A Task-Agnostic Approach to Unified Multi-Activity Gait Phase Estimation via Bilateral Sensing

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Ryan R. Posh & Robert D. Gregg

ICORR

Abstract

Estimating gait phase is key for controlling lower-limb rehabilitation robots. Current control approaches rely on high-level activity classification to then employ a task-specific phase algorithm, which limits adaptability across tasks and introduces misclassification risks.

This study proposes a novel unified phase variable framework that is entirely task-agnostic.

Introduction

Background:

- A **phase variable** is a biomechanical parameter that indicates the progression of a locomotion activity.
- The **piecewise phase variable** structures the phase estimation with a finite-state machine (FSM) consisting of generally monotonic thigh trajectory regions [1, 2].

Problem:

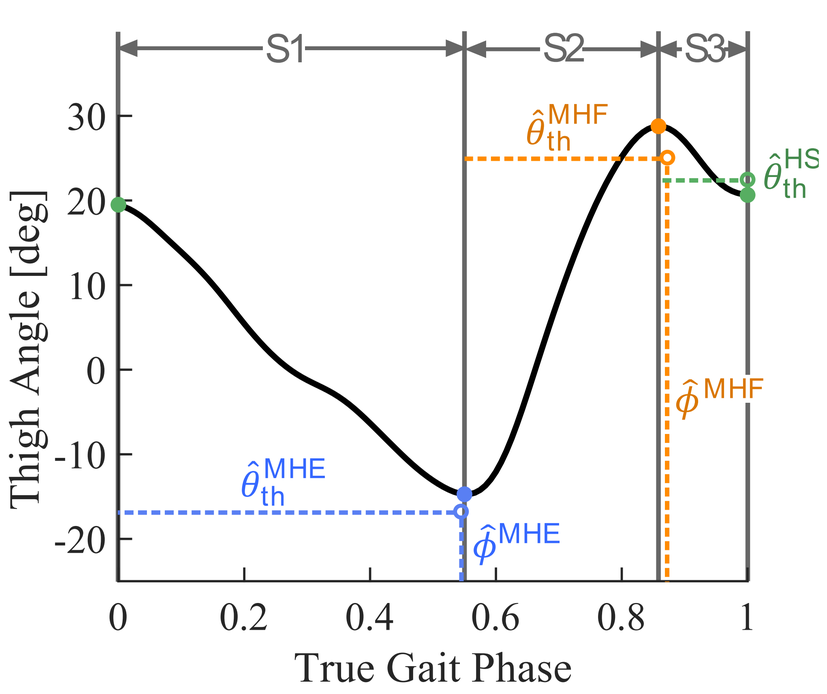
- Model-based phase variables typically have task-specific definitions and thus rely on accurate task classification [3].

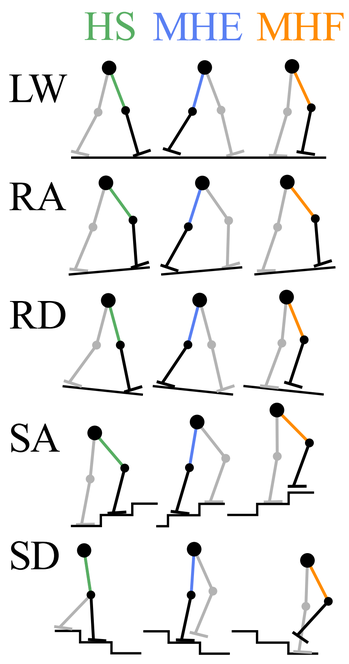
Approach:

- By incorporating bilateral thigh sensing and the most recent gait event information, we present **the first model-based phase variable that is unified across these primary ADLs.**

