5. Project Description

Objectives of the project

Personalization is critical, as it directly affects user comfort and usability—both in rehabilitation and daily applications. However, achieving this level of personalization typically requires long-term human-system interaction for data collection, resulting in extremely high cost and complexity. To address this, virtualization—specifically digital twins technology—becomes essential for lowering the personalization barrier. Instead of relying on prolonged physical calibration, digital twins allow key user-specific characteristics to be reconstructed computationally. In the field of rehabilitation, especially for wearable systems like exoskeletons that involve **human-in-the-loop control**, realistic human modeling is crucial. Such models must accurately reflect the anatomical and functional diversity across individuals to enable effective assistance and comfortable long-term wear. This need is especially urgent for elderly individuals and patients with impaired body coordination or mobility impairments due to muscle weakness or neurological disorders, who often cannot tolerate intrusive sensors or extended setup time. To meet this demand, we have developed a streamlined pipeline through which a fully personalized, assistive exoskeleton can be generated almost instantly ready to deliver targeted, biomechanically informed support.

Who are the target users

One major reason exoskeletons have not been widely adopted is the public's awareness of the vast structural and functional differences between individuals—leading to skepticism about the effectiveness of one-size-fits-all systems. Personalization is key to overcoming this barrier, especially for elderly individuals and those with impaired mobility, who often hesitate to adopt exoskeletons for rehabilitation due to their heightened vulnerability—any additional injury could severely impact their recovery or quality of life. A significant obstacle lies in the long-wear-time required for collecting calibration data in most existing systems, which is particularly burdensome for these populations. To address this challenge, we build personalized neuro-musculoskeletal (NMS) models through a non-invasive pipeline that combines markerless motion capture (MOCAP), EMG recordings, and biomechanical analysis (**Figure 1**).

