5. Project Description

BACKGROUND–In recent years, the influence of wearable exoskeletons in both fitness and clinical rehabilitation has become increasingly prominent. In the fitness domain, these devices play a crucial role in preventing sports-related injuries by activating and stabilizing muscles and joints, maintaining proper posture, and ensuring correct force distribution. This helps avoid compensatory muscle activity, which can otherwise lead to joint swelling, muscle strains, or sprains.

In clinical applications, wearable exoskeletons assist individuals with mobility impairments caused by conditions such as stroke, spinal cord injury, brain trauma, Parkinson's disease, or sarcopenia. These devices support essential movements—such as sitting, standing, squatting, and walking—allowing patients to relearn motor patterns and rebuild neural connections between the brain and muscles. This process encourages neuroplasticity, speeds up functional recovery, and boosts patient morale and motivation throughout rehabilitation.

LIMITATIONS–Traditional wearable exoskeletons generally rely on two types of control models:

1. *Fixed model parameters* – These devices are pre-programmed with basic motion templates, making them simple to deploy. However, they support only a limited range of motion scenarios (e.g., walking on flat ground), and they struggle to adapt to complex or variable terrains such as inclines or stairs. As a result, they often lack flexibility and can lead to poor human-machine coordination, increasing the risk of injury during use.
2. *Adaptive model parameters* – These systems use sensor feedback to learn from users' physiological and kinematic data over time, allowing for a more personalized and coordinated experience. While more sophisticated, these systems require extensive data collection across different terrains and activities to develop a truly adaptable model. Despite this effort, achieving comprehensive versatility and real-time adaptability for all users—especially patients with unique or rapidly changing needs—remains a significant challenge.

SOLUTION–To overcome the limitations of traditional control systems, we propose a digital twin-based framework for rapidly developing personalized control models for wearable exoskeletons, as illustrated in **Figure 1**. This approach enables the creation of highly personalized exoskeleton control models with **(1) high all-terrain versatility** and **(2) diversified movements**, thereby improving user comfort and reducing the risk of movement-related injuries.

To acquire an individual's baseline motor performance, the user first performs natural movements—such as walking—without the exoskeleton, using our lab-developed markerless motion capture (MOCAP) system (https://www.youtube.com/watch?v=za70fA9GLbw). This system requires only a few high-resolution cameras to accurately capture three-dimensional joint positions. There is no need for wearable sensors or physical markers, allowing users to complete the test in everyday clothing. This setup enables the fast, convenient, and detailed collection of user-specific kinematic data.

