IEEE SMC 2026
Bellevue, WA USA

Paper ID:775

Three-Stage WAR-BCI Control of a Lower-Limb Exoskeleton for Stroke Rehabilitation

Authors: Cong-Ying He, Kai-Hsiang Su, Ke-Wei Tung, Po-Hsun Cheng, Chia-Hsin Chen, and Li-Wei Ko

Speaker: Ke-Wei Tung

Institute of Electrical and Control Engineering
National Yang Ming Chiao Tung University

2026/10/07

Outline

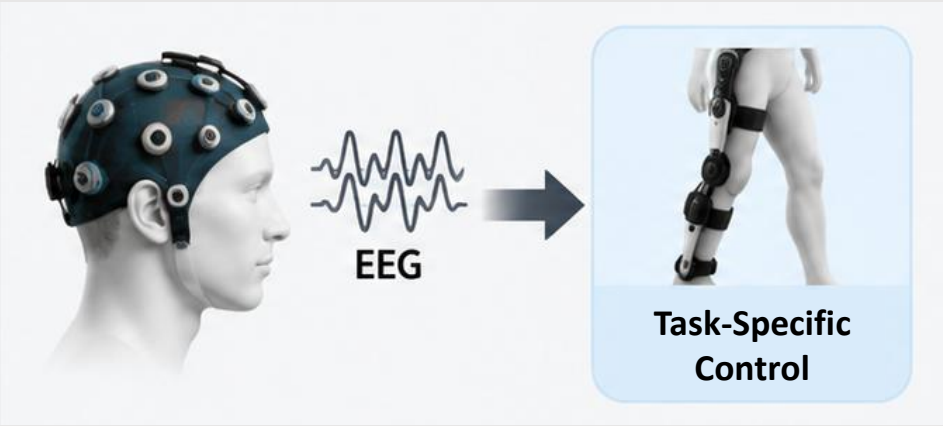
- **Introduction**
  - Stroke Rehabilitation and BCI
  - Study Aim
- **System Architecture**
  - Wearable AR-BCI Exoskeleton System
  - Three-Stage WAR-BCI Control Framework
- **Experimental Validation & Results**
  - Training Paradigm
  - Online Three-Stage Control
  - System Demonstration
  - Performance Evaluation
- **Conclusion**

Introduction

- Stroke Rehabilitation and BCI
- Study Aim

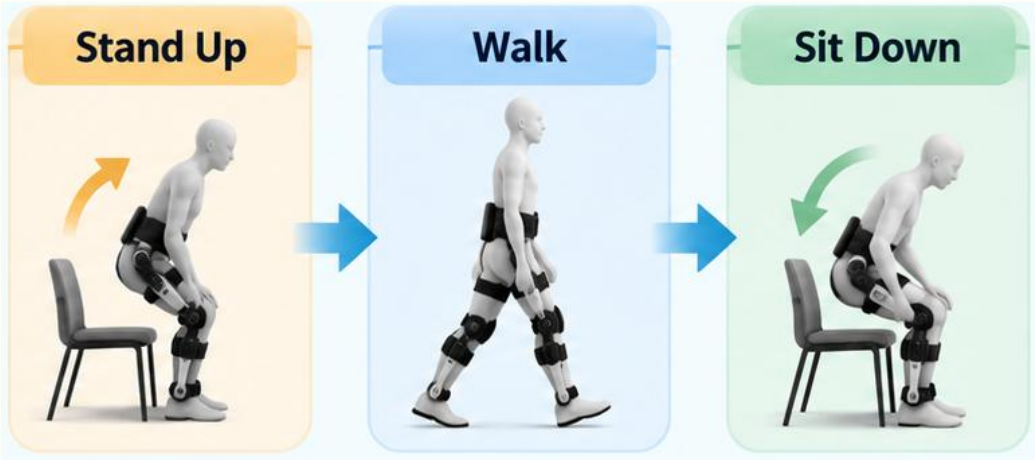
Motivation: Toward Functional Lower-Limb Rehabilitation

Task-Specific BCI Control



- Sitting and standing intention can be decoded from scalp EEG [1].
- Wearable BCI and AR have been explored for robot-based rehabilitation [2].