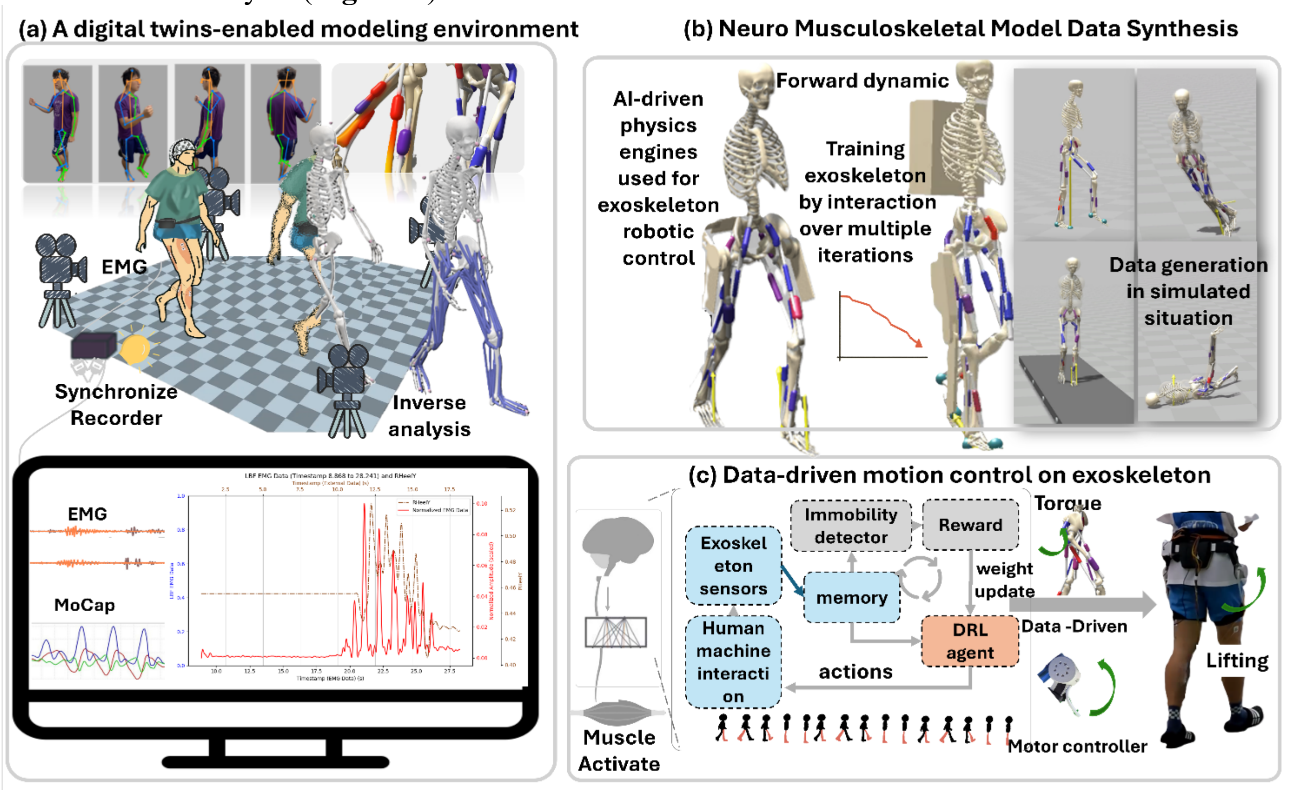


Figure 1. Overview of personalized neuro-muscular exoskeleton control system. (a) A digital

twins-enabled modeling environment Through markerless 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) Neuro Musculoskeletal Model Data Synthesis** Subject movement data that was not recorded can be synthesized under different simulated scenarios. **(c) Integrating EMG with AI MOCAP system** Analysis are operated offline on a server. **(d) Data-driven coordination of motion control on exoskeleton** DRL is the core of our data-driven exoskeleton control framework. Once trained, the model can be deployed to real hardware.

Why does the user need this

By predicting user-specific intent, our system goes beyond most existing approaches that rely on user-initiated motion and react only after movement has occurred. Powered by a personalized NMS model, the deep reinforcement learning controller actively completes movements the user may be unable—or too fatigued—to perform.

- *Proactive Exoskeleton that Predicts User-Specific Intent:* Conventional passive exoskeletons only provide structural support. Most active assistive exoskeletons still require user initiation to trigger assistance. In contrast, our system proactively predicts user-specific intent and allows more sophisticated motion.
- *Reduces the Time-Consuming User Participation Tuning:* the system leverages a virtual training environment to generate synthetic gait data across diverse conditions, eliminating the need for prolonged user participation, streamlining deployment for both clinicians and users
- *Markerless Motion Capture for Digital Twins Development in Elderly Clinical Applications:* Traditional MOCAP requires external markers and tight-fitting clothing, which can be uncomfortable for elderly individuals. In contrast, our markerless MOCAP uses AI to detect joint markers, allowing users to move naturally and freely.
- *The Role of NMS Modeling in Interpreting Diverse Human Gait, including Pathological Cases:* NMS modeling is necessary for interpreting the unique pathological neural signals of patients, allowing for accurate detection of their movement intent and enabling more precise assistance.

Feature design and technologies used

This approach consists of two major components:

- *A personalized digital twins modeling pipeline:* Through this pipeline (**Figure 2**), a NMS model is built based on markerless MOCAP, electromyography (EMG), and biomechanical inverse analysis. We further extend the model using forward dynamics to synthesize training data for different motion scenarios, including walking, stair climbing, unexpected falls due to exoskeleton misalignment, and abrupt halts, etc. This framework potentially lays the groundwork for what could be considered a virtual cerebellum — one that enables a human digital twins to move within virtual environments in a manner resembling real-world locomotion.