Methods

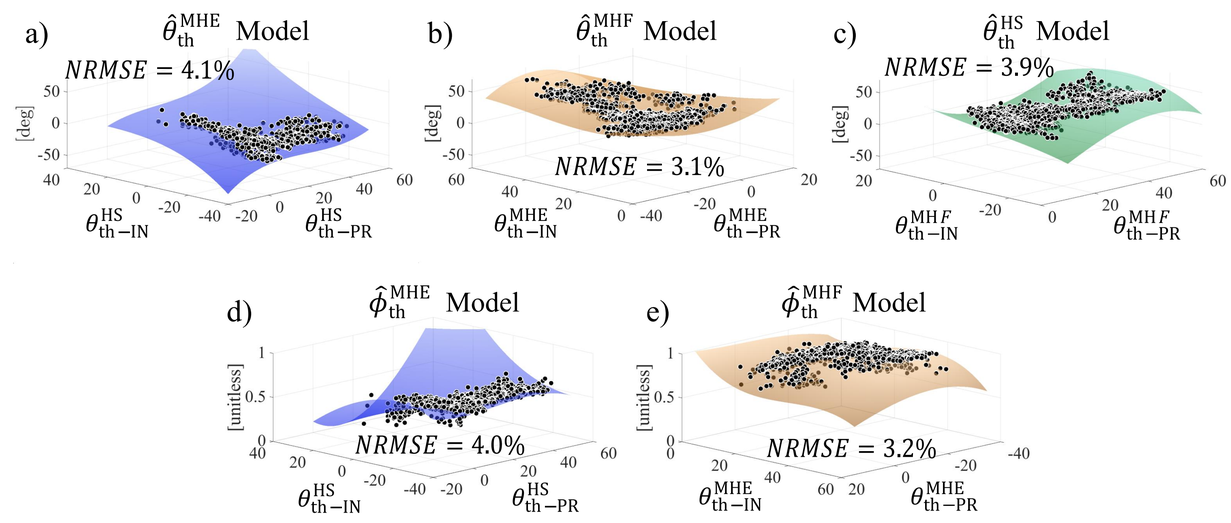
- The phase FSM transitions at **Heel Strike** (HS), **Maximum Hip Extension** (MHE), and **Maximum Hip Flexion** (MHF).





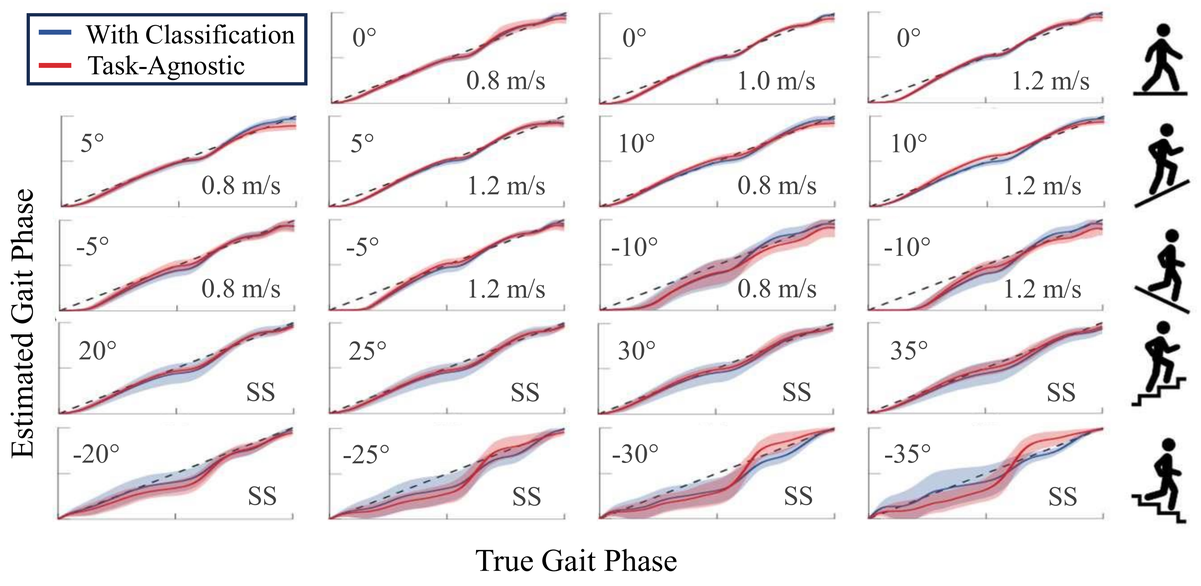
$$\phi = \begin{cases} \dfrac{\theta^{HS} - \theta_{th}}{\theta^{HS} - \hat{\theta}^{MHE}} \hat{\phi}^{MHE} & \text{if S1,} \\ \phi^{MHE} + \dfrac{\theta_{th} - \theta^{MHE}}{\hat{\theta}^{MHF} - \theta^{MHE}} \left(\hat{\phi}^{MHF} - \phi^{MHE}\right) & \text{if S2,} \\ \phi^{MHF} + \dfrac{\theta^{MHF} - \theta_{th}}{\theta^{MHF} - \hat{\theta}^{HS}} \left(1 - \phi^{MHF}\right) & \text{if S3} \end{cases}$$

