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# Learning in Simulation for Autonomous Control of Wearable Robots, and Surgical Robots

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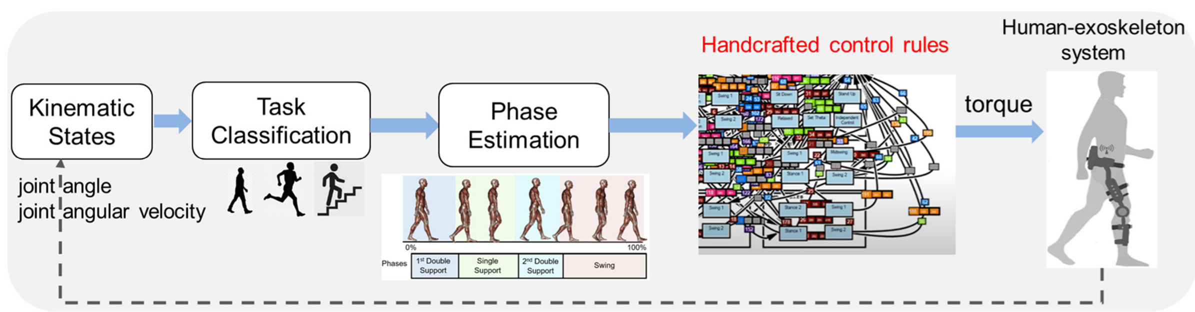
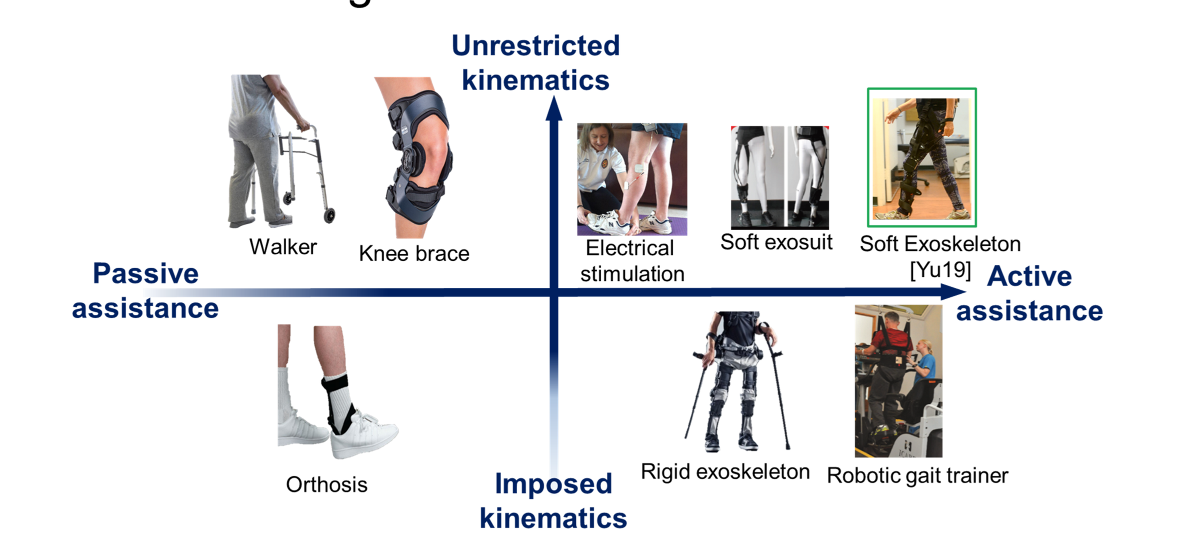
## Objectives and Challenges

- Wearable robots like lower-limb exoskeletons have great potential for mobility restoration and human augmentation
- Challenge 1: Required intensive human testing
- Challenge 2: Required handcrafted control laws