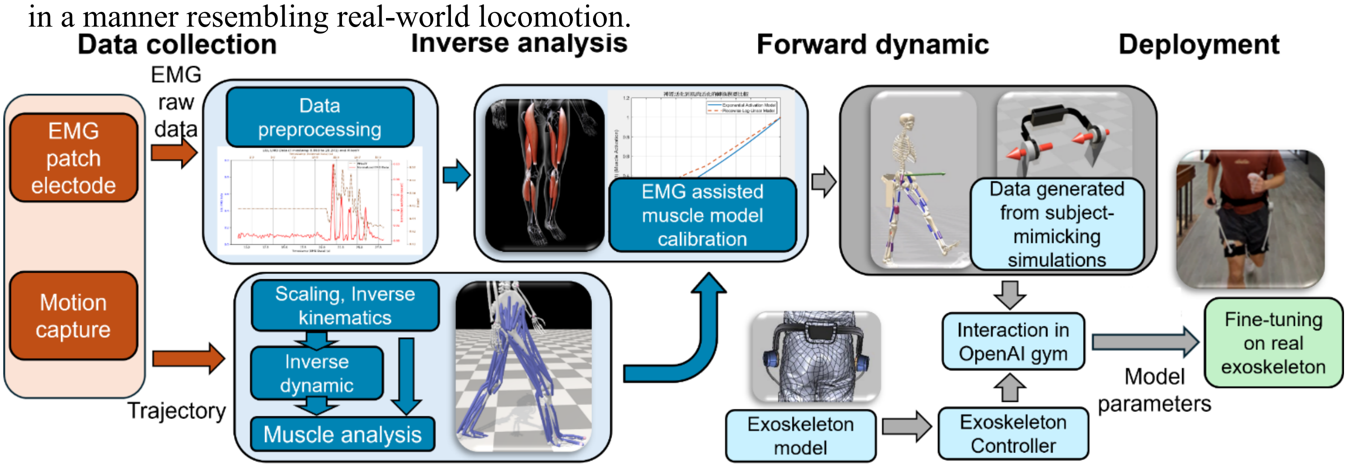


Figure 2. Pipeline of building the subject's digital twins and deploying it to an Exoskeleton. The

pipeline starts with data collection using MOCAP and EMG to track joint trajectories and muscle activation. Inverse analysis scales a generic model to the subject's biomechanics, estimating joint torques and muscle forces via inverse dynamics, muscle analysis, and EMG-assisted modeling is utilized to merge the motion and EMG outcomes. Forward dynamics simulations synthesis additional movement data, which is used to train the exoskeleton controller in a simulated environment (OpenAI Gym). Finally, the trained model parameters are fine-tuned and deployed to a real exoskeleton for effective control.

- *An DRL exoskeleton controller:* The DRL-based framework (**Figure 3**) enables fully automated training. After training, the controller is deployed on the exoskeleton hardware and fine-tuned during real-world use if still needed. This data-driven approach minimizes human-robot interaction and creates a personalized control system tailored to the individual's movement characteristics.