Sequential Functional Rehabilitation



- Functional mobility involves transitions across multiple states.
- A rehabilitation control strategy must address more than a single movement command.

Need: A unified BCI framework for sequential functional rehabilitation rather than a single movement command.

[1] T. C. Bulea, S. Prasad, A. Kilicarslan, and J. L. Contreras-Vidal, "Sitting and standing intention can be decoded from scalp EEG recorded prior to movement execution," *Frontiers in Neuroscience*, vol. 8, p. 376, 2014.
[2] P. Arpaia, L. Duraccio, N. Moccaldi, and S. Rossi, "Wearable brain–computer interface instrumentation for robot-based rehabilitation by augmented reality," *IEEE Transactions on Instrumentation and Measurement*, vol. 69, no. 9, pp. 6362–6371, 2020.

Study Aim



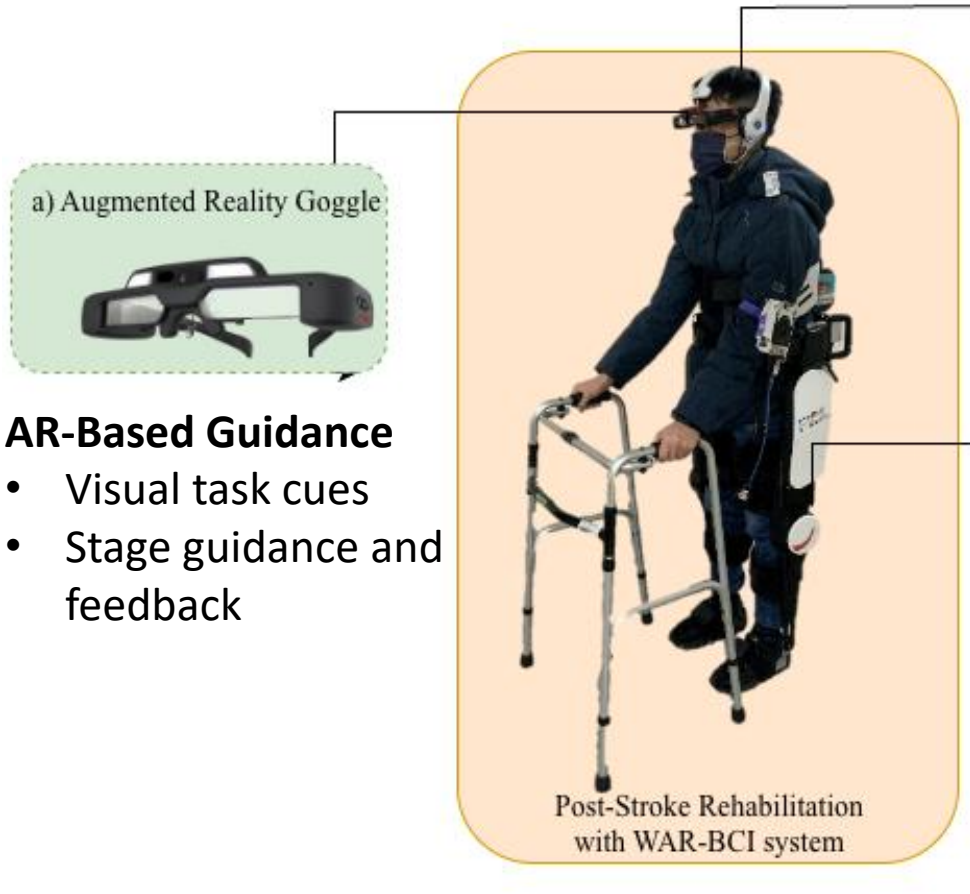
To develop a three-stage wearable AR-BCI framework for sequential lower-limb exoskeleton control for stroke rehabilitation.

1. **Sequential Control**
   Integrate **stand up, walking, and sit down** within one rehabilitation workflow.
2. **Stage-Specific EEG Decoding**
   Use different neural responses for each rehabilitation stage.
3. **Online Validation**
   Evaluate the complete control sequence in both healthy participants and stroke patients.

