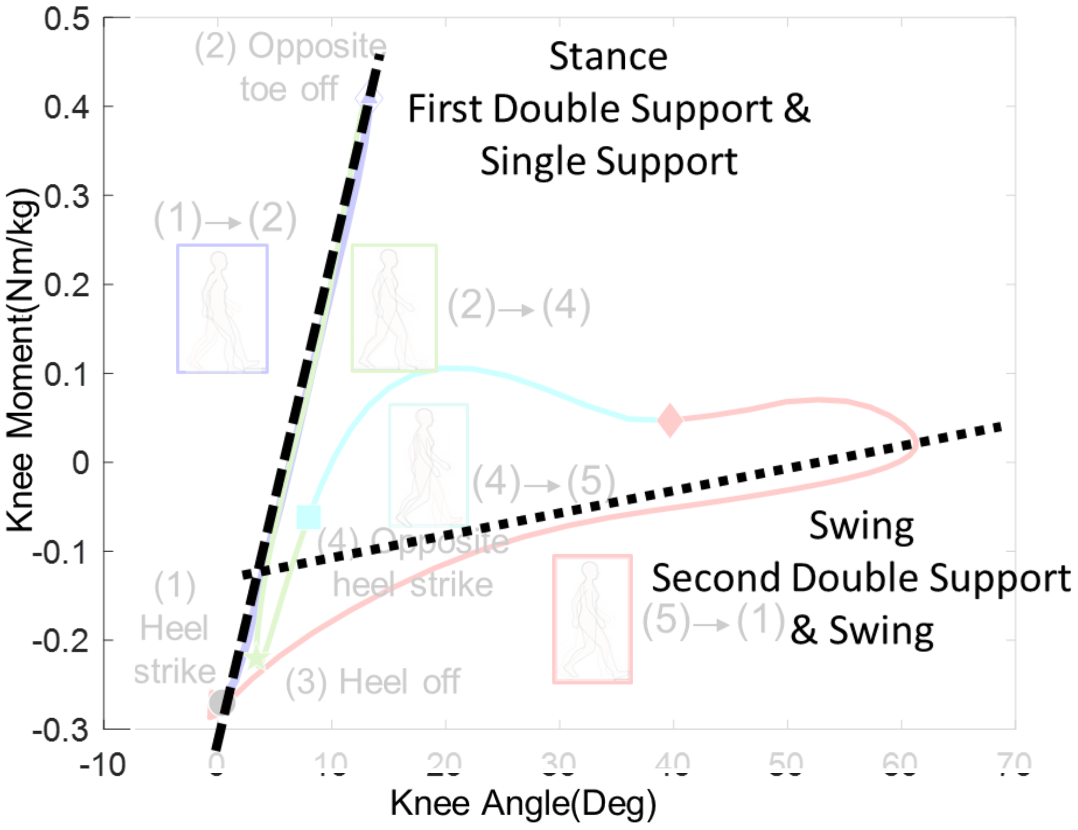
Events	Heel strike	Opposite toe off	Heel off	Opposite heel strike	Toe off	Mid swing	Next heel strike

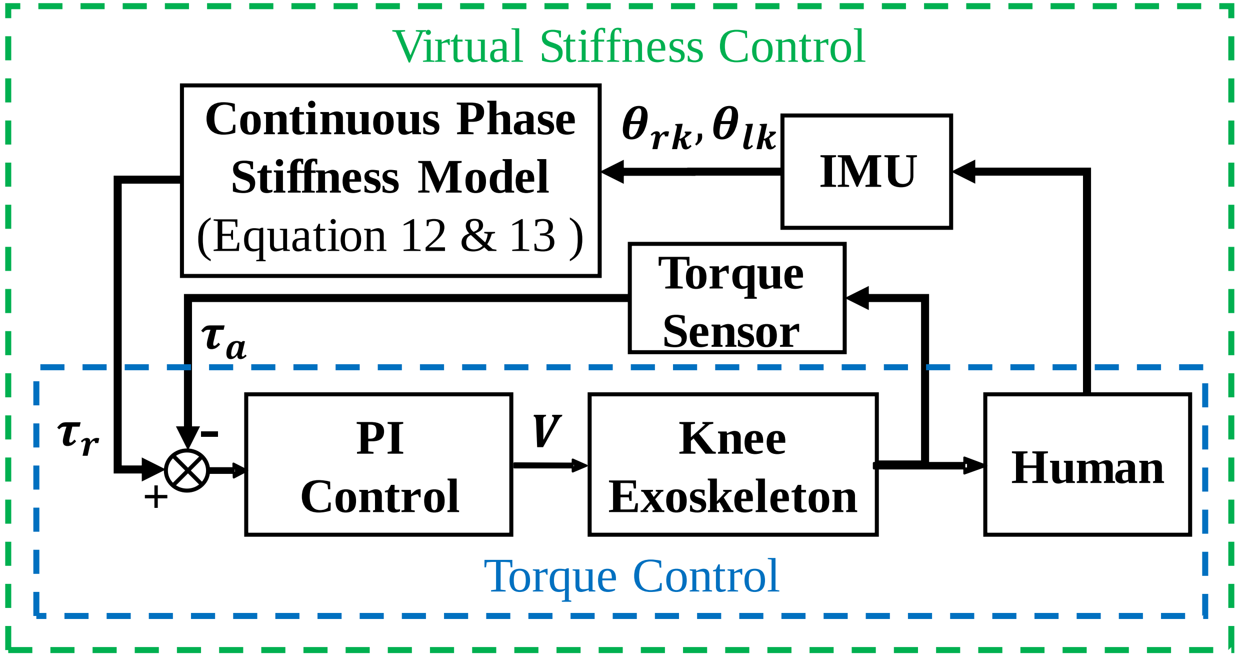
Tasks	Weight Acceptance	Single-limb Support	Limb Advancement
Phases	1st Double Support	Single Support	2nd Double Support / Swing
Moments	Flexion / Extension	Extension / Flexion	Flexion / Extension



Stiffness Model Based Continuous Torque Estimation

- Stance: 1st Double Support Phase + Single Support Phase
- Swing: 2nd Double Support Phase + Swing





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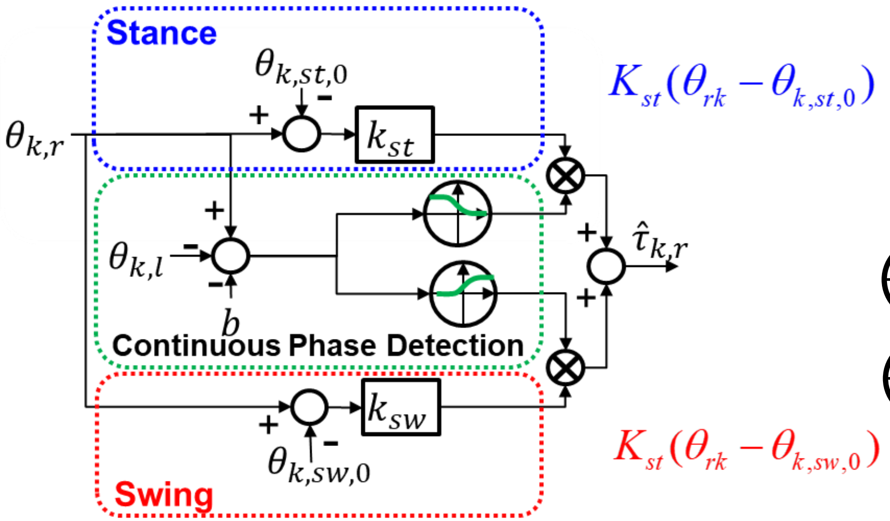
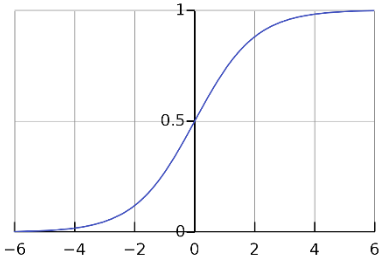
Stiffness Model based Continuous Torque Estimation