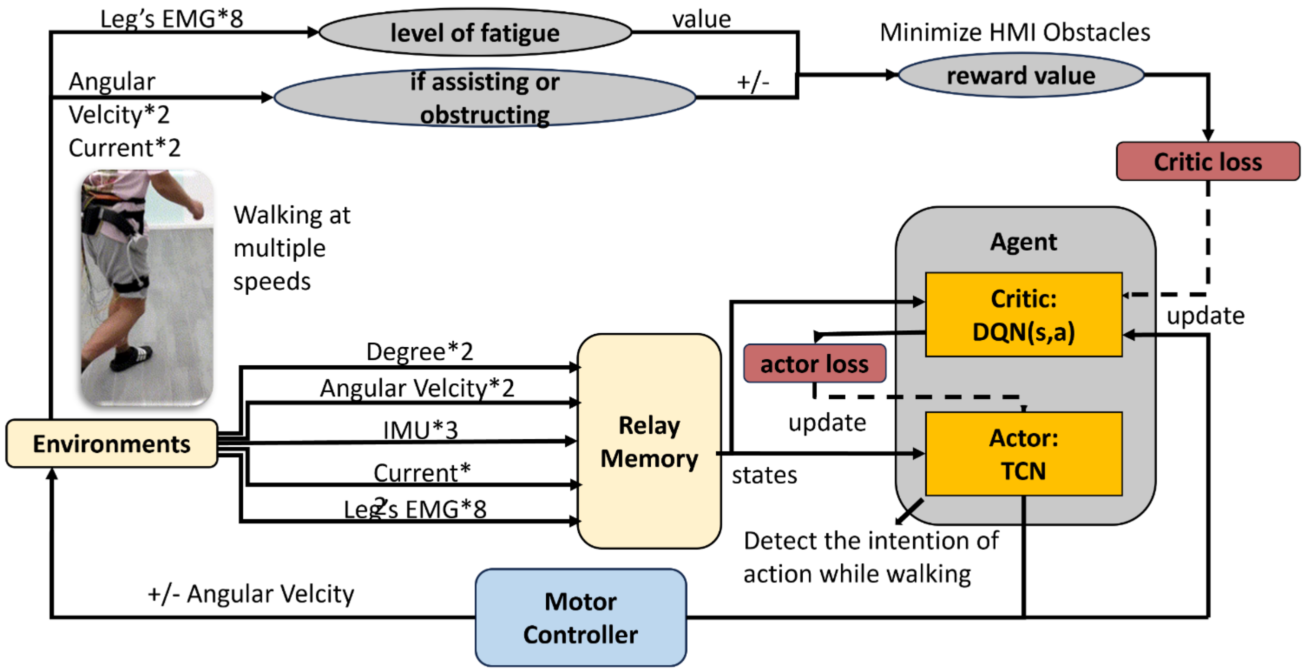


Figure 3. DRL-based Control System for Hip Exoskeleton. The system uses sensors like leg EMG, angular velocity, and IMU to monitor gait and muscle fatigue. The TCN, acting as the actor, detects the user's action intentions, while the DQN evaluates and optimizes the exoskeleton's performance in real-time. The goal is to minimize HMI obstacles by adjusting motor actions based on fatigue and the assistance's effectiveness, with continuous model updates through reinforcement learning for adaptive control.

Safety precaution

A detailed, individualized model is essential for effective assistance. By combining biomechanics, data-driven methods, AI, robotics, and training models, this project advances precision medicine. The NMS model also serves as a safety mechanism, automatically stopping the motor if force or joint angle exceeds human tolerance, ensuring safe assistance.

Preliminary Results

Our system offers general responses to a wide range of gait patterns, catering to everyone from everyday individuals to athletes, and including those with pathological gaits. We have achieved personalized solutions tailored to each individual's needs, through a well-established pipeline (**Figure 4**). **Figure 5** illustrates a more detailed process of transitioning from real-world motion to its virtual counterpart.

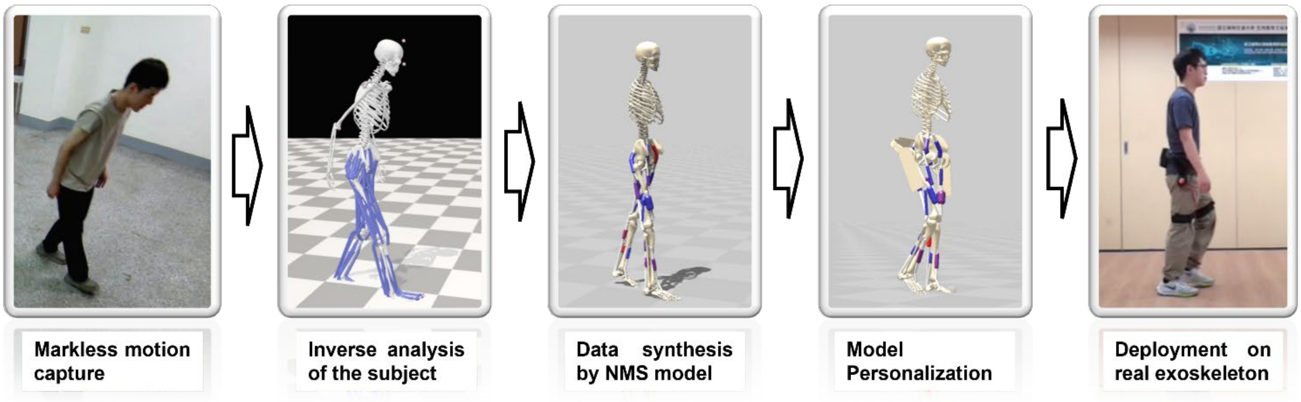


Figure 4 Implementation of a Personalized Solution Pipeline.