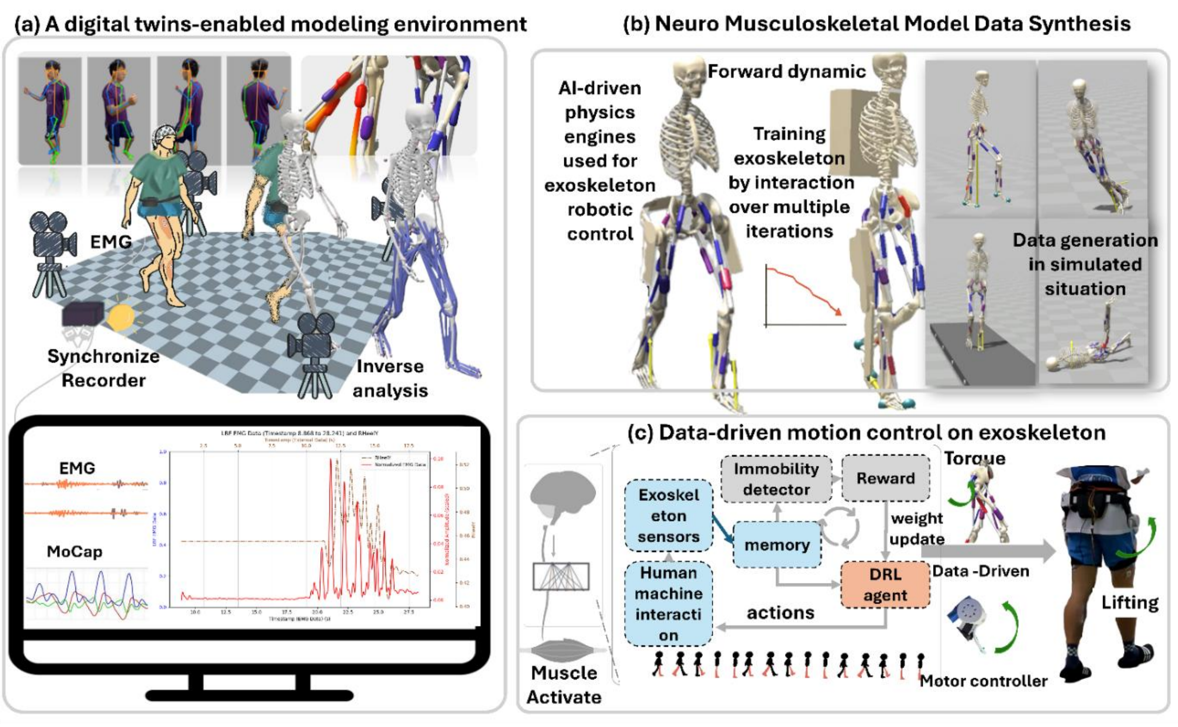

Figure 1. Overview of personalized neuro-muscular exoskeleton control system. (a) A digital twins-enabled modeling environment. Through our MOCAP and inverse analysis, an NMS model that matches the subject's fully NMS characteristics, and the movements are reconstructed on this digital twins. (b) NMS Data Synthesis. Subject movement data that was not recorded can be synthesized under different simulated scenarios in simulation. (c) Data-driven coordination of motion control on exoskeleton. Deep Reinforcement Learning (DRL) is the core of our data-driven model training framework. Once trained, the model can be deployed to real hardware.

Using these kinematic inputs, we implement digital twin technology to simulate and personalize the exoskeleton's control model. Specifically, we build a user-specific neuromusculoskeletal (NMS) model (https://www.youtube.com/@hip_exo) that virtually replicates the user's physiological characteristics. This simulation is capable of generating realistic physiological responses in diverse scenarios—such as stair climbing, walking, running, and even falling.

In parallel, we construct a digital twin of the exoskeleton itself, encompassing both its hardware and software components. This model is trained through simulation to minimize human-machine interaction (HMI) conflicts, such as unintended collisions, by adjusting the exoskeleton's motion patterns in response to the user's unique biomechanics.

All simulation results, including optimized control parameters, are transmitted through a virtual interface that mirrors the real-world exoskeleton software. This ensures that the personalized control model—now finely tuned to the user's habitual movement patterns—can be seamlessly transferred to the physical exoskeleton. As a result, users can immediately begin using a customized exoskeleton that enhances their daily mobility with improved safety, comfort, and efficiency.

APPROACH:

Exoskeleton Hardware: The hip exoskeleton system is designed to be worn over the buttocks, targeting one of the body's core muscle groups. This group includes the gluteus maximus, gluteus medius, and gluteus minimus, as well as the quadriceps, adductor longus, adductor magnus, and piriformis muscles. These muscles work closely together, along with others like the biceps femoris, to form a robust hip structure that transfers the weight of the upper body to the lower limbs, provides a wide range of motion, maintains pelvic alignment, and stabilizes the trunk.

Strong core muscles in the hip region not only enhance athletic performance but also improve and strengthen the physical functions of the general population. Whether balancing, standing, walking, or running, the strength of the hip muscles is essential. In addition to supporting pelvic and core stability, these muscles can significantly reduce the strain on the lower back during lower body activities such as aerobic exercise, running, or jumping. As the body's largest force generator, well-developed gluteal muscles enable heavier lifting, higher jumping, faster sprinting, and stronger swinging, while also helping to prevent injuries to the knees, hips, and lower back.