System Architecture

- Wearable AR-BCI Exoskeleton System
- Three-Stage WAR-BCI Control Framework

Wearable AR-BCI Exoskeleton System



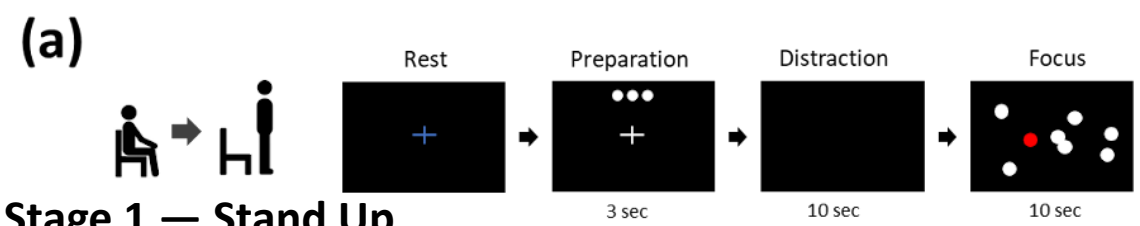
AR-Based Guidance
- Visual task cues
- Stage guidance and feedback

Wireless EEG
- 8-channel EEG acquisition
- Neural signal recording

Lower-Limb Exoskeleton
- Robotic assistance
- Lower-limb movement assistance

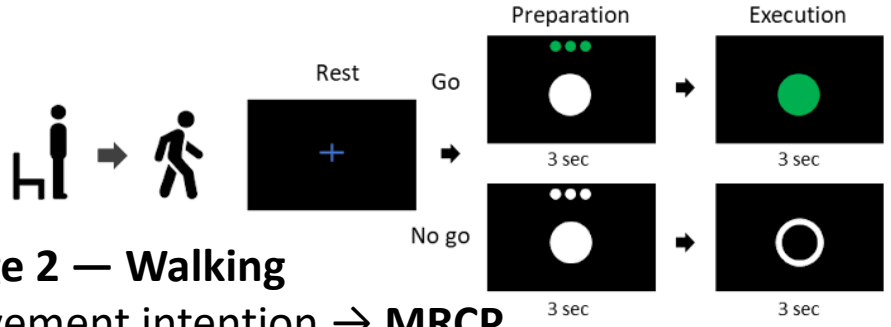
Integration of wireless EEG, AR guidance, and lower-limb robotic assistance