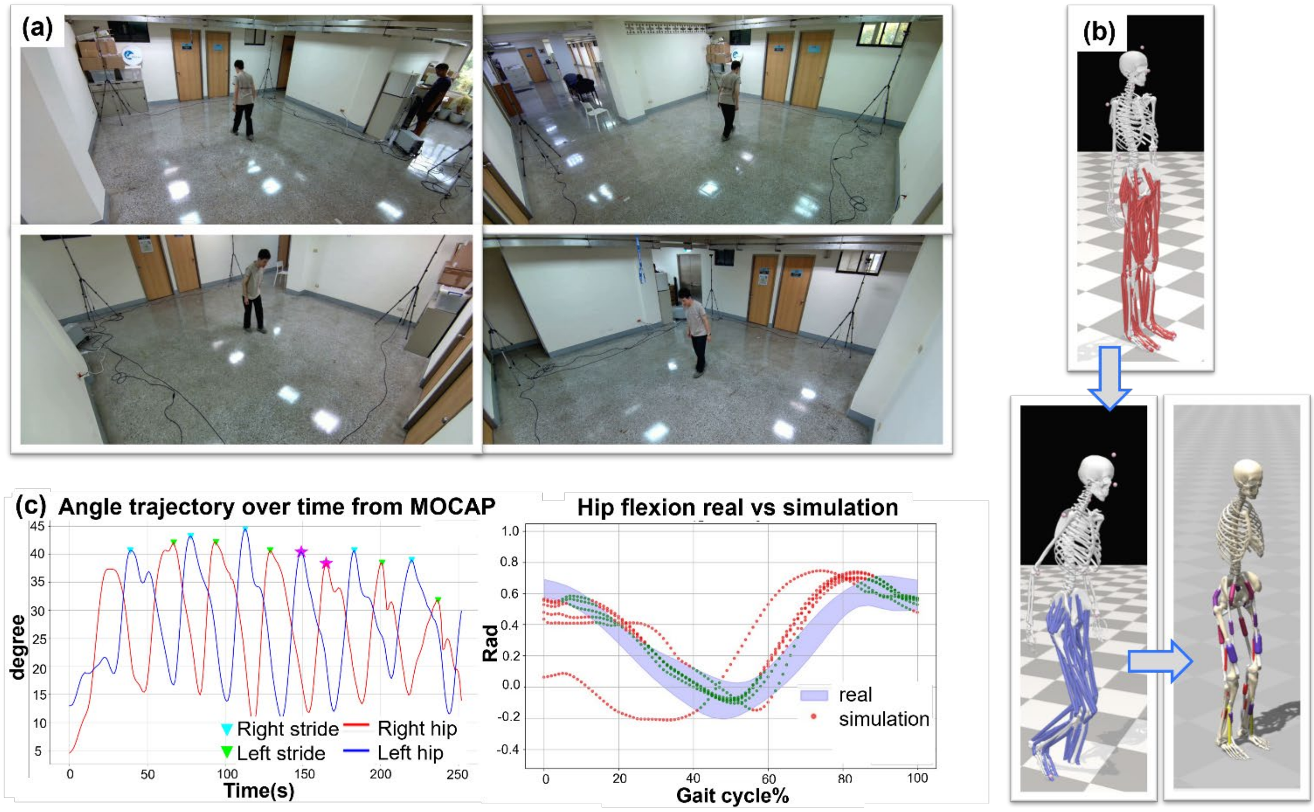
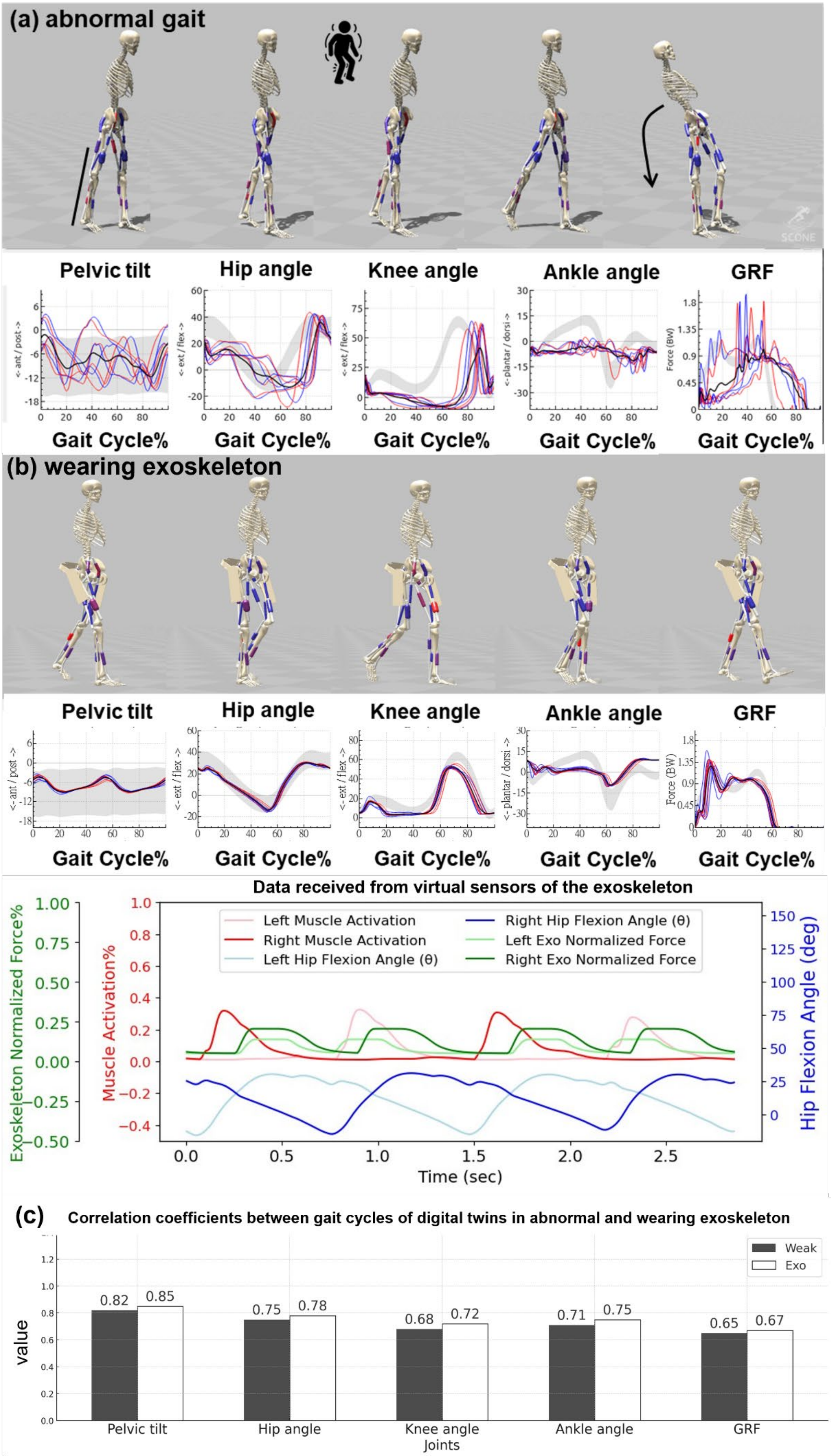