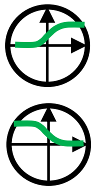
- **Input:** knee angles $\theta_{k,r}, \theta_{k,l}$ and their difference; **Output:** estimated knee torque
- Knee moment estimation by linear combination of stance and swing

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

- Sigmoid function: discrete to continuous

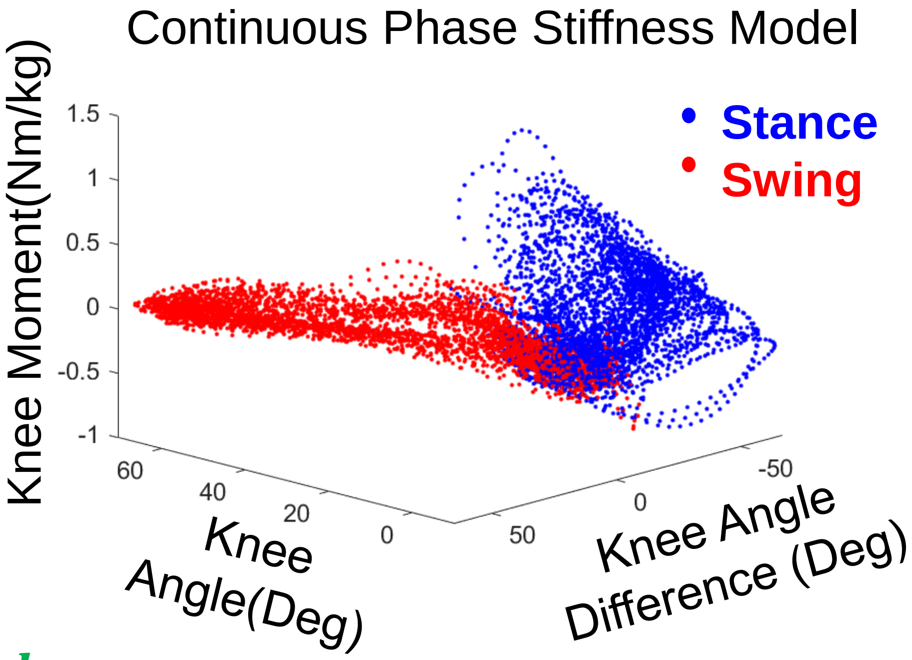






: Sigmoid Function

: 1-Sigmoid Function



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

Stiffness Model based Continuous Torque Estimation

- Knee torque estimation: linear combination of stance and swing stiffness models

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

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

- Nonlinear optimization to identify optimal hyperplane separating gait phases
  - Objective function

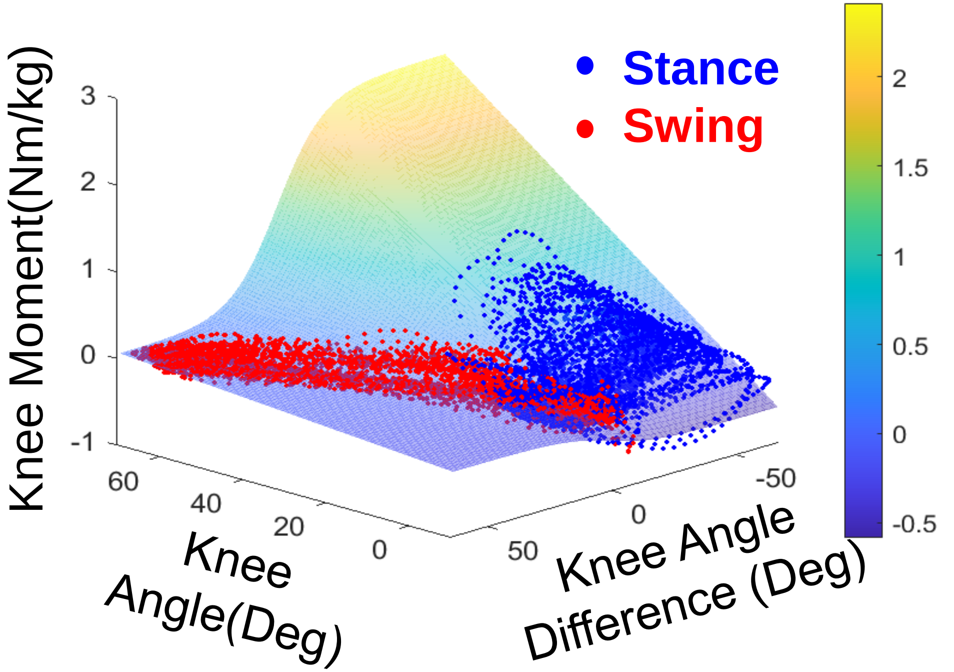
$$\arg\min \sum_{i=1}^{m} (\hat{\tau}_{k,r,i} - \tau_{k,r,i})^2$$