Three-Stage WAR-BCI Control Framework



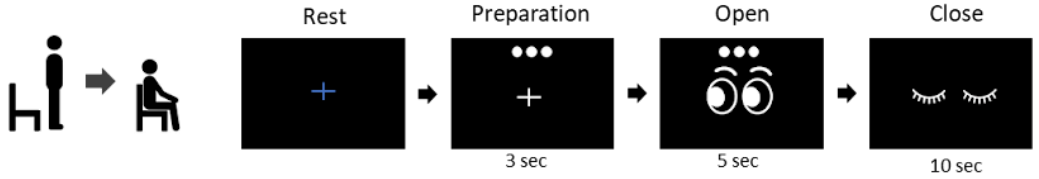
Stage 1 — Stand Up

Concentration task → **Frontal θ**



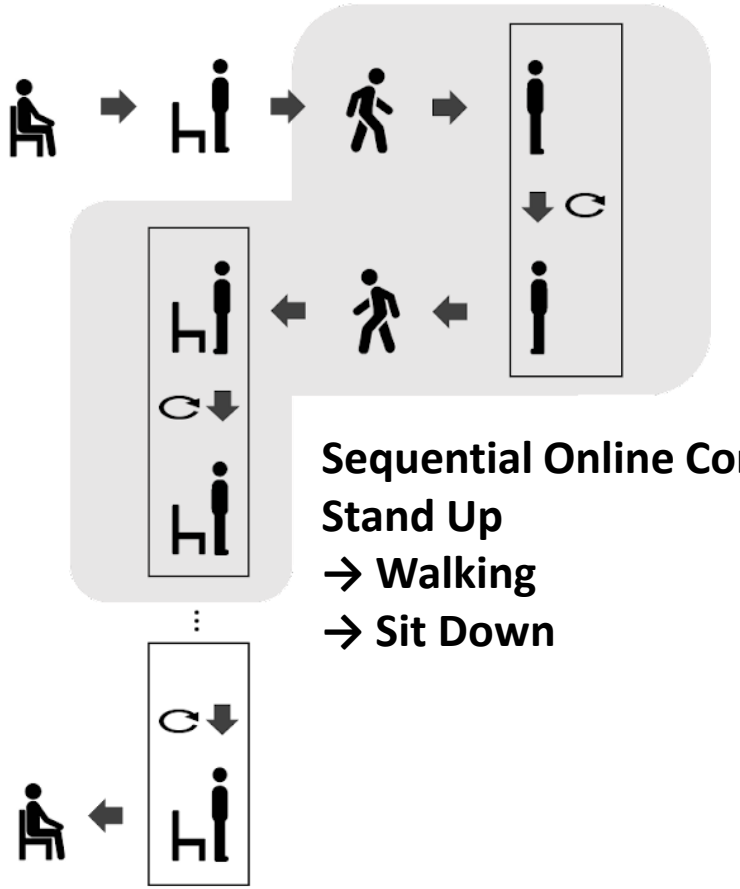
Stage 2 — Walking

Movement intention → **MRCP**



Stage 3 — Sit Down

Eyes closing task → **Occipital α**



Sequential Online Control

Stand Up

→ Walking

→ Sit Down

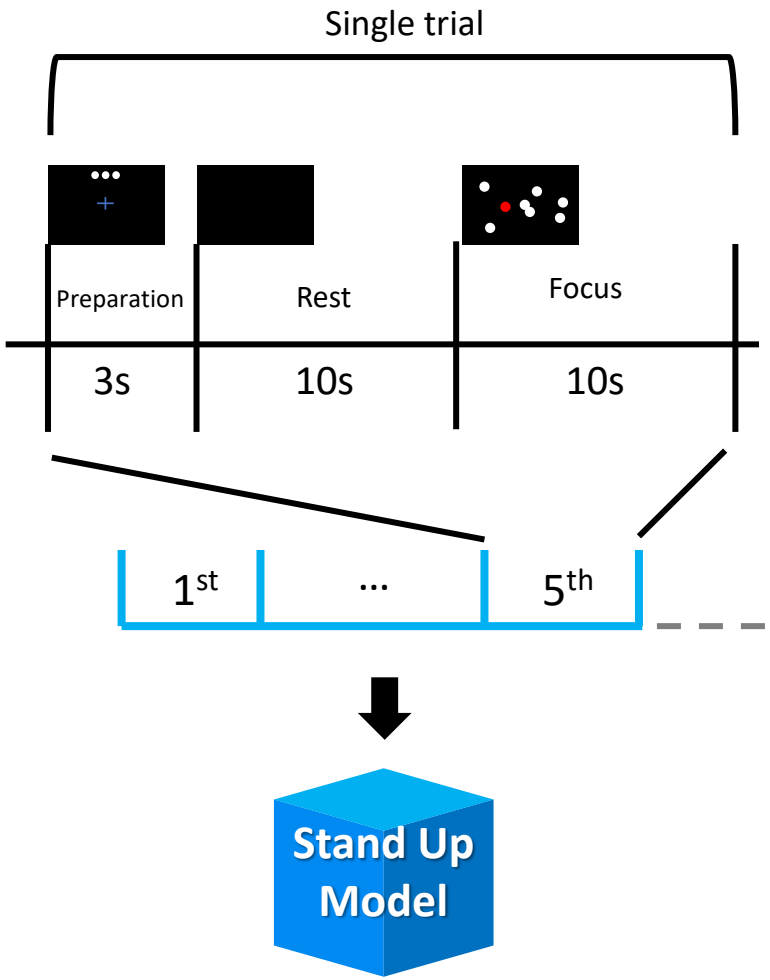
Three task-specific EEG responses enable sequential control of functional lower-limb rehabilitation.