Figure 5 MOCAP-to-simulation workflow. (a) Real-world walking trials captured using markless MOCAP. (b) NMS model calibration driven by MOCAP data, embodies the subject's unique gait patterns through our tuning. (c) Angle trajectories validation between real data and simulation.

We have preliminarily verified the system's ability to provide personalized gait prediction and correction, even under complex pathological conditions (**Figure 6**). Naturally, the same framework is fully capable of adapting to general users, offering customized support, making it a universally applicable solution for improving mobility and overall well-being. In the next step, we returned to MOCAP environment and clearly observed the difference when we compared the model's assistive performance before and after personalization (**Figure 7**), highlighting the significant improvements achieved through individualized adaptation.



(a) abnormal gait
SCONE
Pelvic tilt
Hip angle
Knee angle
Ankle angle
GRF
<- ant / post ->
<- ext / flex ->
<- plantar / dorsi ->
Force (BW)
Gait Cycle%
(b) wearing exoskeleton
Pelvic tilt
Hip angle
Knee angle
Ankle angle
GRF
Gait Cycle%
Data received from virtual sensors of the exoskeleton
Left Muscle Activation
Right Muscle Activation
Left Hip Flexion Angle (θ)
Right Hip Flexion Angle (θ)
Left Exo Normalized Force
Right Exo Normalized Force
Exoskeleton Normalized Force%
Muscle Activation%
Hip Flexion Angle (deg)
Time (sec)
(c)
Correlation coefficients between gait cycles of digital twins in abnormal and wearing exoskeleton
Weak
Exo
value
0.82
0.85
0.75
0.78
0.68
0.72
0.71
0.75
0.65
0.67
Pelvic tilt
Hip angle
Knee angle
Ankle angle
GRF
Joints

Figure 6. 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 sensors 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.