  - Optimization Parameters

$$W = [k_{st}, k_{sw}, \theta_{k,st,0}, \theta_{k,sw,0}, a, b]$$

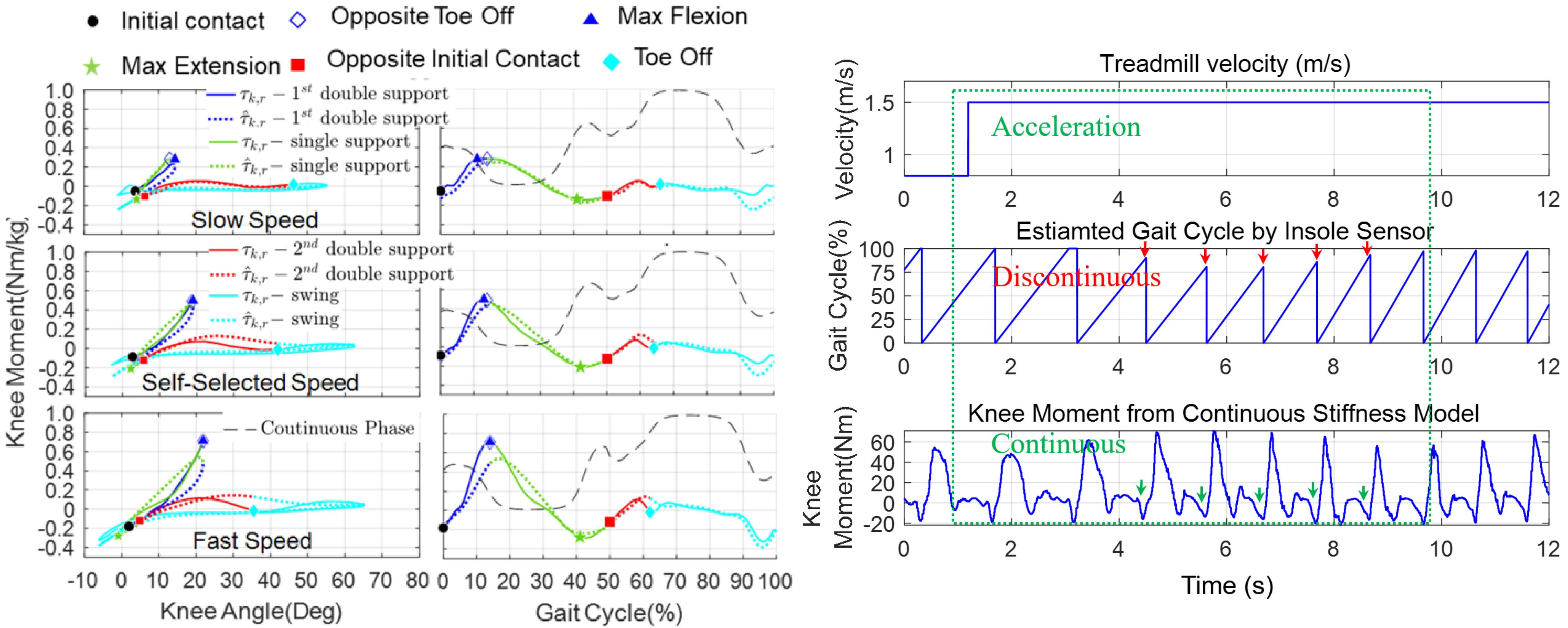
k_{st} & k_{sw}: stance and swing stiffness
$\theta_{k,st,0}$ & $\theta_{k,sw,0}$: the initial angle for two stiffness models
a & b: transition area width and center

Continuous Phase Stiffness Model



Torque Estimation for Gait Synchronization Control

- Estimated torque continuously adapts to biological torque at varying speeds



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Human Subject Experiment

- 8 able-bodied subjects: 6 males and 2 females

1st visit (Habituation)

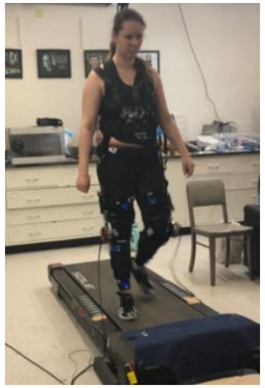
Powered 1	Rest	Unpowered 1	Rest	Powered 2	Rest	Unpowered 2
20 mins	10 mins	20 mins	10 mins	20 mins	10 mins	20 mins

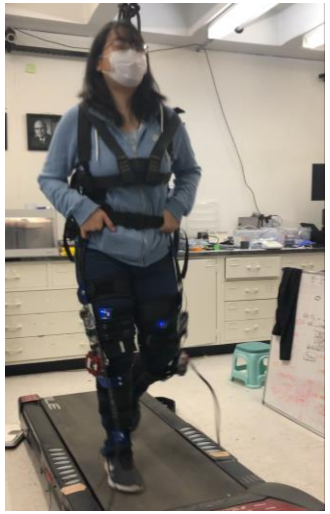
Randomized

2nd visit (Evaluation)

Baseline		Rest 10 mins	Powered		Rest 10 mins	Unpowered	
Adaption	Collect Data		Adaption	Collect Data		Adaption	Collect Data
5 min	60 strides		5 min	60 strides		5 min	60 strides

Randomized




Demo videos

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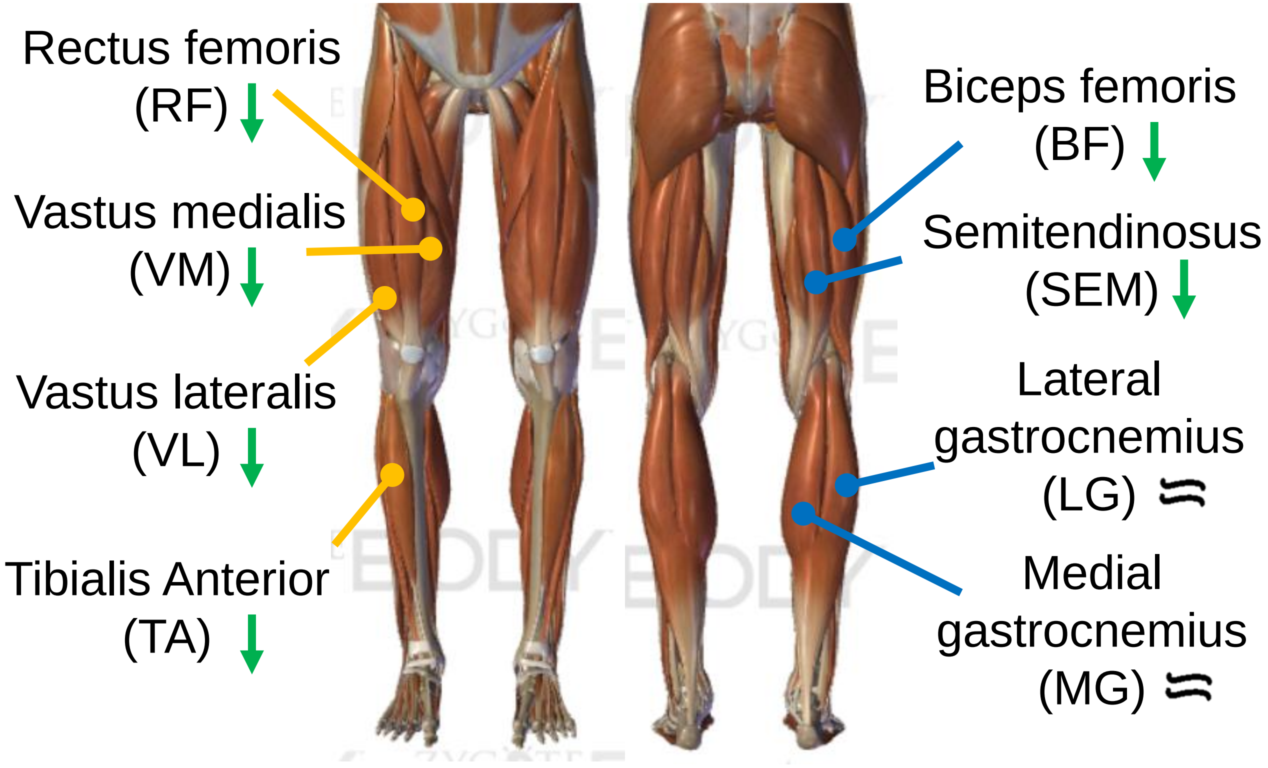
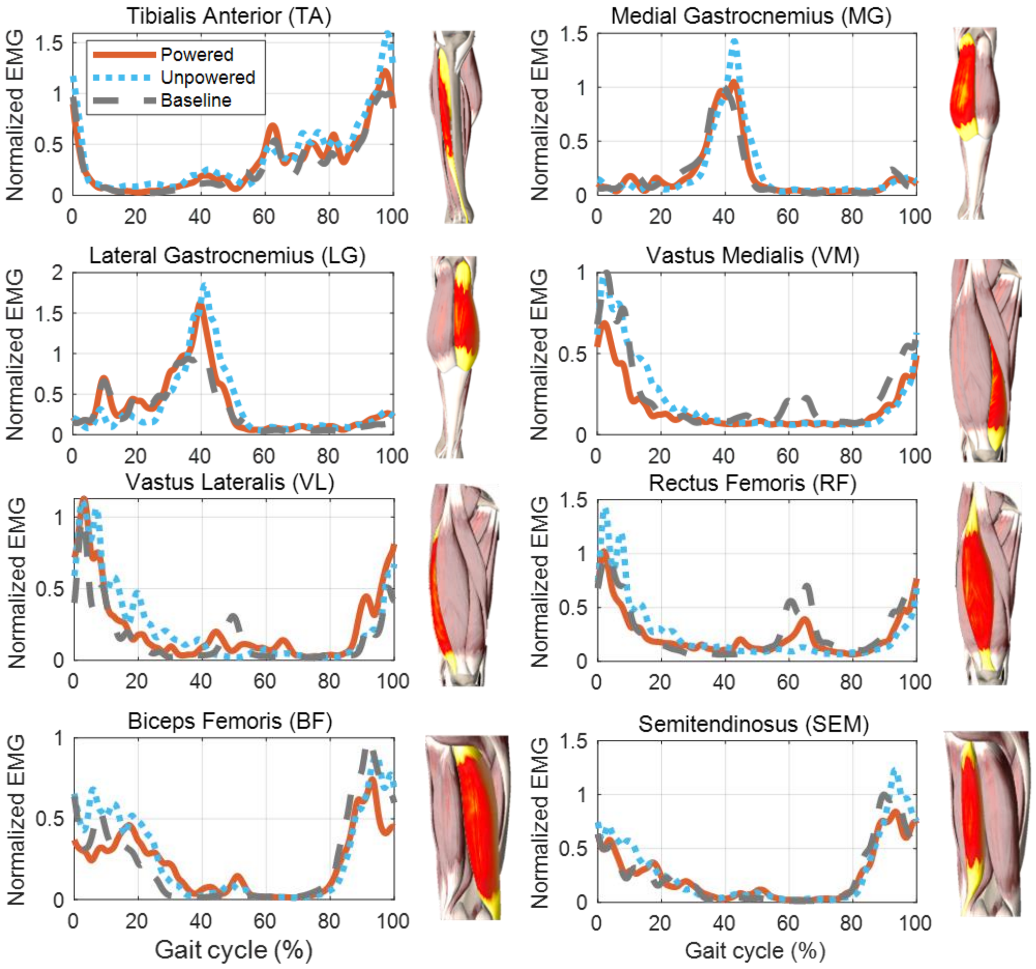
First Work to Show EMG Reduction with Portable Knee Exo