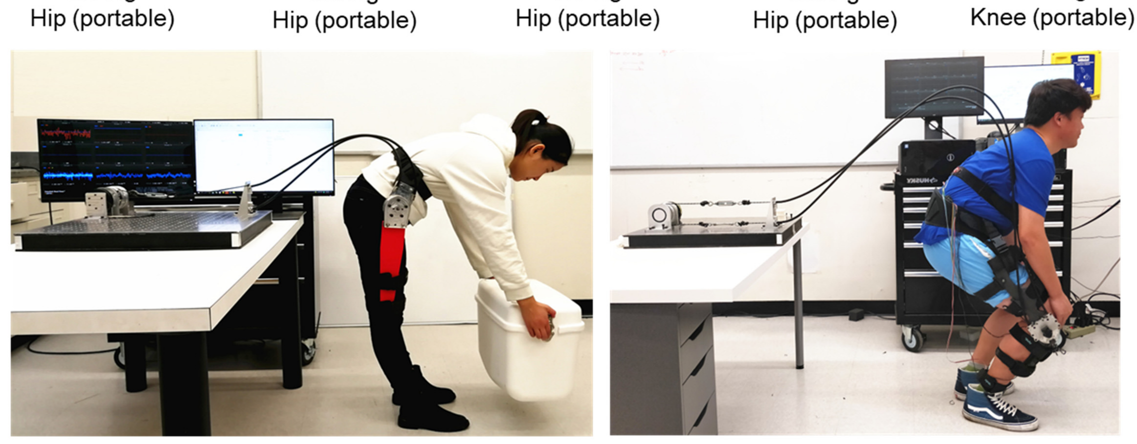



## Designing Lightweight and High Torque Soft Exoskeletons

### Advantages of Our Soft Exoskeleton




Omni-Hip12: 12 Nm peak torque, 2.3 Kg, Hip (portable)
Omni-Hip18: 18 Nm peak torque, 3.0 Kg, Hip (portable)
Omni-Hip28: 28 Nm peak torque, 3.6 Kg, Hip (portable)
Omni-Hip40: 40 Nm peak torque, 3.8 Kg, Hip (portable)
Omni-Knee18: 18 Nm peak torque, 3.0 Kg, Knee (portable)

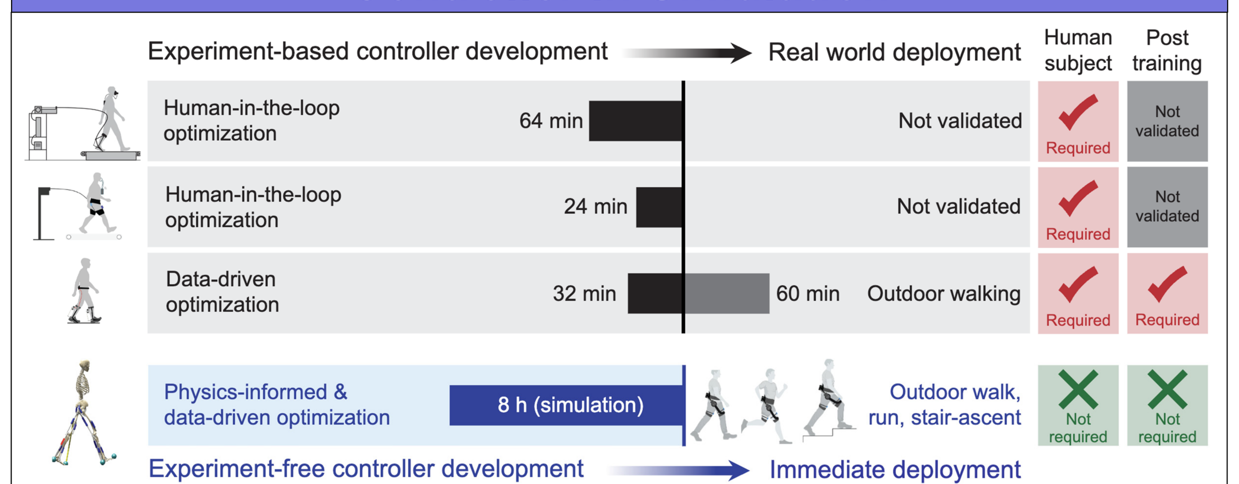


Omni-Hip72: 72 Nm peak torque, Hip (tethered)
Omni-Knee72: 72 Nm peak torque, Knee (tethered)