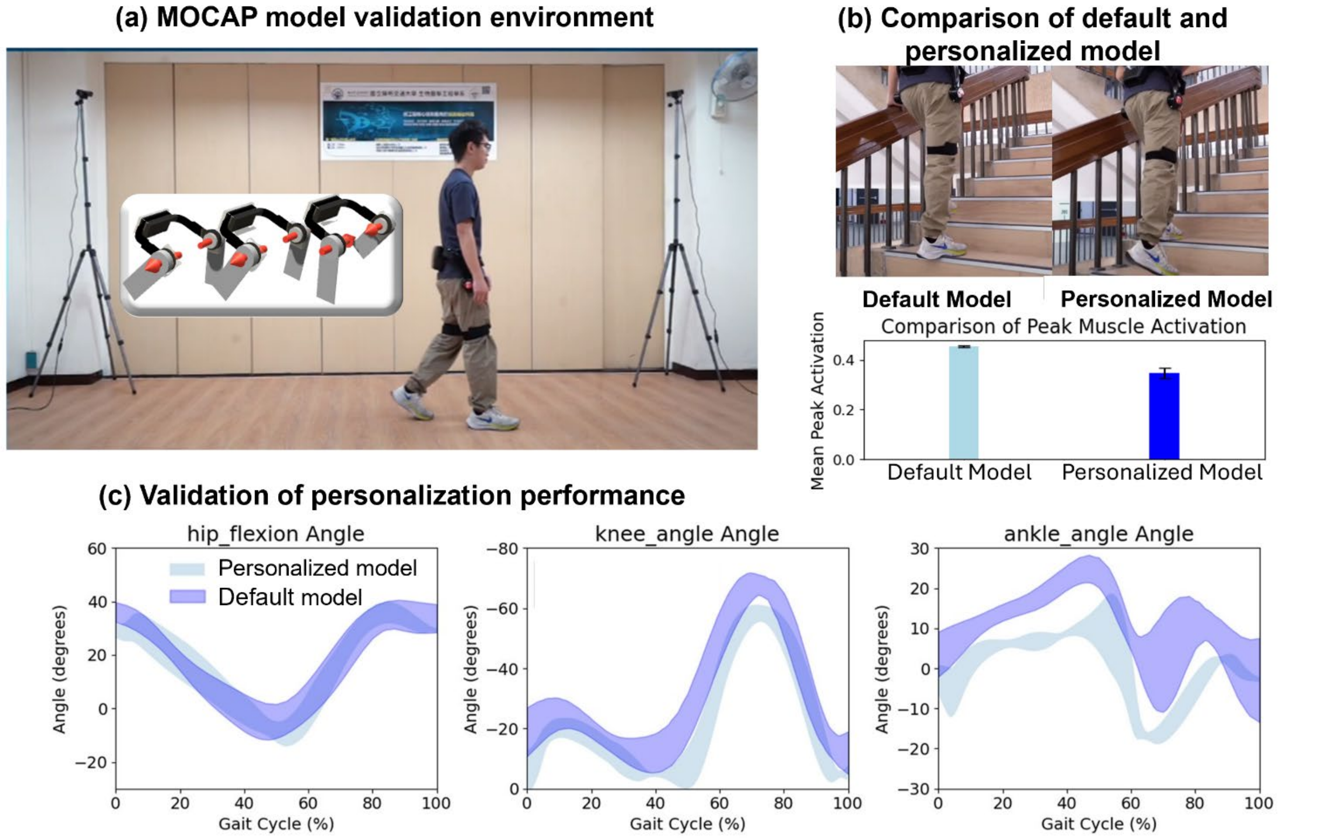


Figure 7. Validation and Comparison of Default vs. Personalized Models. (a) The MOCAP system is also used as a validation environment to assess model accuracy. (b) A clear example is observed during stair climbing: the default model required hand support, while the personalized model adapted well to the terrain. The reduction in peak muscle activation further demonstrates improved biomechanical efficiency. (c) Inverse kinematics analysis shows that the personalized model enables more fine-grained joint coordination than default model, resulting in gait patterns that better reflect individual movement habits.

This system serves as a rapid personalization tool for exoskeletons, leveraging markerless MOCAP and NMS digital twins technology to enable widespread usability. It allows exoskeletons to go beyond athletic or healthy users and address the needs of individuals with pathological conditions or undergoing rehabilitation—achieving a level of generalizability not possible with conventional systems. By combining markerless MOCAP, EMG, and biomechanical inverse analysis, we generate subject-specific NMS models without prolonged calibration. The system proactively predicts user-specific intent through an adaptive DRL framework. Preliminary results demonstrate clear performance improvements after personalization, even under complex pathological scenarios. By integrating biomechanics, AI, robotics, and simulation, this project marks a critical step toward intelligent rehabilitation and precision medicine.

Video links:
Our YouTube channel: hip_exo - YouTube
News about our system: 台團隊推 AI 無標記動作捕捉系統 助精準診斷疾病、追蹤患者狀況｜20250219 公視晚間新聞 - YouTube