MuscleSense: Real-Time Auditory Biofeedback for Lower-Limb Exercise with Sparse Wearables

Wenbo Zhang[1,2], Jagmohan Chauhan[1], Zhanpeng Jin[2]
[1]University College London, UK [2]South China University of Technology, China

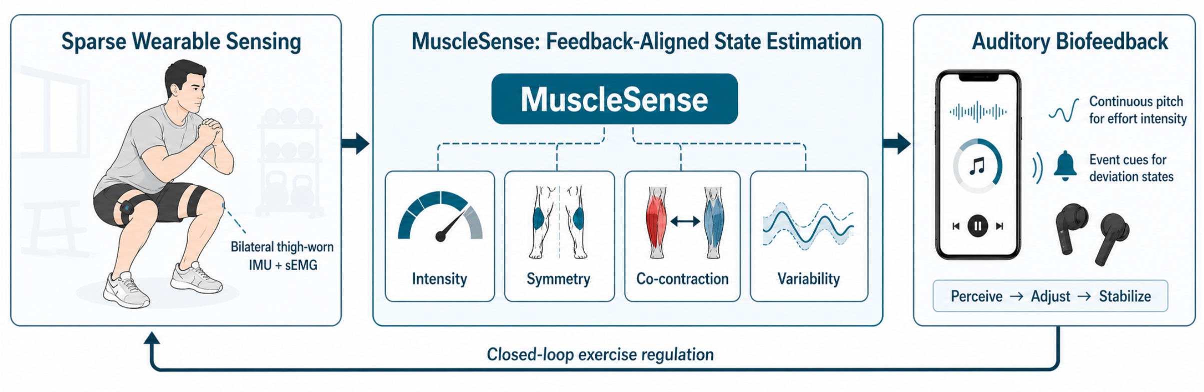

Figure 1: Overview of MuscleSense: sparse wearable sensing, feedback-aligned state estimation, and real-time auditory biofeedback.

Motivation

Mobile and wearable systems increasingly support exercise monitoring outside laboratory environments, yet most feedback still focuses on external motion, such as posture, repetitions, or activity intensity. In strength training, however, users often need to regulate less visible effort-related states: whether the target muscles are sufficiently activated, whether effort is balanced across limbs, whether compensatory co-contraction occurs, and whether effort remains stable across repetitions. Surface EMG can expose these internal dynamics, but raw EMG waveforms are noisy, expertise-heavy, and poorly suited to in-the-loop use during movement. Prior work has highlighted the value of designing wearable sensory feedback around body sensations during physical activity [1]. This motivates a wearable interface that translates sparse biosensing into eyes-free, actionable feedback.

MuscleSense System

Building on prior work in lower-limb wearable sensing [2], we present **MuscleSense**, an audio-first wearable biofeedback system for lower-limb exercise. As shown in Figure 1, MuscleSense combines sparse wearable sensing, feedback-aligned state estimation, and real-time auditory biofeedback in a closed-loop exercise regulation pipeline. MuscleSense uses a minimal bilateral thigh-worn sensing setup, combining IMU and sEMG signals, and runs a causal on-device inference pipeline on a smartphone. Rather than directly sonifying raw biosignals, the system estimates a compact feedback-aligned effort state designed for real-time regulation: *Intensity* captures overall effort magnitude, *Symmetry* captures left–right imbalance, *Co-contraction* captures compensatory antagonist activation, and *Variability* captures short-horizon instability.

These states drive a two-layer auditory feedback design. A continuous pitch channel represents effort intensity and supports moment-to-moment regulation without requiring visual attention. Sparse event cues highlight sustained deviation states, such as imbalance, excessive co-contraction, or unstable effort, using gating and pacing rules to avoid alert fatigue. The system therefore treats sensing, inference, and feedback as a single closed loop: users perceive effort, adjust movement, and stabilize subsequent repetitions.

Prototype and Evaluation

We evaluated MuscleSense using data from 17 participants performing locomotion, strength, plyometric, and unilateral lower-limb movements. Multi-channel reference EMG was used only to construct and evaluate feedback-state labels; deployment relies on the sparse thigh-worn IMU+sEMG setup. In the input-modality ablation, the sparse IMU+EMG setup achieved the best overall performance among input configurations, with an average MAE of 0.0479 and PCC of 0.8656 across Intensity, Symmetry, and Co-contraction.

The real-time prototype aligns wearable streams at 20 Hz, estimates effort states over 1.0 s sliding windows with 0.1 s hops, updates the feedback state at 10 Hz, and renders pitch at 5 Hz. Smartphone profiling showed stable operation with an end-to-end latency of approximately 285 ms, supporting in-the-loop perception–action coupling. In a short within-subject squat study, MuscleSense shifted participants toward a more deliberate cadence and improved perceived in-the-loop control compared with no feedback and mirror-based visual feedback. We are further extending the evaluation to examine how deviation event cues support correction of asymmetry, co-contraction, and unstable effort patterns.

Discussion

MuscleSense illustrates how wearable biosensing can move beyond passive monitoring toward perception augmentation: making otherwise hidden effort states audible, interpretable, and actionable during movement. For MobiUK, this work raises broader questions about how mobile and wearable systems should represent physiological states, how to design low-burden sonification for sustained exercise, and how to evaluate closed-loop biofeedback systems where user-facing value depends not only on prediction accuracy, but also on timing, interpretability, and perceived control.

References

[1] J. Ley-Flores et al. 2024. Co-designing Sensory Feedback for Wearables to Support Physical Activity Through Body Sensations. IMWUT 8(1).

[3] W. Zhang et al. 2025. KineticsSense: A Multimodal Wearable Sensor Framework for Modeling Lower-Limb Motion Kinetics. IMWUT 9(3).