## Quasi Direct Drive Actuation Paradigm

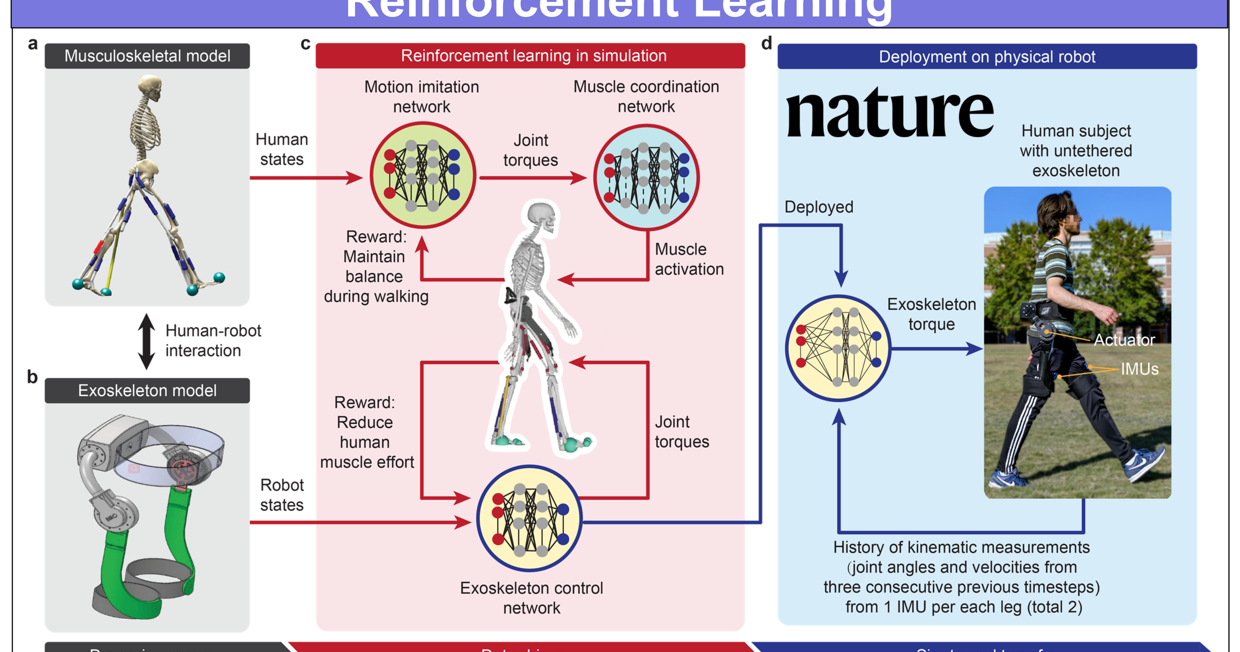
| | Geared Motor with Force/Torque Sensor | Series Elastic Actuator | Quasi Direct Drive Actuator [Ours] |
|---|---|---|---|
| Compliance | Low ✗ | Medium ~ | High ✓ |
| Bandwidth | High ✓ | Low ✗ | High ✓ |
| Efficiency | Low ✗ | Medium ~ | High ✓ |
| Actuation Paradigm | High ratio gear; Conventional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

## Experiment-free Learning of Exoskeleton Controller In Simulation




- Drawbacks of state-of-the-art methods to get exoskeleton controllers:
  - Requires intensive human experiments for training → This adds formidable cost when applied to another activity or participant
  - Typically for a single activity with steady-state motion → It cannot handle versatile activities or transitions between different activities
- Learning controllers entirely in simulation eliminates the need for human experiments. However, it is still unavailable for wearable robotics community. Key challenges are:
  - Incorporating controller design in the simulation
  - Incorporating human-robot interaction in the simulation
- Proposed Solution:
  - Eliminates the need for human experiments, learns the exoskeleton controller purely from simulation, and provides immediate energetic benefit to humans
  - Provides synergistic assistance to different subjects for walking, running and stair-climbing