Experimental Validation and Results

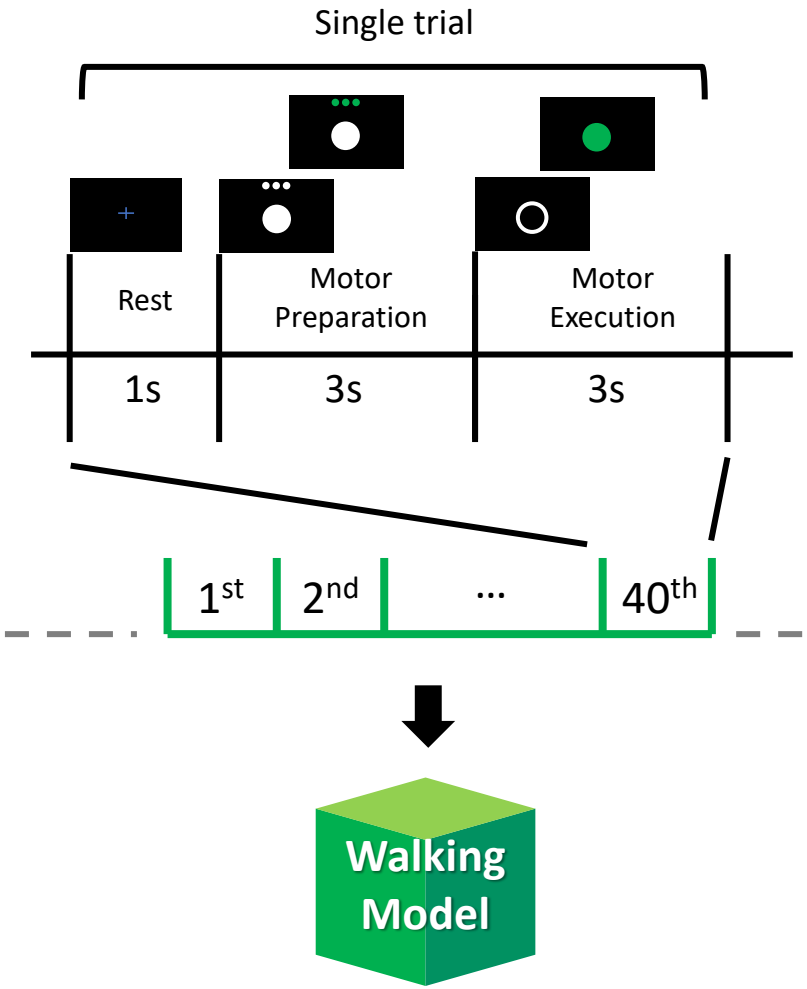
- Training Paradigm
- Online Three-Stage Control
- System Demonstration
- Performance Evaluation

