Before the Fall: An AI-Driven Multimodal Wearable System for Early Detection and Fall Protection in Ménière's Disease

Fan, Heyi (School: The Pennington School)

EquiliMind is a multimodal fall-prevention system designed to address the unpredictable vertigo, imbalance, and sudden fall risk associated with Ménière's disease. Current clinical approaches are largely reactive and depend on intermittent evaluation, making it difficult to detect instability before a dangerous event occurs. This study aimed to develop and validate a closed-loop system that combines early neural-state recognition with real-time mechanical assistance for proactive fall-risk mitigation. The system integrated 11-channel electroencephalography (EEG), a head-mounted inertial measurement unit (IMU), dual-channel surface electromyography (EMG), an EEGNet-based deep learning model, and a lower-limb exoskeleton prototype. EEG, IMU, and EMG data were collected under three conditions: normal, vertigo, and fall. The EEG signals were preprocessed using filtering, re-referencing, independent component analysis, and segmentation, while IMU and EMG signals were processed for motion and muscle-activation features. These data were used to train a lightweight EEGNet classifier for three-state recognition, and the resulting state predictions were linked to graded warning and exoskeleton intervention. The EEGNet model achieved 93.2% test accuracy with a weighted F1-score of 0.93 across the three classes. In 30 simulated fall trials, the system reached a 93.3% intervention success rate, an average response time of 85 ms, and reduced maximum body tilt angle by 32% with exoskeleton assistance. These results demonstrate that multimodal physiological sensing can detect instability-related patterns and support timely protective action.

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