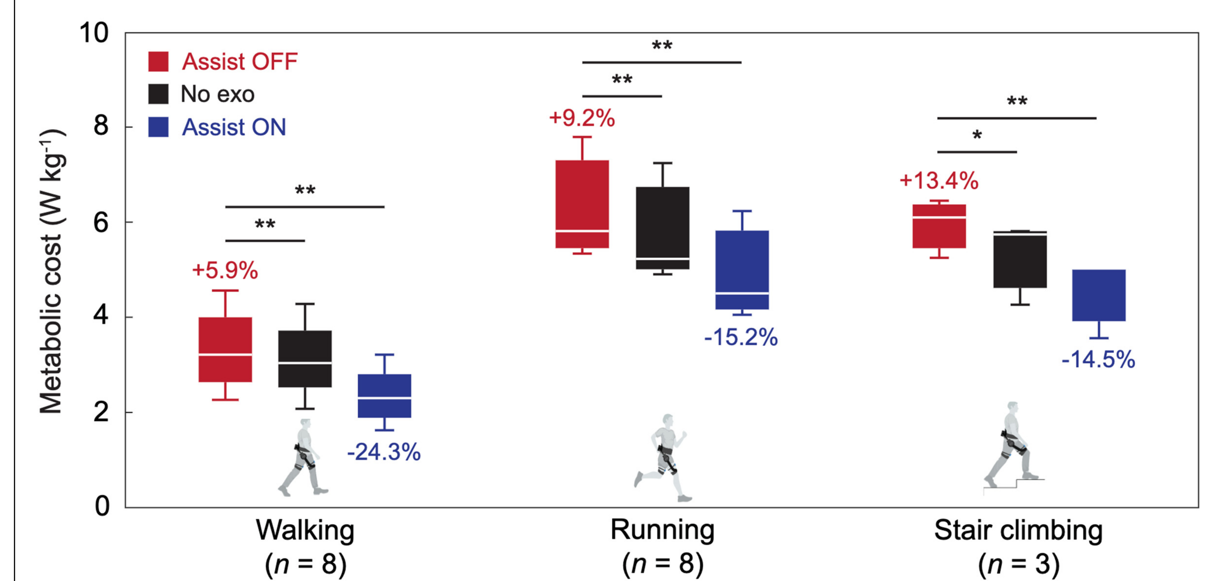
## Physics-informed And Data-driven Reinforcement Learning