Training Paradigm

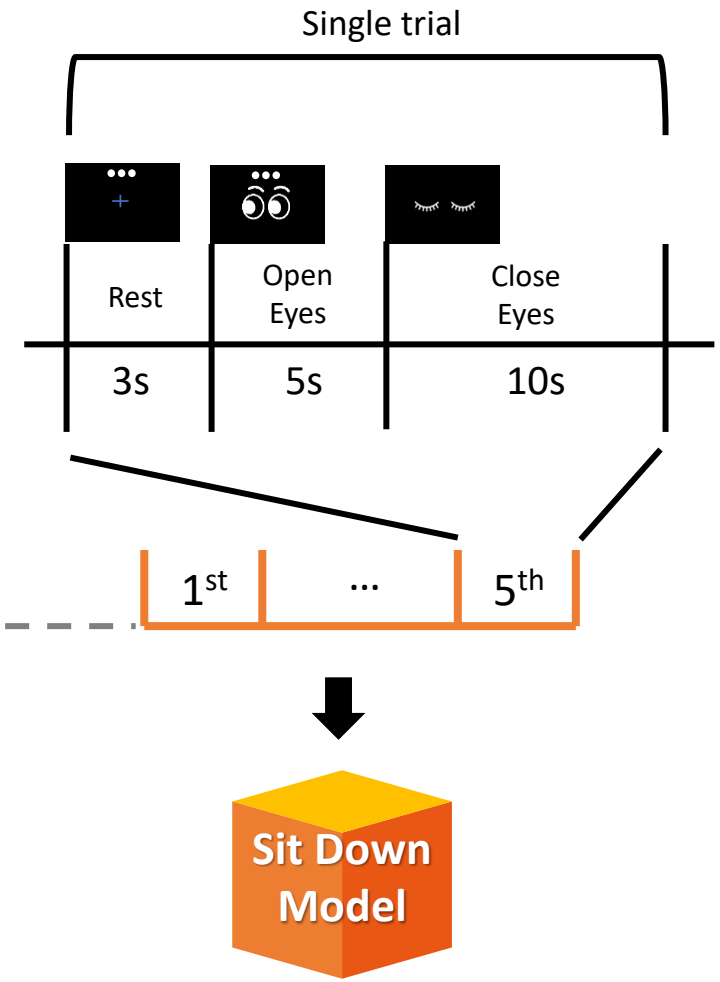
➢ **Concentration tasks (Frontal θ)**



➢ **MP-ME tasks (MRCP)**

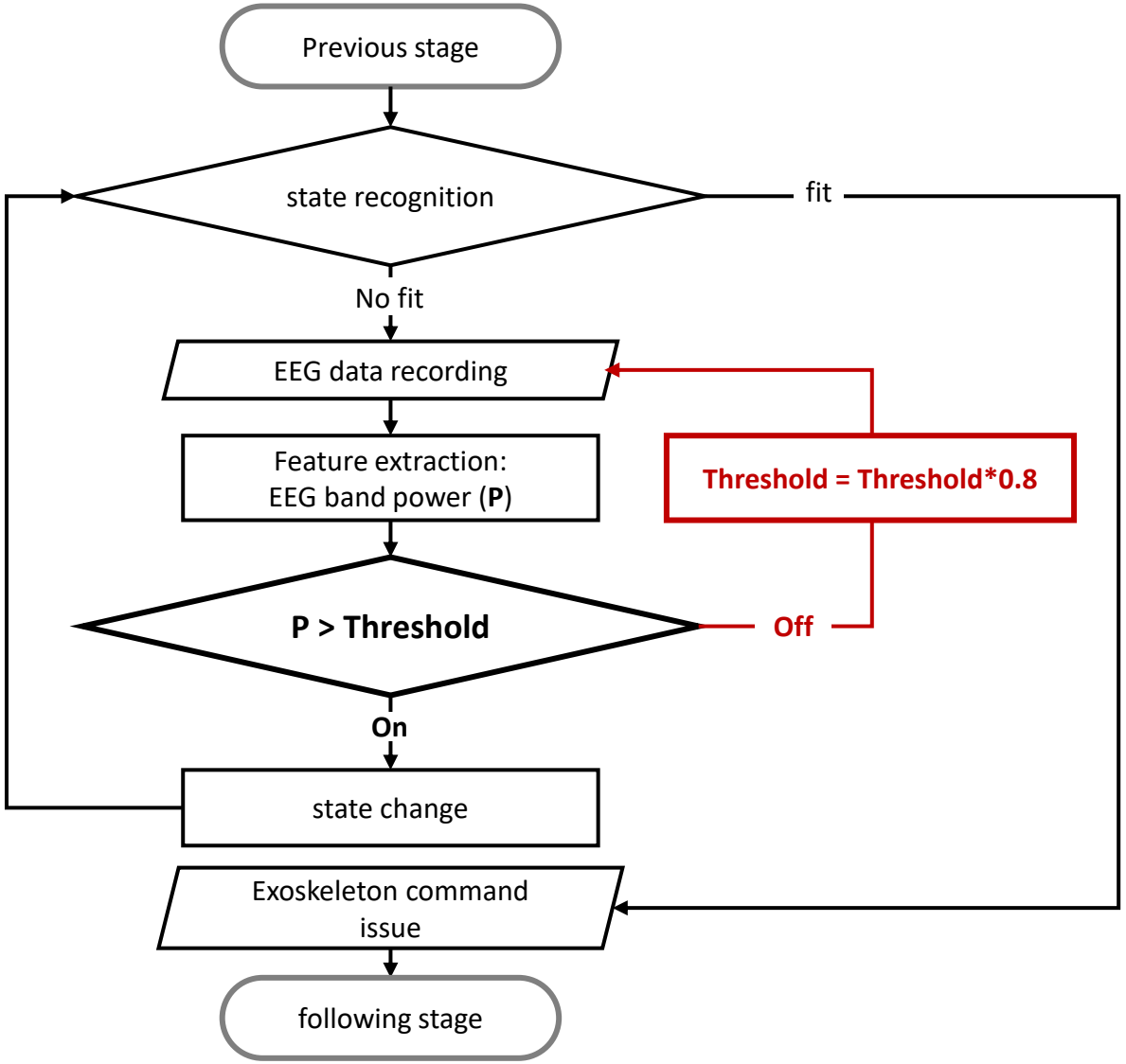


➢ **Eyes-closing tasks (Occipital α)**