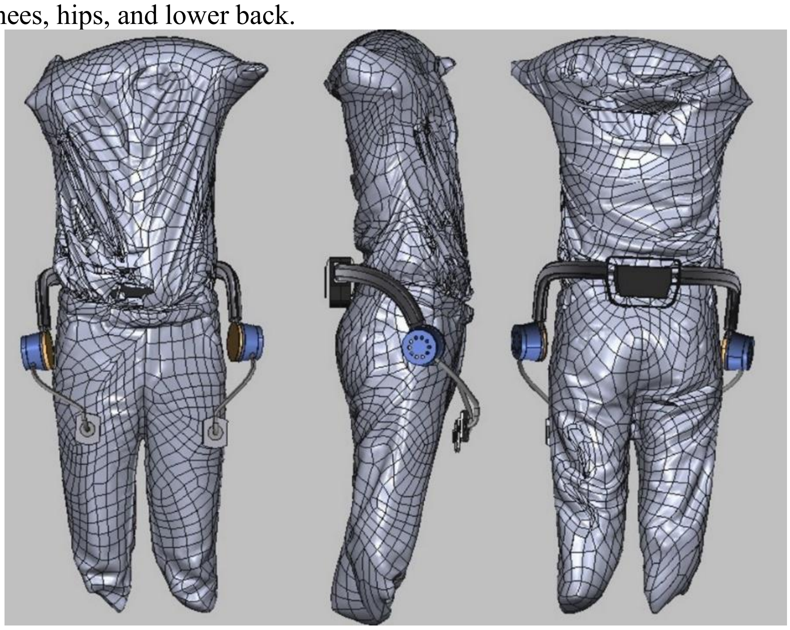

Figure 2. The hip exoskeleton device designed for this study features three degrees of rotational freedom for each hip joint, enabling it to support various movements such as gait walking, jogging, and squatting, with a primary focus on flexion and extension. The mechanism incorporates a U-shaped supporting frame, made from alloy, which houses the thigh link and allows for passive abduction and adduction rotations. A MAXON DC motor controls the flexion and extension of the hip, while the U-shaped frame, lined with soft foam for comfort, is secured to the wearer's waist with attached straps. This design ensures stability and comfort during movement, enhancing the wearer's balance and turning ability while walking. (*Data are not formally published*)

Actuators and Sensors: The hip exoskeleton will be equipped with servo motors to provide controlled assistance. Sensors will include inertial measurement units (IMUs) to monitor body posture, and electromyography (EMG) sensors placed on relevant muscle groups (e.g., quadriceps, hamstrings) to capture muscle activity. The Cygnus EMG system is a pioneering integration of software and hardware designed for enhancing exoskeleton technology through the precise capture and analysis of EMG signals. These signals, generated by muscle contractions, are accurately detected by high-sensitivity, noise-resistant sensors. The accompanying software processes these signals in real-time, translating human muscle activity into controlled exoskeleton movements for rehabilitative support or enhanced physical capabilities. This system enables a seamless connection between human intention and robotic precision, offering users improved autonomy and efficiency. The dimensions of the dongle connecting to the computer are 6.40 cm × 2.54 cm × 1.50 cm, highlighting its sleek and functional design for seamless integration with EMG systems. Conversely, the dongle that connects to the EMG wires measures 6 cm × 4.78 cm × 1.83 cm, demonstrating the system's compact and efficient component architecture. Additionally, the electrode patches, essential for capturing electromyographic signals, are square-shaped with dimensions of 3.53 cm × 3.53 cm, ensuring precise and comfortable placement on the skin.

Hardware specification	
Property	Value
Nominal Voltage	42V
Motor Nominal Torque	2 Nm
Motor Peak Torque	6 Nm
Motor Nominal Speed	1500 RPM
Gear ratio	6:1
Actuator Output Nominal Torque	16 Nm
Actuator Output Peak Torque	45 Nm
Actuator Output Speed	188 RPM
Mass (without battery)	2.6 kg
Mass (with battery)	3.4 kg
Flexion/Extension Abduction/Adduction	130°/40° 90°/60°
Actuation type	Portable
Battery life	2 hours

Figure 3. Hardware specifications and wearable setup of the hip exoskeleton system. The specification sheet outlines key performance metrics including torque, speed, and range of motion. The photographs depict the exoskeleton from front, side, and back views, demonstrating its ergonomic design and positioning on the user’s body for effective support during gait activities. (*Data are not formally published*)

To help the user maintain physical functions in daily life, the hip exoskeleton can assist in establishing a neutral spinal posture during walking. By enhancing the strength of the legs and hips, the lower body is better equipped to support the body's weight, reducing the risk of falls and maintaining exercise capabilities. This system has been designed specifically to assist lower limb movement by providing support at the hip joints, as illustrated in **Figure 2**, and corresponding hardware specification and physical human-exoskeleton setup as shown in **Figure 3**.

Digital Twin Modeling: **Figure 4** illustrates our end-to-end workflow of the proposed exoskeleton personalization framework. The process begins with data collection, where EMG signals are recorded via patch electrodes and synchronized with MOCAP trajectory data. In the inverse analysis stage, the collected data undergo preprocessing, followed by scaling, inverse kinematics, inverse dynamics, and muscle force estimation. These analyses culminate in EMG-assisted calibration of subject-specific neuromuscular models.

The calibrated model is then used for forward data synthesis, simulating diverse movement scenarios that reflect the individual's biomechanical and muscular characteristics. These synthetic data feed into an OpenAI Gym environment to train a DRL based exoskeleton controller. This environment enables iterative interaction between the synthesized digital twin and the exoskeleton control model to optimize performance.