- Reduced 3.7 - 15.7% muscle activation for knee extensors and flexors, and ankle extensors





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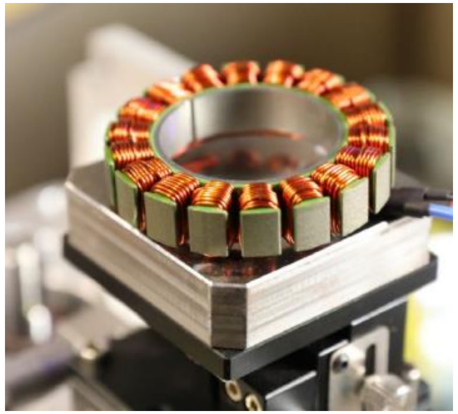
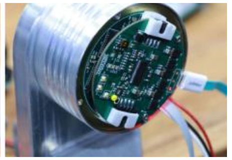
Reinforcement Learning and Control of a Lower Extremity Exoskeleton

Israel Dominguez, Menghan (Meghan) Jiang, Shuzhen (Susan) Luo, and Hao Su[1*]

[1]Lab of Biomechatronics and Intelligent Robotics, Mechanical and Aerospace Engineering, North Carolina State University (NCSU)





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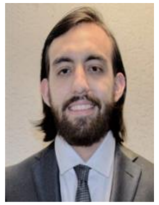
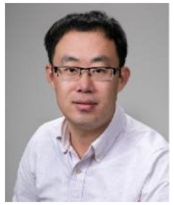


Israel Dominguez
(Ph.D. student)

Shuzhen Luo
(Postdoc)

Menghan Jiang
(PhD Student)

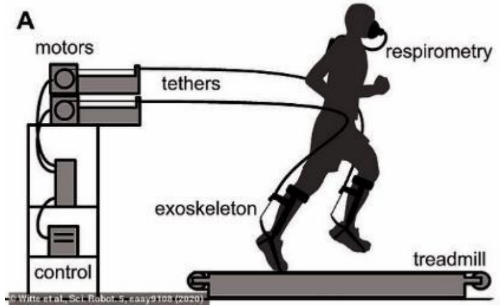


Hao Su
(PI)

BIOMECHATRONICS AND INTELLIGENT ROBOTICS

Paradigm Shift from Lab to Community Use

Tethered Exoskeleton

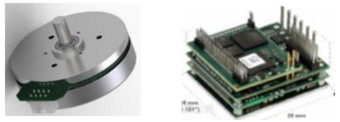


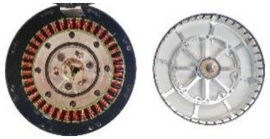
- 12.5-30 Kg
- High friction
- Resistive

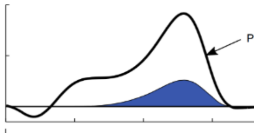
Portable Exoskeleton

2012 Ekso Bionics
Increased metabolic cost

Rigid Exoskeletons	Challenges	Innovations
Low torque motors	Low torque, high speed	High torque motor
High ratio transmission	Resistive to natural movements	Quasi-direct Drive: Low ratio gear
Discrete Controller	Steady-state walking only	Versatile Continuous







