A REAL-TIME ALGORITHM FOR DETECTING GAIT EVENTS IN LOWER-LIMB PROSTHESIS USERS USING A MARKERLESS MOTION CAPTURE SYSTEM

Liang-Wei Huang[1], Mu-Hua Wang[1], Bo-Hung Chen[1], Kai-Han Su[2], Cheng-Hung Tsai[3], You-Yin Chen[1], *Hui-Ting Shih[2]

[1]National Yang Ming Chiao Tung University, Department of Biomedical Engineering, Taiwan

[2]National Yang Ming Chiao Tung University, Department of Physical Therapy and Assistive Technology, Taiwan

[3]III Software Technology Institute, Institute for Information Industry, Taiwan

*Corresponding author's email: huiting.shih@nycu.edu.tw

Introduction: Markerless motion capture systems greatly reduce the time required for data collection and processing, thereby enhancing the efficiency of motion analysis [1]. Additionally, real-time gait analysis enabled by the markerless motion capture system has the potential for immediate assessment and feedback [2,3]. People with amputation typically undergo a period of physical therapy to rehabilitate and adapt to their prosthetic devices. However, amputation-related rehabilitation requires significant time and resources, posing a substantial challenge for healthcare systems [4]. The markerless system with a real-time algorithm provides opportunities for this population's recovery. Precise gait analysis is based on the accurate detection of heel strike (HS) and toe-off (TO) [5]. Previous gait detection algorithms were designed for marker-based motion capture systems and post-processing circumstances [6]. Therefore, we propose a real-time algorithm for identifying gait events in lower-limb prosthetic users, offering improved accuracy compared to existing methods.

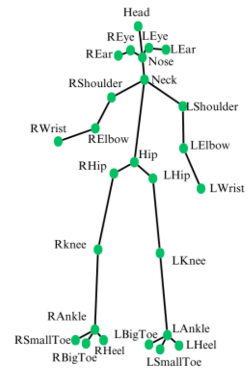

Figure 1: The definition of 26 key landmarks of the AI models.

Methods: Four participants with unilateral lower limb amputation volunteered, including three with above-knee (AK) and one with below-knee (BK) amputations. They walked a 5-meter walkway three times at a self-selected pace surrounded by our markerless motion capture system. The system consisted of two RGB cameras (30 Hz) positioned 2.5 meters from the walkway's centerline to capture sagittal plane data. An AI model extracted 26 key landmarks per frame (Fig. 1), providing pixel-based coordinate information. All gait events were manually labeled through video annotation. We compared the HS and TO identified by previous and current methods against the manual labels and calculated the frame discrepancy.

The baseline algorithm [6] detects HS events using the local maximum of the x-coordinate difference between the pelvis and ankles, while TO events are based on the local minimum. A 4th-order low-pass filter (cutoff = 7 Hz) with a real-time window of 17 frames was applied. The coordinates of the ankles and hip were used. HS detection is based on the x and y coordinate differences of the heels to compute horizontal (Vx) and vertical (Vy) velocities, with Vxy = Vx × Vy. The peak Vxy of each gait cycle serves as a reference, and HS is detected when Vxy and its slope fall below dynamic thresholds (Fig. 2). TO detection follows the same process using small toes, identifying events when Vxy and its slope exceed set thresholds (Vxy > 5, slope > 2). A moving average filter (window = 4) reduces noise.

$$V_{xy} = V_x \times V_y$$

$$\text{Threshold} = \frac{5*peak\ value}{100}$$

$$\text{Slope} = \frac{2*peak\ value}{100}$$

Figure 2: The formula of HS detection.

Table 1. The mean and standard deviation of frame error.

	Non-Amputated Limb		Amputated Limb	
BK 1	HS	TO	HS	TO
Previous Method	0.65±0.61	2.22±1.06	0.73±0.79	1.89±1.36
Proposed Method	0.65±0.70	0.67±0.77	0.93±0.88	0.67±0.91
AK 1	HS	TO	HS	TO
Previous Method	0.44±0.53	1.92±0.79	1.75±0.75	1.00±1.15
Proposed Method	0.67±0.71	0.41±0.51	0.83±0.72	0.62±0.51
AK 2	HS	TO	HS	TO
Previous Method	0.44±0.53	2.58±0.90	1.85±0.90	1.14±1.10
Proposed Method	0.89±0.33	0.25±0.45	1.46±1.20	0.43±0.65
AK 3	HS	TO	HS	TO
Previous Method	0.88±0.64	2.43±1.51	1.00±0.82	2.56±1.59
Proposed Method	0.75±0.89	0.71±0.49	0.71±0.48	0.78±1.64

Results & Discussion: Experimental results (Table. 1) show that for the non-amputated limb, both our method and the previous method exhibited similar HS detection accuracy, while our method performed better in TO detection. For the amputated limb, our method consistently achieved higher accuracy in both HS and TO events. This improvement may stem from our approach, which considers both horizontal and vertical heel velocities (Vxy), capturing the moment when both approach near zero at HS. In contrast, the previous method relies on horizontal displacement between key points, which may be less reliable for abnormal gait patterns. The more accurate TO detection across both limbs suggests that TO is a more distinct event, while HS variability in the non-amputated limb may result from natural gait asymmetry. These findings highlight our method's potential for more robust gait event detection in amputee users, particularly in abnormal gait patterns.

Significance: The results of this study demonstrate that our real-time algorithm accurately detects gait events in prosthetic users, especially for amputated limbs. This enables precise gait training with markerless motion capture, supporting personalized rehabilitation while reducing costs.

Acknowledgments: Taiwan National Science and Technology Council grant 113-2221-E-A49 -015 -MY2 and 113-2321-B-A49 -016.

References: [1] Wade et al. (2022), PeerJ 10; [2] Vun et al. (2024), Gait & Posture 112(95-107); [3] Darter et al. (2011), Phys Ther 91(9); [4] Pasquina et al. (2015), AMA J Ethics 17(6); [5] Maqbool et al. (2017), IEEE Trans Neural Syst Rehabil Eng 25(9); [6] Vafadar et al. (2022), Gait & Posture 94(138-143).