- The key insight is that these gait events are shared across **level walking** (LW), **ramp ascent/descent** (RA/RD), and **stair ascent/descent** (SA/SD).
- By measuring the global thigh orientation from ***both* the prosthesis-side** (PR) and **intact-side** (IN) legs, we can model the thigh orientation and timing of the next gait event ***without task knowledge.***

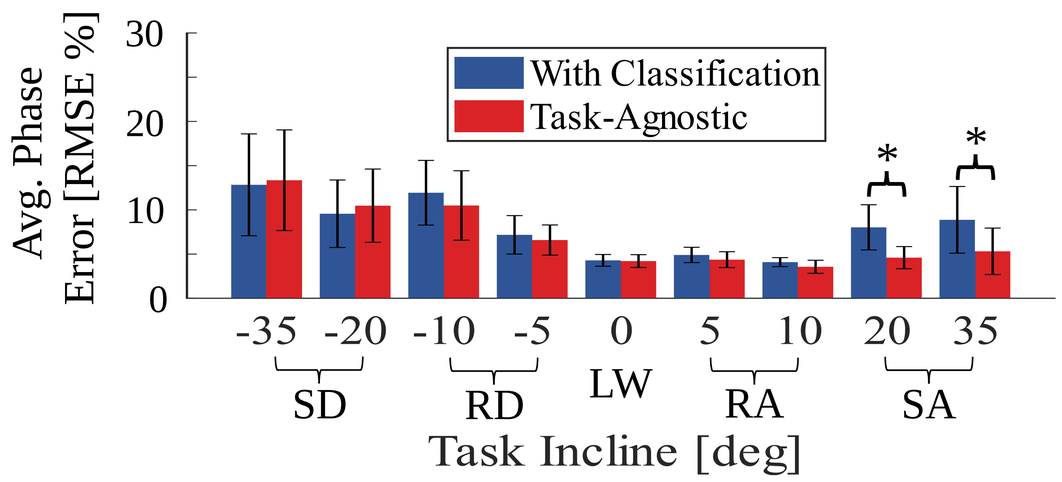


- We used an **able-bodied dataset** [4] - with 5 individuals for model training, and 5 for evaluation - to train and assess the performance across tasks **with multiple inclines and speeds**

Results



- Simulated **average phase RMSE** of 6.8% with unilateral classification approach and **6.3% with bilateral task-agnostic.**
- Statistically significant improvement during stair ascent.



Conclusion

- By unifying phase definitions across these tasks, this approach **improves accuracy, robustness, and versatility** of the piecewise phase variable, addressing existing limitations of classification reliance.

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[1] Best et al., *IEEE T. Robot*, 2023.
[2] Cheng et al., *IEEE T. Biomed Eng*, 2023.
[3] Cortino et al., *IEEE T Med Robot Bionics*, 2023.
[4] Reznick et al., *Sci Data*, 2021.

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