In the final deployment stage, the trained model parameters are transferred to a real exoskeleton system (**Figure 3**). A fine-tuning step ensures accurate adaptation and optimal assistance in real-world use. This fully integrated pipeline enables rapid, accurate, and user-specific exoskeleton control with minimal human intervention.

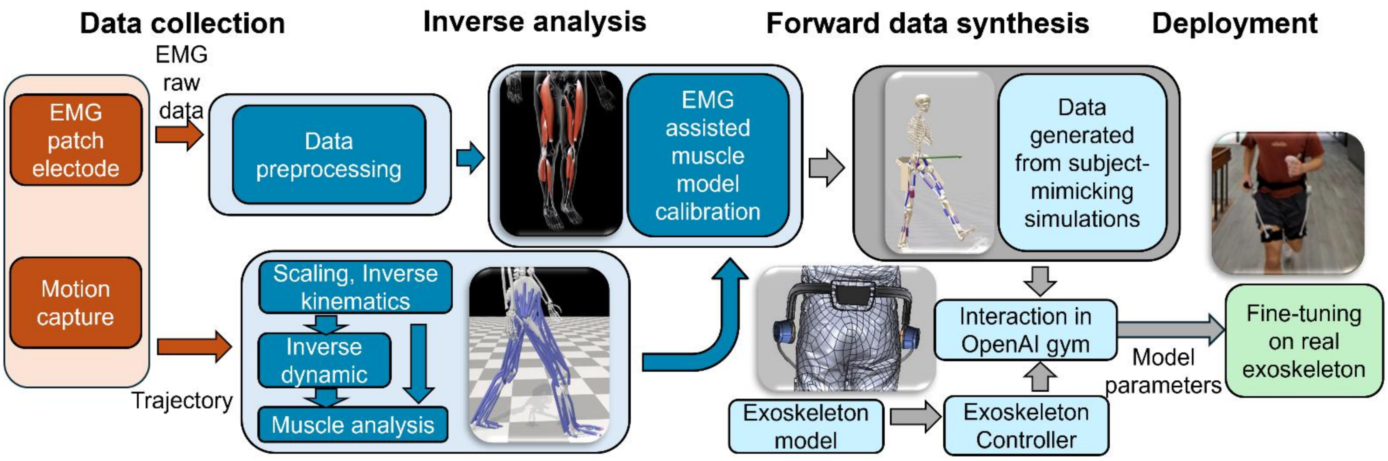

Figure 4. Overview of the digital twin-driven exoskeleton personalization pipeline. The pipeline consists of four main stages: data collection, inverse analysis, forward data synthesis, and deployment.

PRELIMINARY RESULTS:

We have preliminarily verified the system’s ability to provide personalized gait prediction and correction, even under complex pathological conditions (**Figure 5**), which underscores the critical role of incorporating NMS models for individualized control While the benefits are especially pronounced in pathological cases, the same NMS-driven framework is fully generalizable to healthy or athletic users, where it can deliver customized support aligned with habitual movement patterns or performance goals. In the final step, the MOCAP system was used to evaluate the effectiveness of motor assistance before and after deploying the digital twin-driven control model on the actual hip exoskeleton while worn by the user, as shown in **Figure 6**. The results highlight the significant improvements achieved through individualized adaptation.