Online Three-Stage Control: Stand Up / Sit Down

➢ Flow Chart of **Stand-Up** and **Sit-Down** Control

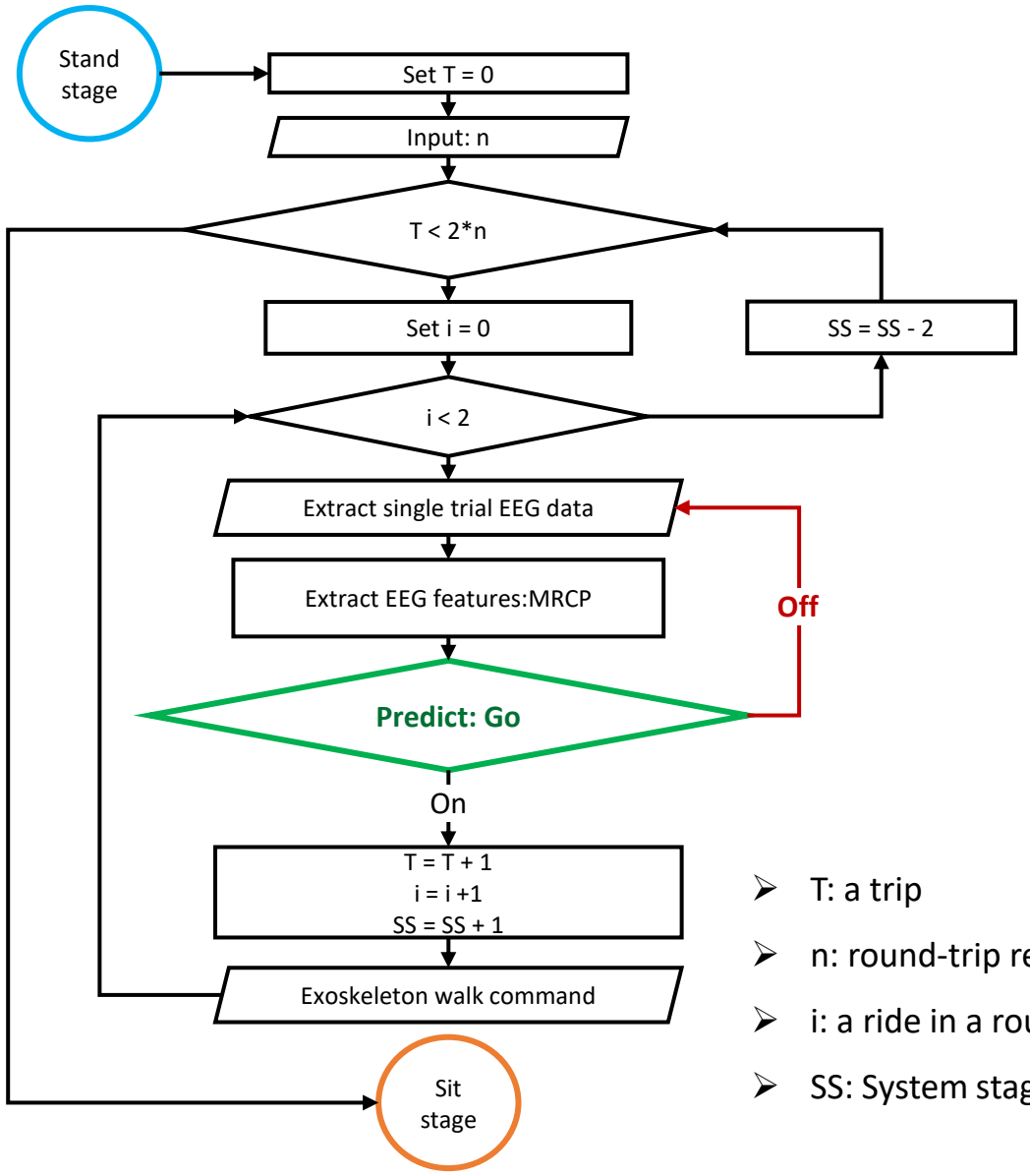


➢ Stage-specific EEG is evaluated online.

