

USER-INDEPENDENT, MODE-UNIFIED INTENT RECOGNITION OF A POWERED KNEE-ANKLE PROSTHESIS USING DEEP LEARNING

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Introduction: Powered knee-ankle prostheses are designed to enable transfemoral amputees to address various walking environments they face in their daily lives. Since each ambulation mode (e.g., level walking, stair ascent) demands specific limb dynamics, many prosthesis studies focus on estimating user's ambulation mode and switching to corresponding controller [1]. However, it is challenging to avoid critical misclassifications and unintended controller switches that can lead to falls or injuries, as people take thousands of strides every day. To address this issue, some studies like [2] have demonstrated a continuous adaptive system without discrete activity classification. Studies in human biomechanics have shown that numerous kinematic and kinetic properties naturally scale with the steepness of walking environments [3]. We introduce a framework for intent recognition that unifies ambulation modes into a continuous system, applying deep learning via a Temporal Convolutional Network (TCN) [4] informed by prosthesis sensor data. We propose that a continuous slope estimator, capable of assessing context within and across different ambulation modes, will be more effective than a conventional mode classifier, which is limited to distinguishing between distinct modes.

Methods: We recruited 15 transfemoral amputees and collected data via 6 sensors attached (Figure 1-(a)) on the Open Source Leg (OSL) [5] as subjects navigated various terrains, detailed in Figure 1-(b): level ground walking (LW), ramp ascent (RA) and descent (RD) with various slopes (8° - 12°), and stair ascent (SA) and descent (SD) with angles ranging from 19° to 35° (10cm - 18cm). We trained TCN-based [4] classifiers and estimators on these modes, as shown in Figure 1-(c). The full mode classifier and unified slope estimator encompassed all modes, while the ramp-specific versions were trained only on LW and RA/RD data. For classifiers, mode served as the ground truth, while the slope estimators used the terrain slope. Performance of the models was assessed through leave-one-subject-out test, using RMSE measure. To translate TCN-derived slope estimates into biomimetic control commands for the joint actuators, we analyzed correlation between terrain slope and joint angle at heel strike from an able-body biomechanics dataset [3]. As shown in Figure 1-(d)-(2), we observed strong positive correlations between the increasing terrain slopes and the heel strike joint angles at the knee ($r = 0.93$), ankle ($r = 0.96$), and hip ($r = 0.87$).

Results & Discussion: As shown in Figure 1-(c), the unified slope estimator (2.53 ± 0.79) significantly outperformed the full-mode classifier (4.37 ± 0.8) (*1, $p < 0.05$), and the ramp-specific slope estimator (1.84 ± 0.5) similarly outperformed the ramp-specific mode classifier (3.57 ± 0.59) (*2, $p < 0.05$). These findings support our hypothesis that slope estimators in a continuous domain are more effective than mode classifiers in a discrete domain. The TCN slope estimates were utilized to simulate control commands to joint actuator as shown in Figure 1-(d). The proposed system successfully mimicked human biomechanics across varied conditions (12° ramp, 19° stair, 35° stair), adjusting knee (46° , 55° , 62°) and ankle angles (3° , 4.3° , 7.2°) dynamically. This capability to create a range of commands within the same mode stands in contrast to the discrete classifications, which could only generate a single command per mode. This limitation is significant, as highlighted in Figure 1-(d)-(2), because human joint kinematics adapt continuously to varying contexts within a mode.

Significance: We recognize that traditional classifiers are incapable of scaling within modes, and this is a significant limitation given that human biomechanics depend not only on the mode but also on context within modes such as slope of the ramp or stair. Since it's crucial to recognize this within-mode level of scaling for accurate biomimetic assistance, we present a unified system that removes the need for a traditional classifier and scales naturally across level walking, ramps, and stairs.

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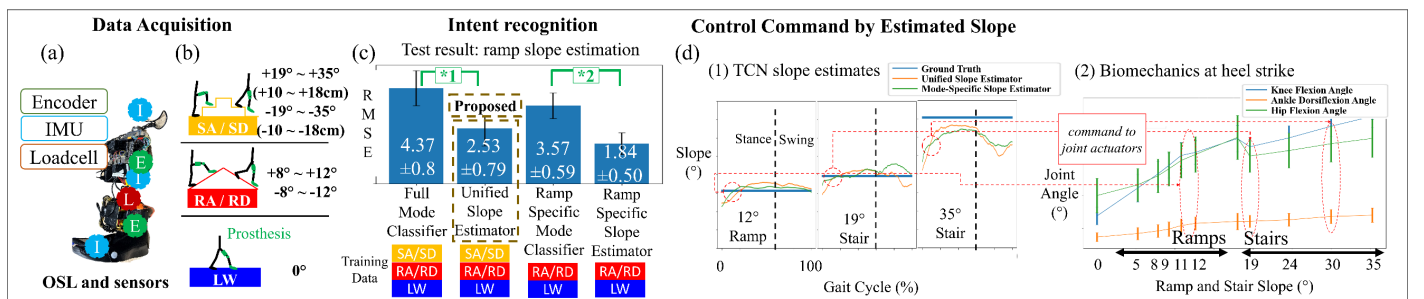


Figure 1: (a) Sensor arrangement of OSL (b) Data collection in various terrains (c) RMSE comparison of 5 different models using different data combinations (d) Slope estimation results and control commands scaled by terrain slope using lower limb biomechanics