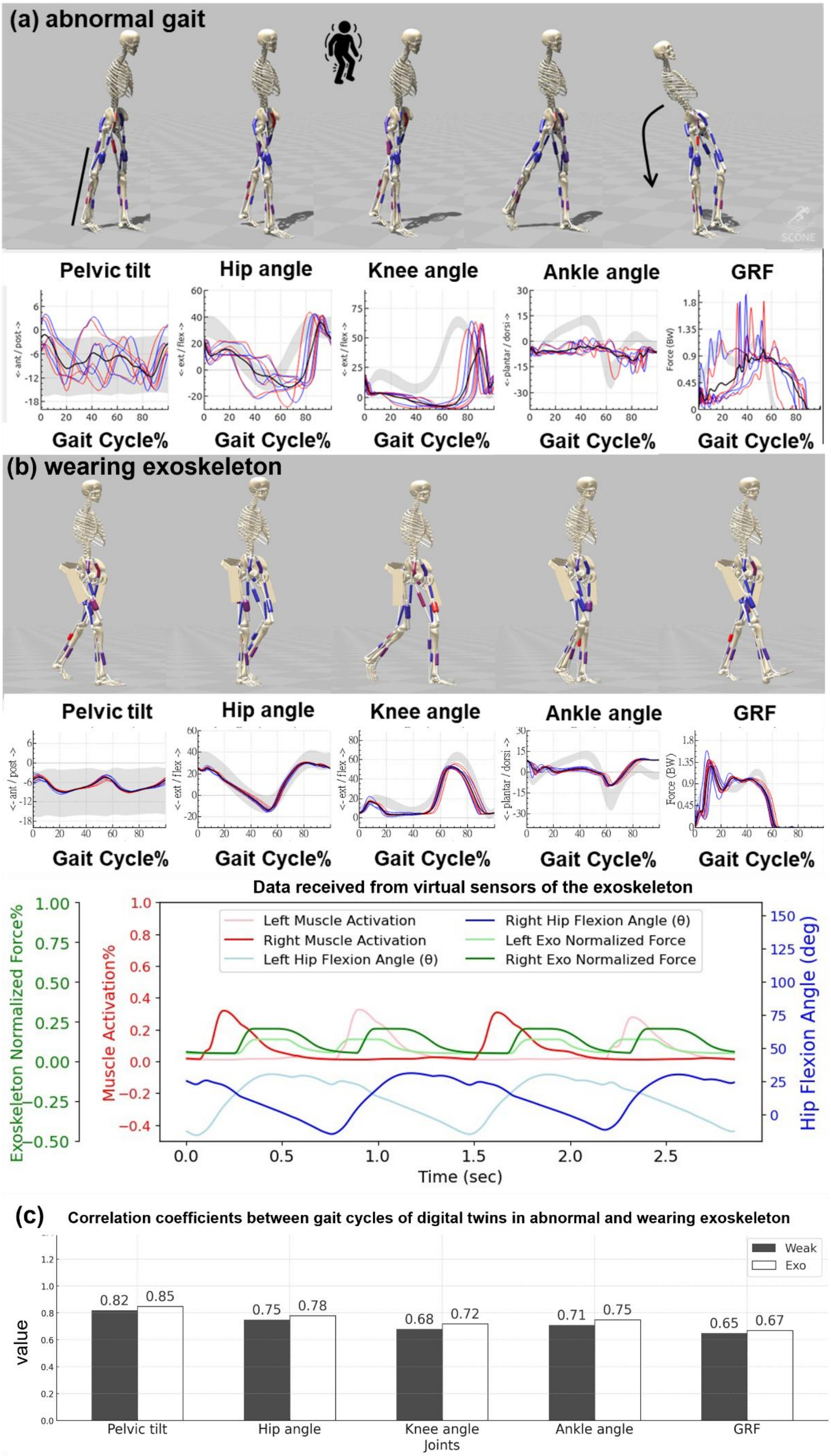

Figure 5. Personalized model tuning in simulation. (a) Abnormal gait shows initial knee stiffness, delayed movement, large step variability, and ends in a fall. (b) Wearing an exoskeleton improves gait stability significantly. The exoskeleton receives data in a virtual sensor that mirrors what would be obtained from a real exoskeleton, enabling a smooth transition from

simulation to reality. (c) We use correlation coefficients to quantify the differences between gait cycles digital twins in abnormal and wearing exoskeleton.