➢ A command is issued only when the decision criterion is satisfied.

➢ The controller proceeds to the next stage after successful completion.

Online Three-Stage Control: Walking



- T: a trip
- n: round-trip repetition
- i: a ride in a round-trip
- SS: System stage

- MRCP-based intention is classified as Go / No-Go.
- Walking commands are generated online.
- The controller repeats walking cycles as required.

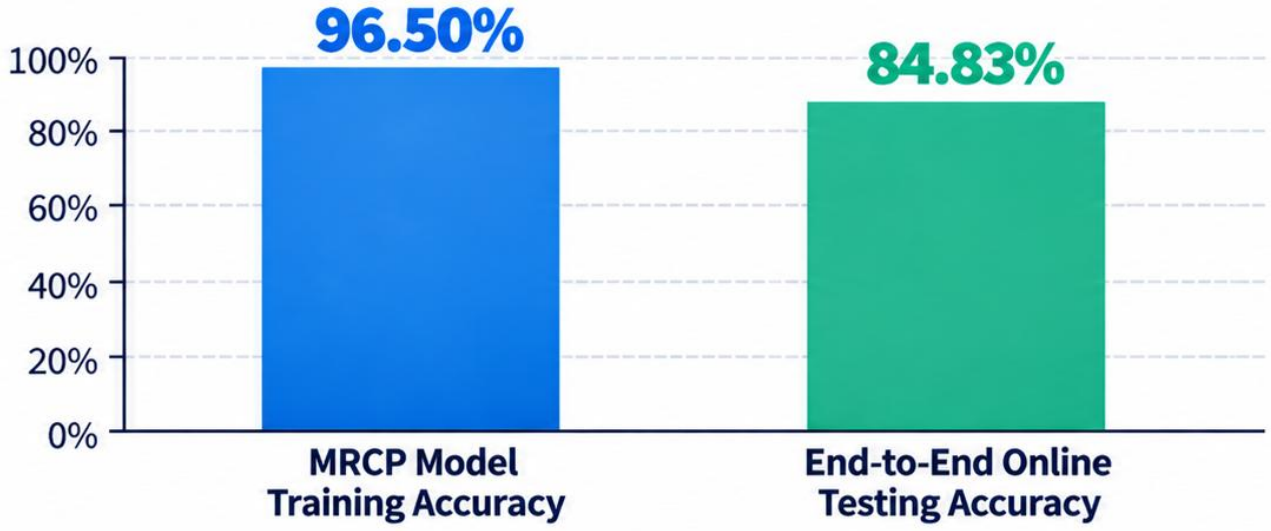
System Demonstration



Performance Evaluation

10
Healthy Participants

14
Stroke Patients



9 / 10
Healthy Participants
Completed the online three-stage control task

10 / 14
Stroke Patients
Completed the online three-stage control task

The system achieved 84.83% end-to-end online accuracy, with successful online control in 9/10 healthy participants and 10/14 stroke patients.

Conclusion

Conclusion



1. Three-Stage WAR–BCI Framework

We developed a wearable AR–BCI framework that integrates Stand Up, Walking, and Sit Down into one sequential lower-limb rehabilitation workflow. Different EEG responses were used to generate stage-specific control commands throughout the complete sequence.

2. Real-Time Control Performance

The MRCP-based walking model achieved 96.50% training accuracy, while the complete three-stage system achieved 84.83% end-to-end online testing accuracy. These results demonstrate that the proposed framework can support real-time sequential exoskeleton control.

3. Feasibility for Rehabilitation Applications

Successful online control was completed by 9 of 10 healthy participants and 10 of 14 stroke patients. The results support the feasibility of integrating neural intention, AR guidance, and robotic assistance for future lower-limb rehabilitation applications.

Thank you / Q&A