Our Exoskeleton

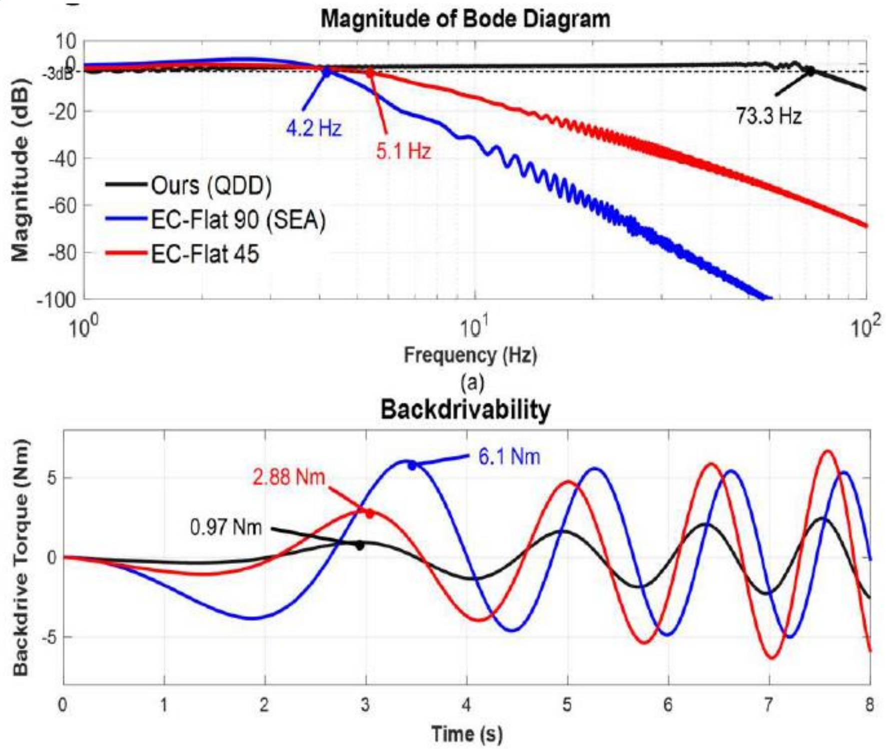
- Lightweight: 1.7 Kg (unilateral)
- Compliant
- Versatile

- Yu, Huang, Yang, Jiao, Yang, Chen, Yi, Su. Quasi-direct drive actuation for a lightweight hip exoskeleton with high backdrivability and high bandwidth. **IEEE Transactions on Mechatronics** , 2020 **(Best student paper award)**
- 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, **IEEE Transactions on Robotics**, 2022

Paradigm Shift from Lab to Community Use

- Our actuators have low backdrive torque and high bandwidth

	Backdrive Torque	Torque Control Bandwidth
Conventional	2.9 Nm (Middle)	5.1 Hz (Low)
SEA	6.1 Nm (High)	4.2 Hz (Low)
Ours	1.0 Nm (Low)	73.3 Hz (High)



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- 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, **IEEE Transactions on Robotics**, 2022
- 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

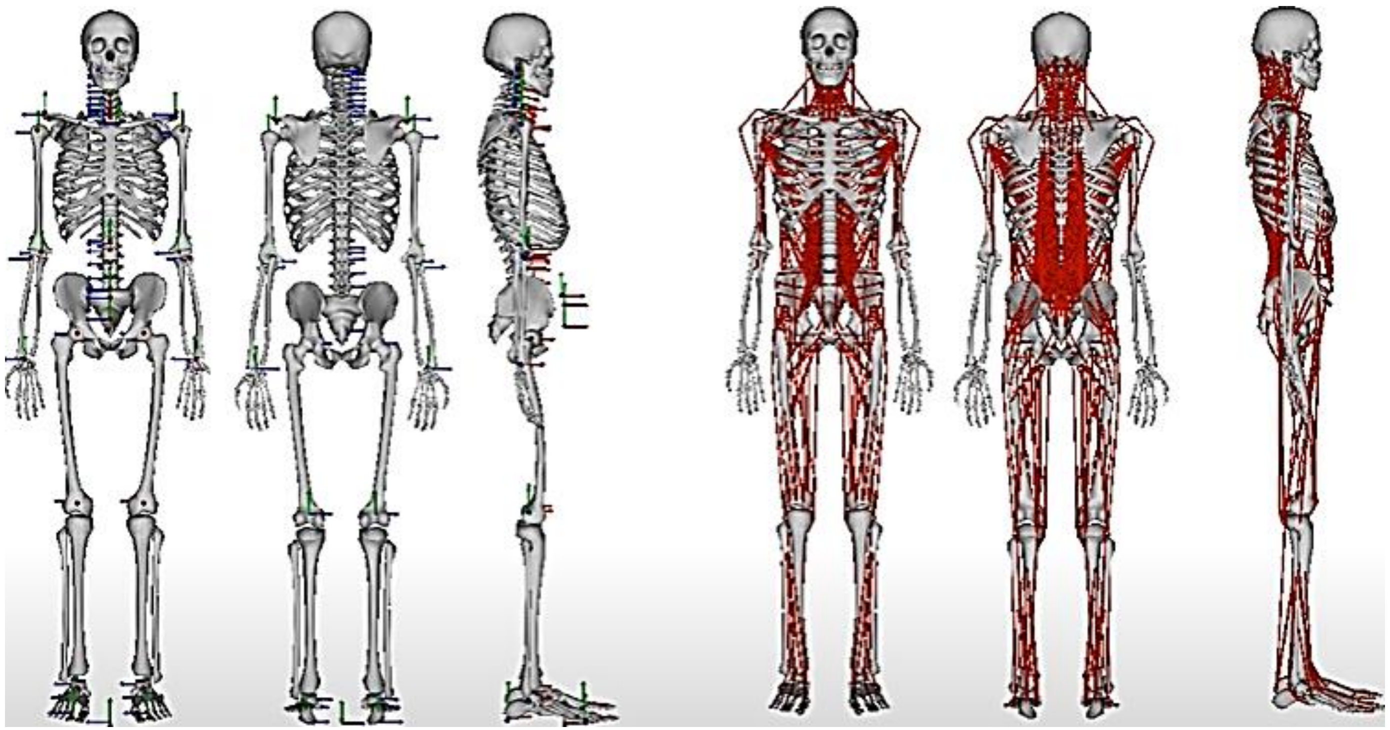
Challenge in State-of-the-Art

Challenge 1: intensive human testing, time-consuming, laborious

https://exoedu.lu/materials/recorded-webinar-usage-of-medical-exoskeletons-04-11-20/

Solution 1: High-Fidelity Simulation

- Human musculoskeletal Models: 50 DoFs whole-body models with 284 muscles



- Dynamics of musculoskeletal system:

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{c}(\boldsymbol{q}, \dot{\boldsymbol{q}}) = \boldsymbol{J}_m^T \boldsymbol{f}_m(\boldsymbol{a}) + \boldsymbol{J}_{ext}^T \boldsymbol{f}_{ext}$$

- Forward ($\ddot{q}$), and hybrid dynamics
- Many joint types:
  - Fixed, translational, rotational,
  - Spherical/ball, multi-DOF functional joint, etc.
- Muscle force types (Hill type muscle tendon unit)

$$F = [a \cdot F_L(l) \cdot F_V(\dot{l}) + F_P(l)] \times F_{max}$$

Luo, Shuzhen, Ghaith Androwis, Sergei Adamovich, **Hao Su**, Erick Nunez, and Xianlian Zhou. "Reinforcement Learning and Control of a Lower Extremity Exoskeleton for Squat Assistance." *Frontiers in Robotics and AI* 8 (2021).