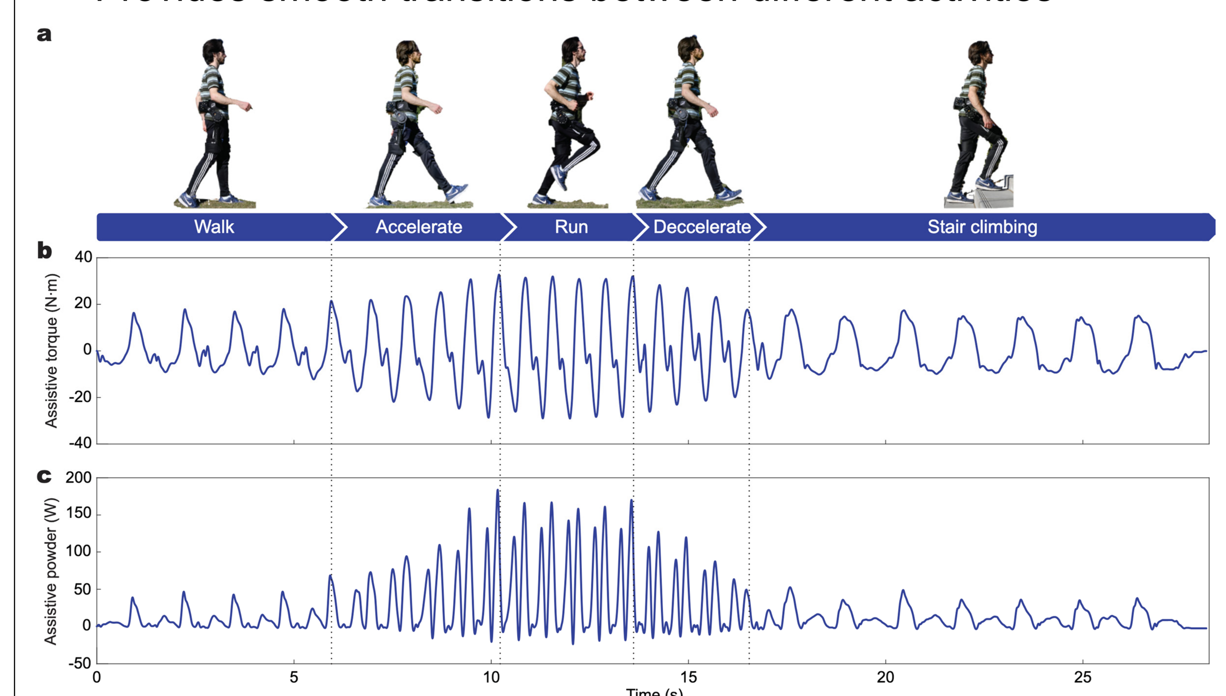

- Physics-informed modeling and data-driven learning:
  - Physics-informed modeling of human musculoskeletal dynamics, exoskeleton, and human-robot interaction
  - Data-driven learning through publicly available human kinematic motion capture dataset
- Three networks are trained simultaneously in co-evolution:
  - Motion imitation network
  - Muscle coordination network
  - Exoskeleton control network
- Dynamics randomization was used to facilitate Sim-to-real transfer of the trained control policy

## Significant Energetic Cost Reductions on Versatile Activities

- 8 human subject (5 males, 3 females) experiments utilizing a lightweight, untethered and compliant hip exoskeleton
- Reduced significant metabolic cost by 24.3% for walking, 15.2% for running, and 14.5% for stair climbing



