Soft Exosuit with Freezing-of-Gait Detection for Haptic Cueing in Parkinson's Disease

Junyu Chen, Yichen Wu, Juncheng Zhou, and Hao Su

Abstract—**Freezing of gait (FOG) severely limits mobility in individuals with Parkinson's disease. We present an untethered soft pneumatic exosuit that provides hip extension assistance to deliver timely haptic cues. Our system utilizes lightweight, textile-based pneumatic actuators controlled by an embedded microcontroller unit (MCU), delivering precisely timed haptic cues that provide a notable reduction in freeze duration. These results indicate that hip extension constitutes a promising complementary approach to traditional flexion-based interventions.**[1]

I. Introduction

Freezing of gait (FOG) is characterized by sudden gait disruptions, contributing to falls and loss of independence among approximately 60% of individuals with Parkinson's disease [1] [6]. Existing interventions based on auditory or visual cues can reduce freezing but impose cognitive burdens that reduce patient compliance [2]. A prior study [3] demonstrated that soft robotic apparel can reduce FOG using hip flexion cues, but anterior placement can cause discomfort and disrupt gait mechanics, including skin irritation, restricted leg lift, and altered swing phase kinematics. To address this concern, we propose a hip-extension-based approach that provides biomechanical leverage, reduced actuation force requirements, and improved comfort. Extension cues encourage weight shifting and step initiation while preserving natural stride patterns, making them a viable alternative for long-term wear [13], [16–18].

II. Method

A. System Hardware

The soft pneumatic exosuit consists of a textile waist belt integrated with thermoplastic-polyurethane (TPU)-coated nylon bladders fabricated through a precision heat-press sealing process. Actuation is provided by a Schwarzer diaphragm micro-air pump (SP-622-EC-BL-DUP-DV), regulated through an SMC solenoid valve (VQ110U-5M-M5). The Honeywell pressure sensor (SSCDANN100PGAA5) provides feedback to a PID control loop managed by a Teensy 4.1 microcontroller. The system delivers sufficient pneumatic power at peak pressures ~35 kPa within 120 MS and consumes less than 2 W during inflation cycles [7], [9–11]. The PID loop ensures consistent actuation pressure, enhancing cue reliability and patient comfort.

Two Alubi wireless inertial measurement units (IMUs) are mounted on both thighs to capture gait kinematics. The placement of IMUs on the thighs allows for precise detection of asymmetries in gait cycles and stance-to-swing movement transition, which are indicative of FOG events [6].

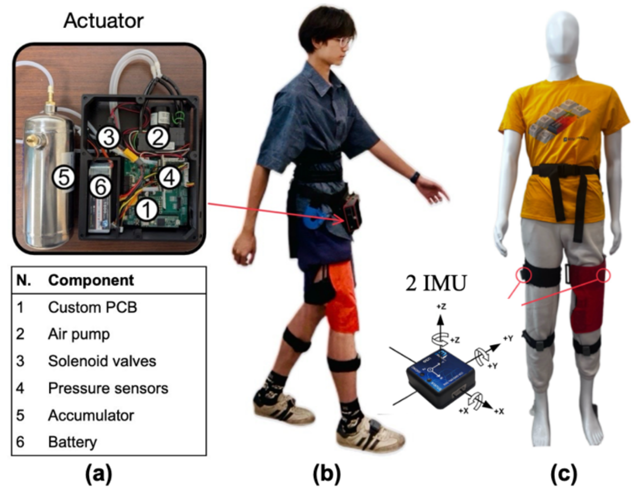

Fig. 1. Prototype of the soft pneumatic exosuit. (a) Actuation module with labeled components, including custom PCB, air pump, solenoid valves, pressure sensors, accumulator, and battery. (b) Human subject demonstration showing integration of the actuator with the waist belt and thigh-mounted pneumatic bladders. (c) Manikin demonstration showing placement of two IMU sensors on the thighs.