Challenge in State-of-the-Art

Challenge 2: Lack robustness to subject-specific conditions, require rigorous heuristic handcrafting of control parameters

https://med.uth.edu/blog/2019/08/29/international-symposium-on-wearable-robotics-coming-oct-16-18/

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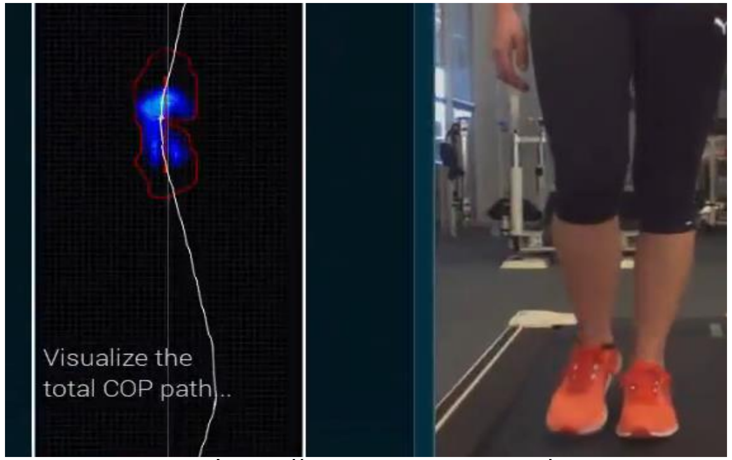
Solution 2: Dynamics Randomization of Muscle Strength Improves Robustness

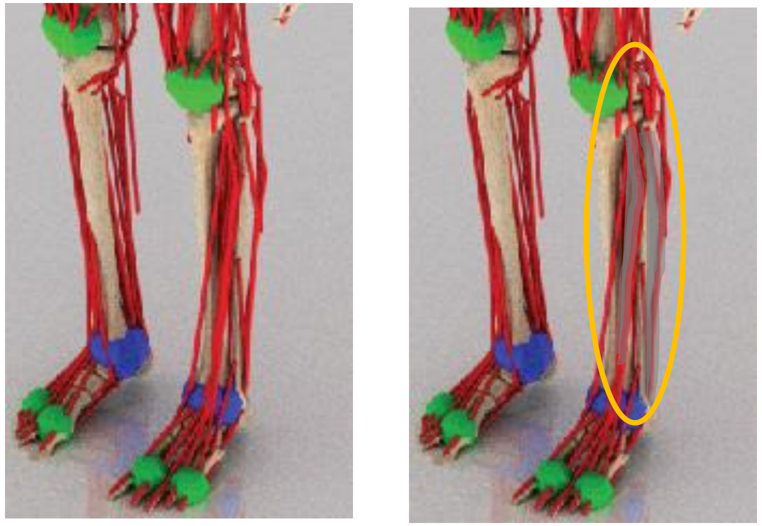
- **A Generalized controller that adapts to human variabilities**
- **Dynamics Randomization Machine Learning Method: randomizing muscle strength** during control policy training facilitates robustness towards varying, or hemiplegic human conditions such as passive muscles (quadriplegic), muscle weakness

- **Balance reward**: The movement of system CoP highly correlates with stability and balance. Thus, reward is to motivate the current CoP position to stay inside a stable region around the center of the foot support
  - Reward $r_t = w^m r_m + w^p r_p + w^{root} r_{root} + w^{cop} r_{cop} + w^{\tau} r_{\tau}$



https://www.noraxon.com/

Normal Muscles Weakened Muscles

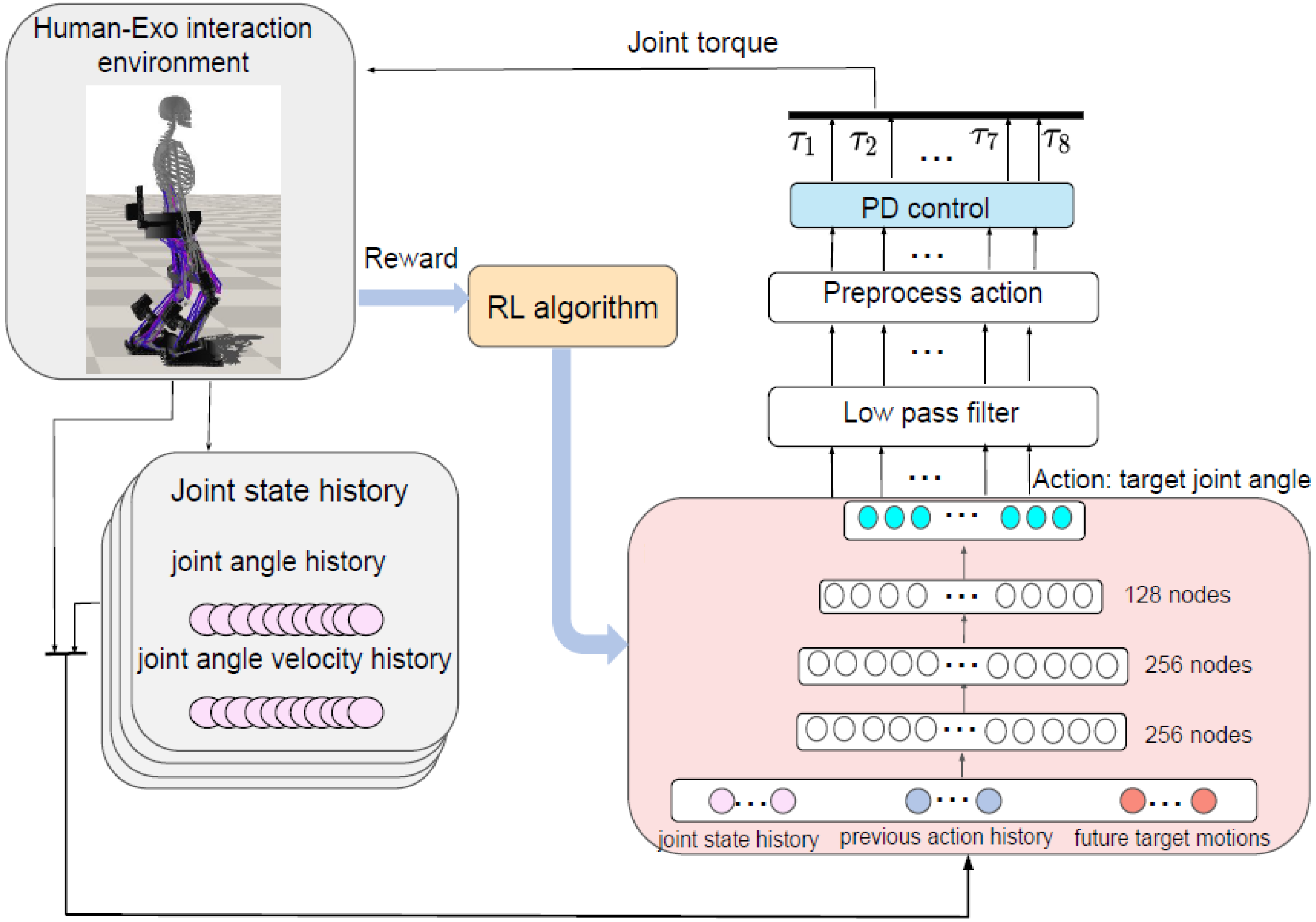


- Shuzhen Luo, Androwis Ghaith, Adamovich Sergei, Erick Nunez, Hao Su, and Xianlian Zhou. "Robust Walking Control of a Lower Limb Rehabilitation Exoskeleton Coupled with a Musculoskeletal Model via Deep Reinforcement Learning.“ (under review)