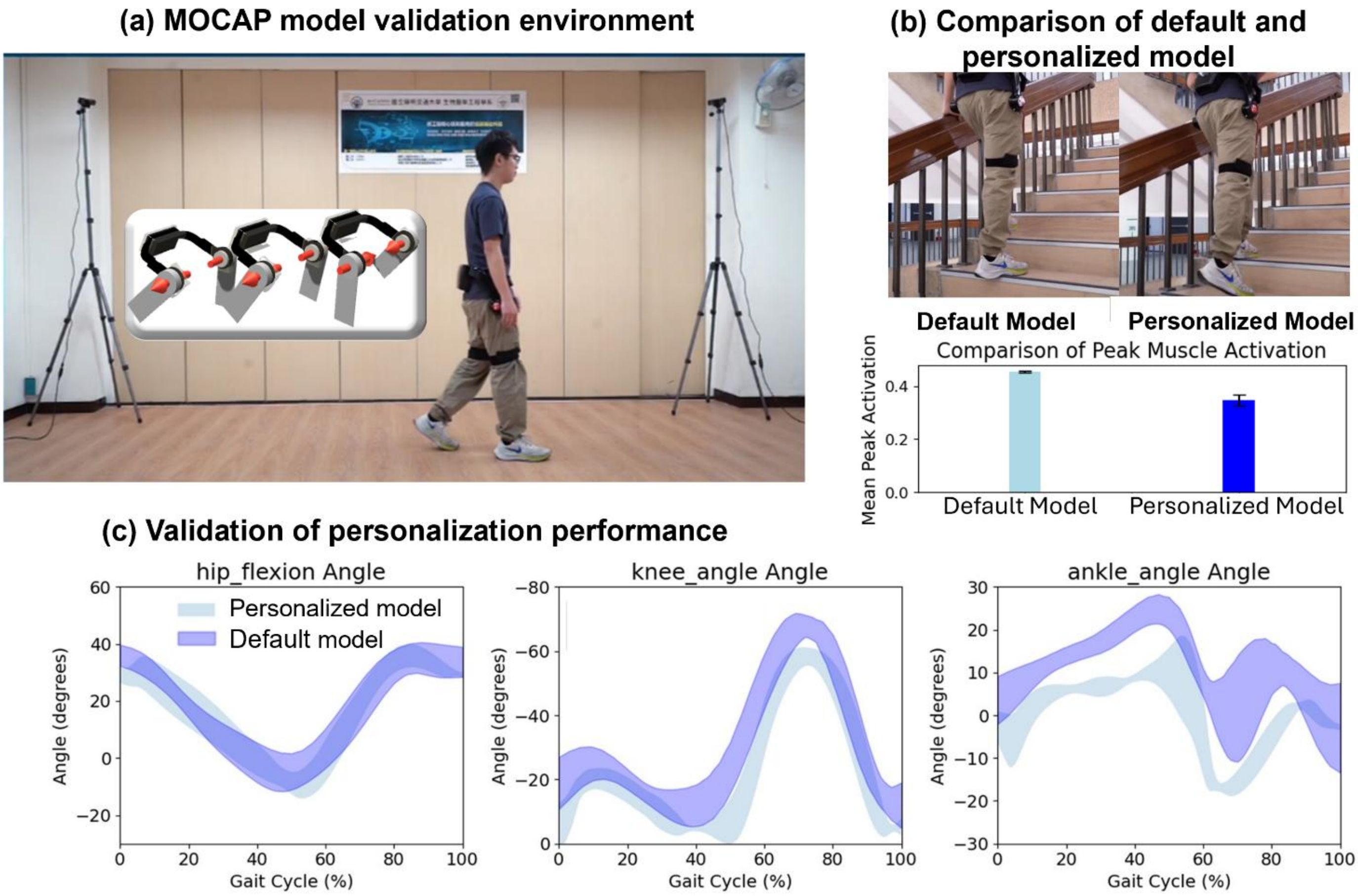

Figure 6. Validation and Comparison of Default vs. Personalized Models. (a) illustrates the MOCAP validation setup used to collect ground-truth joint trajectories during human gait. Multiple cameras track motion without requiring physical markers on the user, ensuring natural movement recording. (b) compares the default and personalized models during stair-climbing trials. The top images depict the physical setup of a subject ascending stairs, highlighting postural differences. The bar graph below shows a quantitative comparison of mean peak muscle activation between the two models. The personalized model yields significantly lower peak activations, indicating more efficient and biomechanically aligned assistance. (c) provides a detailed validation of joint angle trajectories across the gait cycle for three major joints: hip flexion, knee angle, and ankle angle. For all joints, the personalized model demonstrates reduced variance and closer alignment with physiological norms compared to the default model. The shaded regions represent variability, and the improved tracking by the personalized model confirms its superior adaptability to individual biomechanics.

CONCLUSION:

This project presents a transformative framework for exoskeleton personalization by integrating our lab-designed MOCAP system, NMS digital twin modeling, and deep reinforcement learning. Through the development of a scalable and automated simulation pipeline, the proposed system significantly reduces the barriers of HMI and manual tuning, enabling real-time, individualized control that adapts to the user's specific physiological and biomechanical traits. Our pipeline not only ensures biomechanical accuracy and user comfort but also enhances safety through model-driven actuation constraints. Preliminary validations demonstrate robust adaptability to both normal and pathological gait patterns, underscoring the system's potential for rehabilitation, mobility support, and broader real-world applications. By enabling rapid deployment and iterative personalization, our approach sets a new standard in precision assistive technology, contributing substantively to the future of human-centered wearable robotics.