B. Algorithm

We evaluated two algorithms for FOG detection and prediction using the DAPHNet dataset. The first is a frequency-domain (FD) method adapted from Bächlin et al. [8]. This method processes shank accelerometer data in 4-second windows, classifying FOG based on a dual-threshold analysis of spectral power density in locomotor (0.5–3 Hz) and freeze (3–8 Hz) bands. The second is a Long Short-Term Memory (LSTM) model designed for proactive FOG prediction. It employs sequences of 9-axis IMU data as input to a stacked architecture of two LSTM layers. By processing temporal sequences, the LSTM model is trained to learn the kinematic patterns that precede FOG events, aiming for higher predictive accuracy and robustness than the reactive FD method.

III. Results

Our results demonstrate that the LSTM model significantly outperforms the traditional frequency-domain (FD) algorithm. As shown in **Fig. 3(a)**, the FD algorithm achieved only a 59.62% True Positive Rate (TPR) with a high False Positive Rate (FPR) of 10.68%. In contrast, the LSTM model in **Fig. 3(b)** achieved an excellent TPR of 92.38% while maintaining a low FPR of

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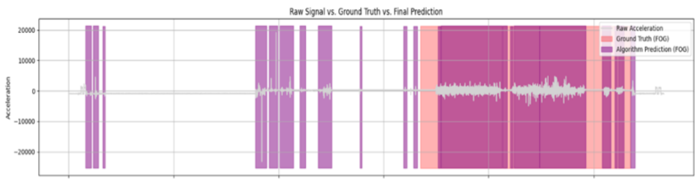
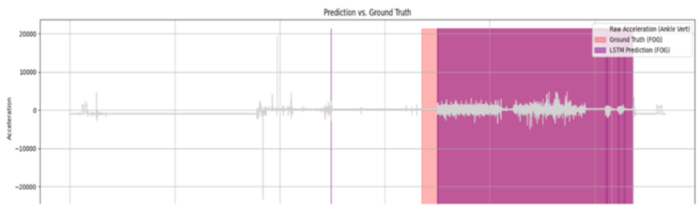
just 0.34%. These results highlight the LSTM's ability to learn complex temporal-series gait patterns, making it a far more accurate and reliable choice for developing a wearable FOG assistance system.



(a) FOG Detection using the FD algorithm



(b) FOG Detection using the LSTM algorithm

Fig. 3. Comparison of FOG detection between the FD algorithm and the LSTM model. (a) Prediction of FOG events using the FD algorithm. (b) Prediction of FOG events using the LSTM model, showing improved accuracy and reduced false positives.

Furthermore, the Receiver Operating Characteristic (ROC) analysis in **Fig. 4** shows the LSTM model reaching an area under the curve (AUC) of 0.99, demonstrating its superior detection performance.

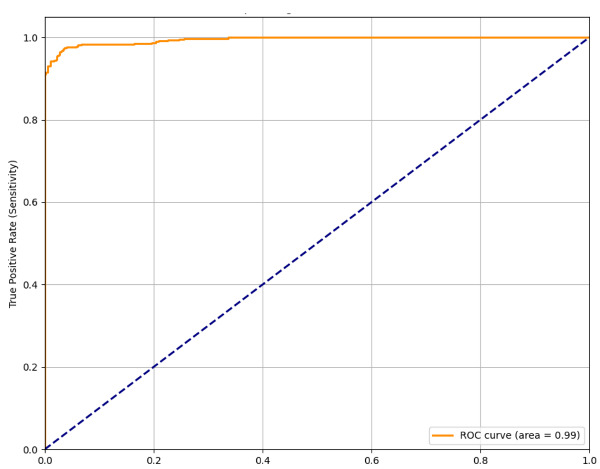


Fig. 4. Receiver operating characteristic (ROC) curve of the LSTM model on the DAPHNet dataset, demonstrating superior detection performance with an AUC of 0.99.

VI. Conclusion

This study validates a hip-extension-based pneumatic exosuit as a feasible platform for real-time **FOG** mitigation. Coupled with an LSTM detector (AUC 0.99), the system reduces false alarms by ~97% versus an FD baseline, enabling timely haptic cueing.

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