The Complete Picture

- **Reinforcement Learning paradigm** together with **simulation environment** developed a torque control policy for walking assistance

- Our Trained Control Policy is:
  1. **Alleviates** need for human intensive testing
  2. **Robust** to human-exoskeleton interaction forces
  3. **Independent** of subject-specific conditions
  4. **Not subject** to myriad control parameter tuning



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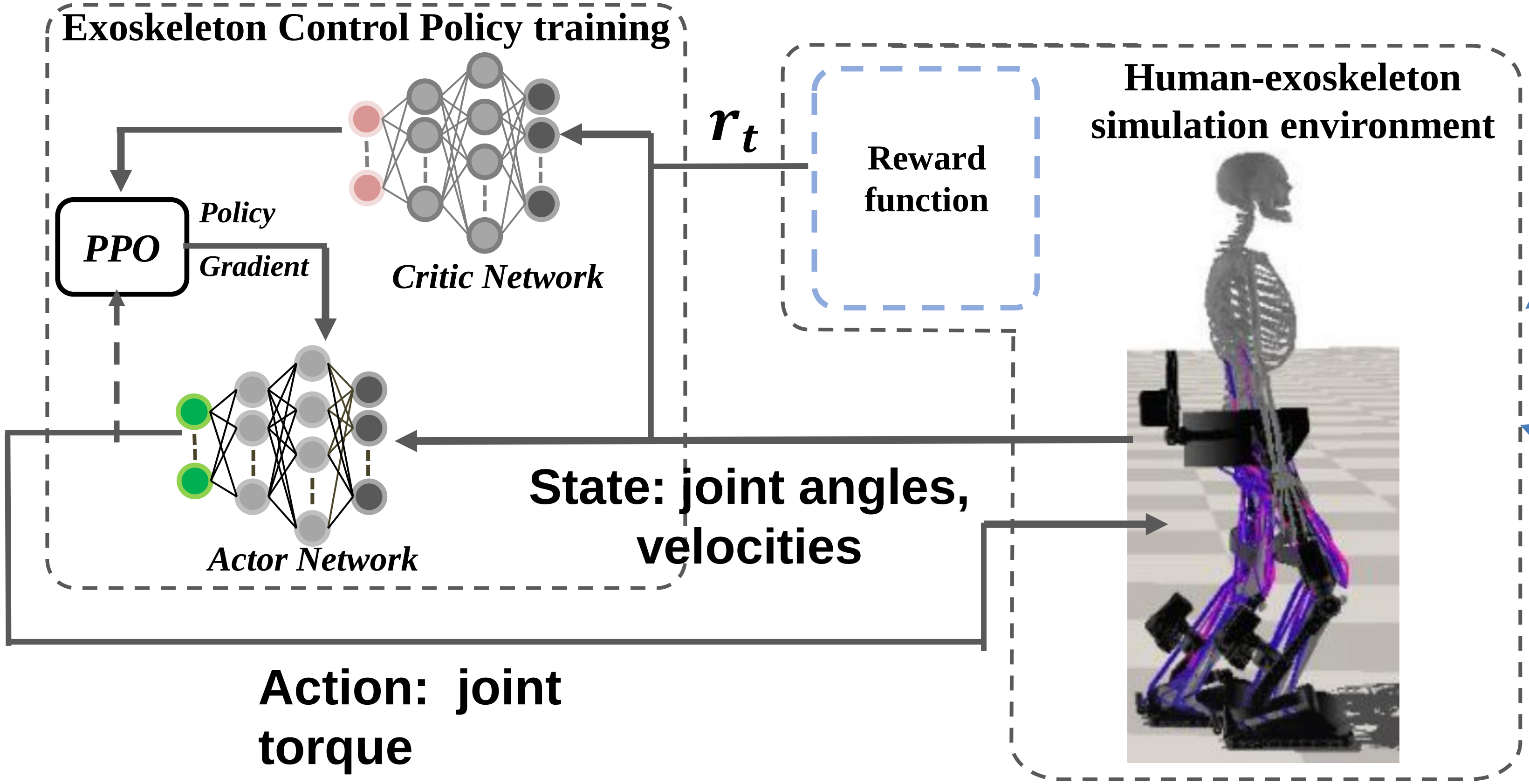
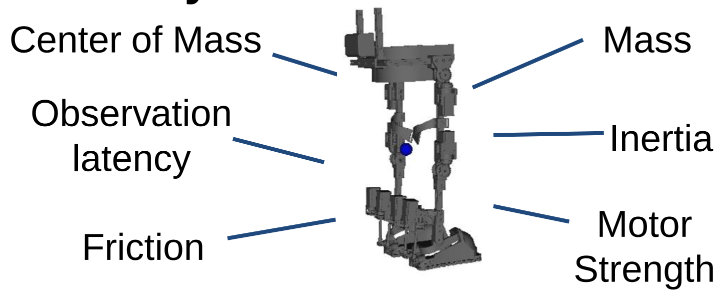
Accelerate Sim-to-Real Transfer

- Gap between simulation environment and real world degrades the performance of policies when transferred to robots
- We randomized various parameters to inject dynamic uncertainties during the training process.
- This **expedites** Sim-To-Real transfer of trained policy and **improves** robustness of control



Robot dynamics randomization:



Dynamic Parameters	Training Range	Testing Range
Friction coefficient	[0.9,1.6]*default value	[0.7,2.0]*default value
Mass	[0.8,1.2]*default value	[0.7,1.5]*default value
Motor strength	[0.8,1.2]*default value	[0.7,1.3]*default value
Observation latency	[0,0.04]s	[0,0.06]s
Inertial	[0.5,1.5]*default value	[0.4,1.6]*default value
Center of Mass	[0.9,1.2]*default value	[0.8,1.3]*default value