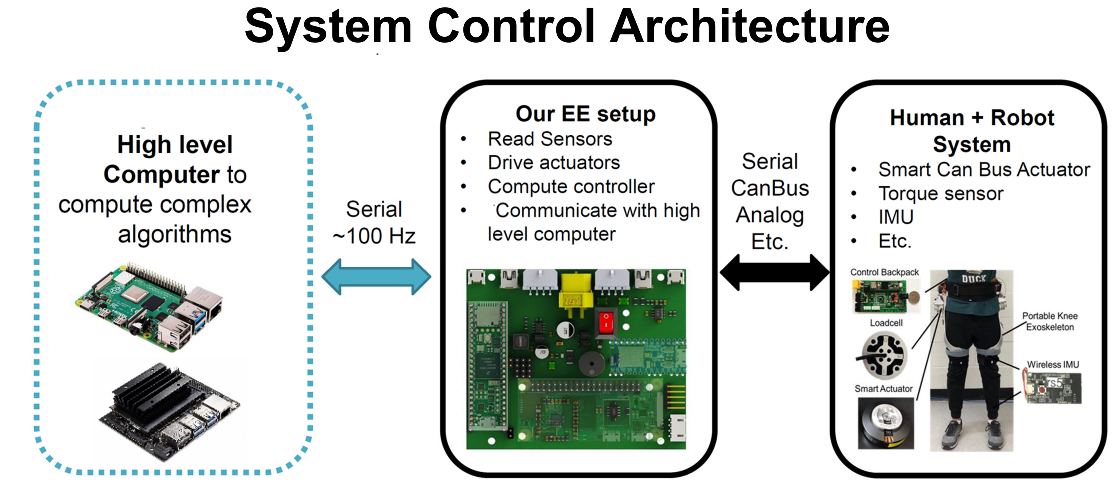

- Provides smooth transitions between different activities



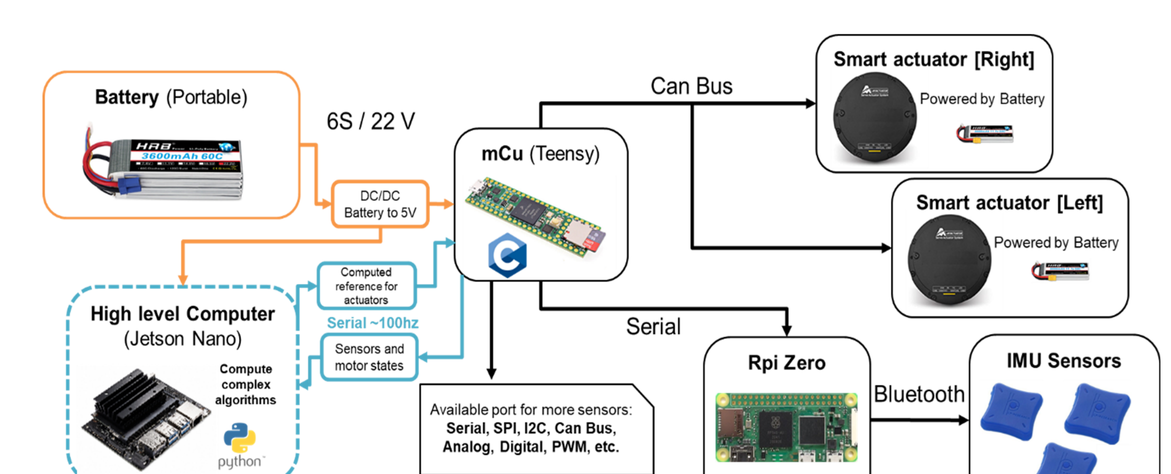

## Portable Mechatronics Architecture

- Powerful control electronics architecture using a hierarchical structure with a high-level computer and a low-level microcontroller

### System Control Architecture

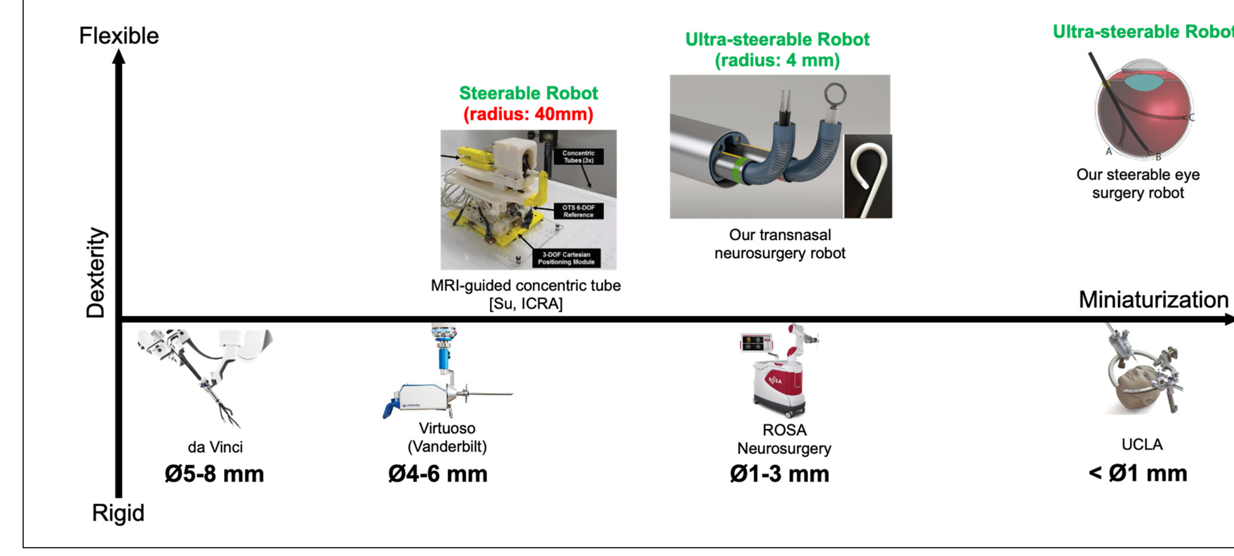



- Able to run complex control algorithms and improve speed, accuracy, and efficiency of exoskeleton's control system, leading to better performance, user comfort, and safety



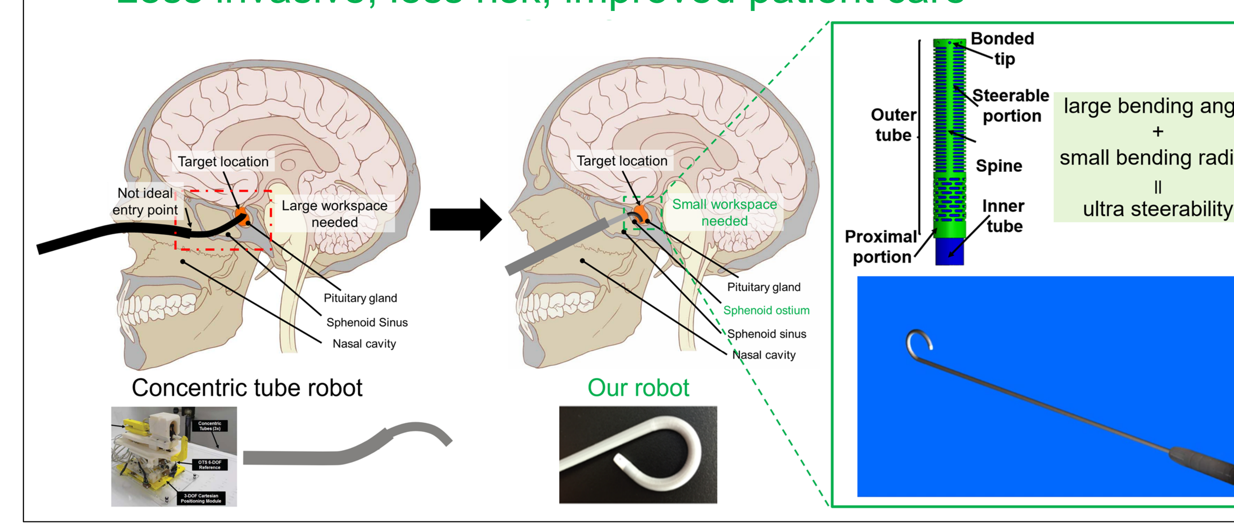

## Opportunity: Snake-like Robot for Microsurgery

- Small cavity surgery needs small robot with superb dexterity



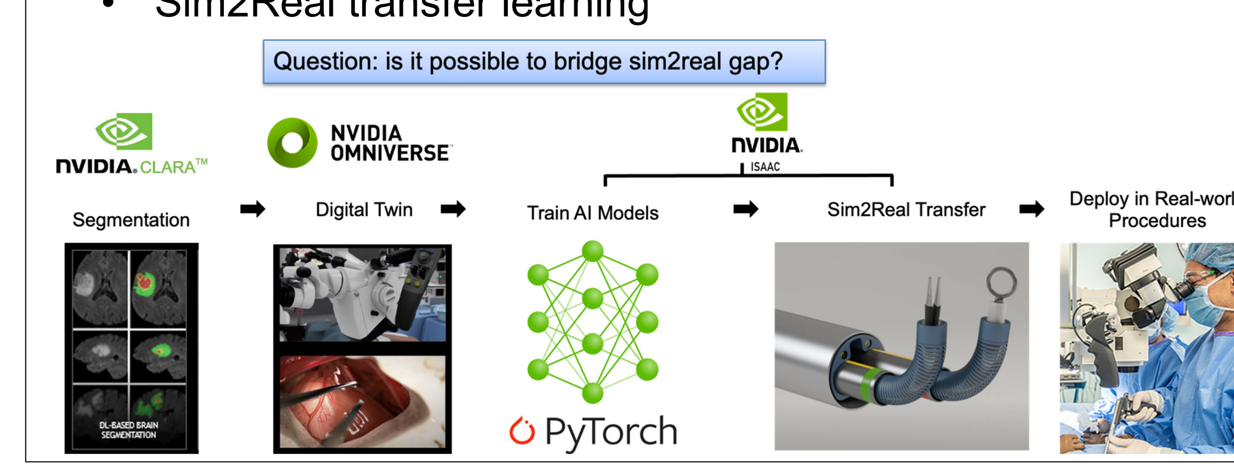

## Ultra-Steerability Enables Dexterity in Small Cavities

- Concentric tube robot: large radius, small angle
- Our robot: small radius, large angle
- Less invasive, less risk, improved patient care




## Accelerate Development of Surgical Robots via Learning in Simulation

- Robot development requires intensive human tests: digital clinical trial?
- Accelerate translation of AI-powered control into surgical procedures
  - High fidelity digital twins of human and devices
  - Sim2Real transfer learning

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