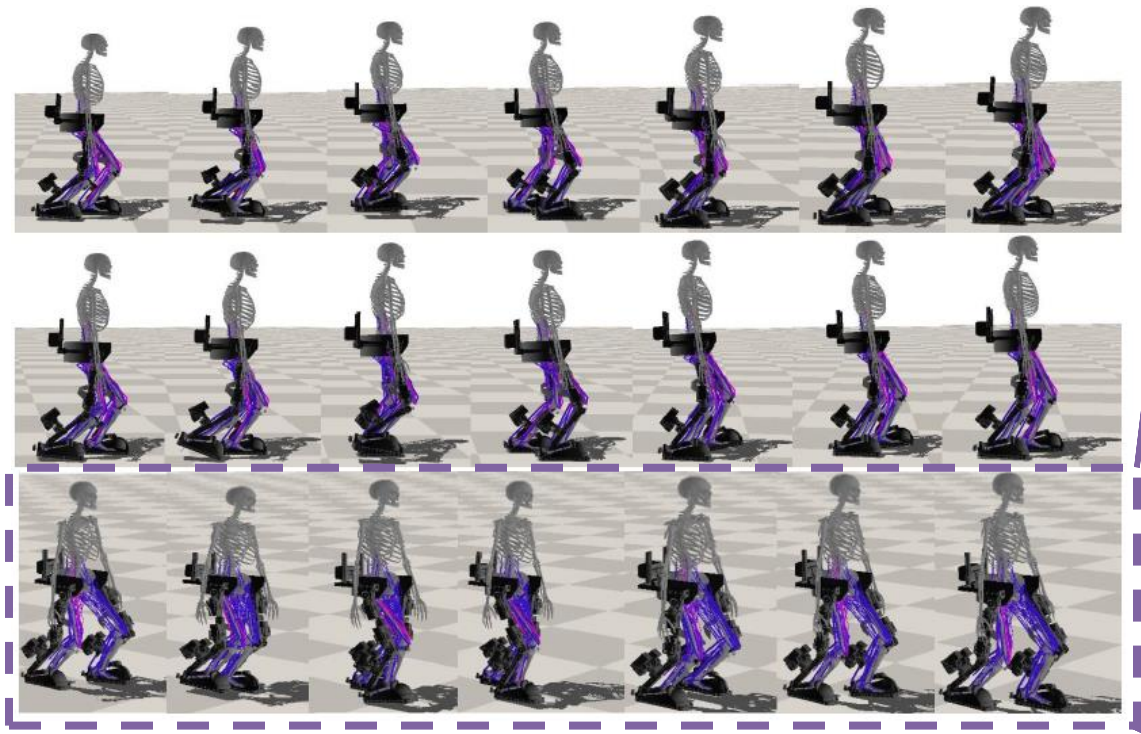
Luo, Shuzhen, Ghaith Androwis, Sergei Adamovich, **Hao Su**, Erick Nunez, and Xianlian Zhou. "Reinforcement Learning and Control of a Lower Extremity Exoskeleton for Squat Assistance." *Frontiers in Robotics and AI* 8 (2021).

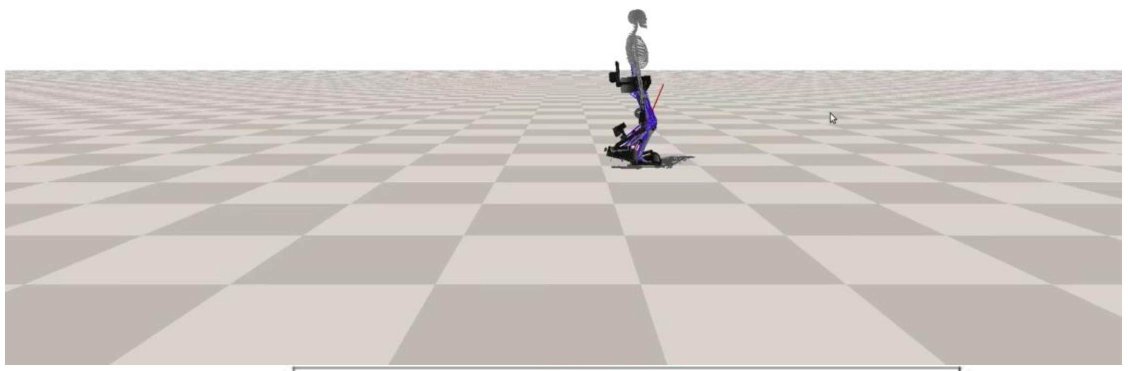
Single Control Policy Handles Varying Conditions

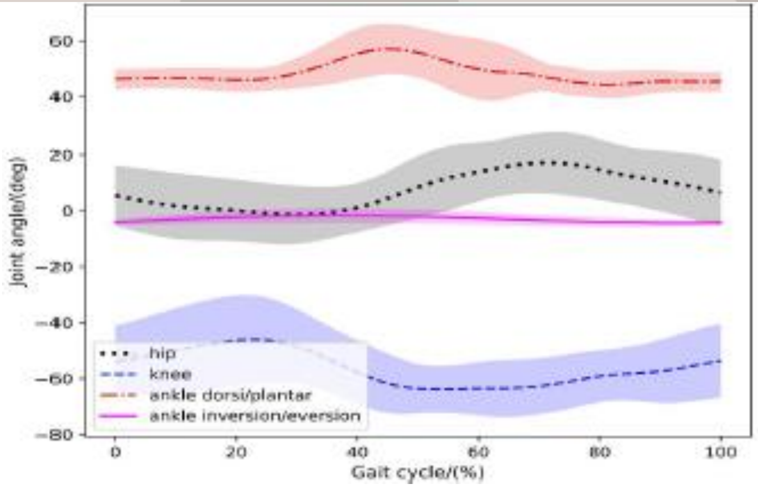
Controller is **robust** to varying conditions:

a) Healthy human
b) Human with weak muscles
c) Human with left hemiparesis

a)
b)
c)







- Shuzhen Luo, Androwis Ghaith, Adamovich Sergei, Erick Nunez, **Hao Su**, and Xianlian Zhou. "Robust Walking Control of a Lower Limb Rehabilitation Exoskeleton Coupled with a Musculoskeletal Model via Deep Reinforcement Learning (under review)

Soft Robots for and as Medicine to Empower Humanity

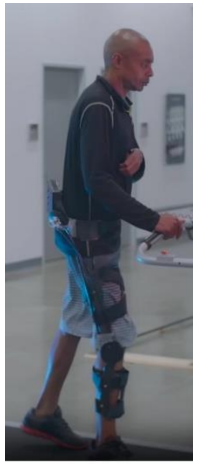
Hao Su

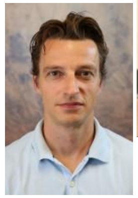
Director of Lab of Biomechatronics and Intelligent Robotics

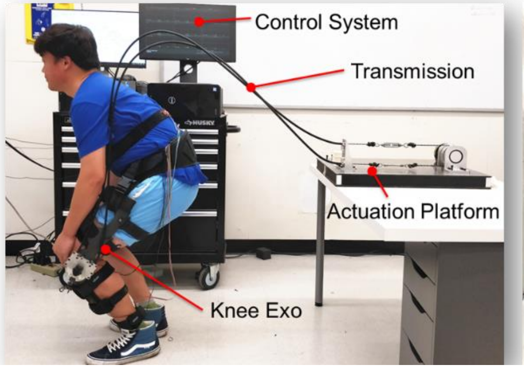
https://haosu-robotics.github.io

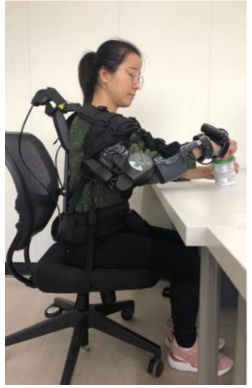
Mechanical and Aerospace Engineering

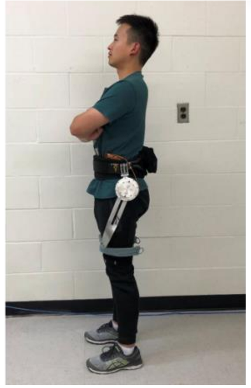
North Carolina State University (NCSU)











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