Chapter 15
Footfall Forensics: Real-Time Reactive Balance Classification from Sparse Floor-Vibration Sensing

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Abstract Falls remain a major source of injury and mortality among older adults, motivating the development of unobtrusive methods that can detect early signs of instability. This study presents a building-integrated, contact-free approach that uses floor vibrations as diagnostic indicators of balance control, capable of distinguishing *reactive-balance* responses from nominal gait. Unlike wearable or camera-based systems, this framework treats the floor as a distributed sensing medium and leverages vibration-based system identification to extract gait signatures directly from structural responses. Experiments were performed in Michigan Tech's H-STEM Functional Mobility Laboratory on a reinforced-concrete floor bay instrumented with eight seismic accelerometers arranged in a single-bay grid. The array included five PCB 393B04 and three PCB 393B31 sensors to capture broadband vertical responses during low-amplitude excitation. A pilot study with one participant evaluated performance across two surface conditions—an anti-slip mat and a low-pile carpet. On each surface, two tests were conducted: a nominal gait trial, where the participant walked at a self-selected pace to establish baseline footfall patterns, and a reactive-balance trial using a lean-and-release apparatus that induced forward perturbations at 10° and 18° lean angles. The resulting vibration data revealed distinct spatiotemporal features associated with balance recovery dynamics. These signatures demonstrate that reactive-balance events produce measurable deviations in modal content and force distribution compared to steady walking. The proposed vibration-centric framework thus enables scalable, privacy-preserving, and continuous monitoring for early fall-risk detection in real architectural environments.

Keywords Gait analysis · Reactive balance · Seismic accelerometers · Fall detection · Mobility

Introduction

Falls are a leading source of nonfatal injury and a major contributor to injury-related mortality among older adults in the United States [1, 2, 3, 4]. Incidence rises sharply with age—about one in three adults over 65 falls each year [5, 6], with risk increasing further beyond 80 [7, 8]—and annual rates span $\sim 25\%$ for community-dwelling seniors to as high as 75% in nursing homes [9, 10, 11]. In 2021, falls led to nearly three million emergency-department visits, over 800,000 hospitalizations, and more than 38,000 deaths among those aged 65+ [12]; prior falls substantially elevate recurrence risk (likelihood ratio 2.3– 2.8) [13, 14]. Costs for nonfatal falls have grown from \$23.3 billion (2008) to $\sim$ \$80 billion (2020) [15, 16]. Risk is multifactorial: intrinsic contributors (age-related declines in strength, neuromuscular control, proprioception, reaction time; gait/balance impairments) interact with extrinsic hazards (poor lighting, slippery or uneven surfaces, unexpected perturbations) [17, 18]; deconditioning and fear of falling further reduce stability [19, 20]. These trends motivate the development of unobtrusive indicators that detect incipient balance loss before a fall occurs.

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Structural dynamics provides such an avenue: instrumented floors can serve as distributed sensors that convert footfalls into measurable responses. Building on the foundations of experimental modal analysis for estimating natural frequencies and mode shapes in bridges and buildings [21, 22, 23, 24, 25], recent “smart building” deployments use floor responses for operational assessments. Source–identification techniques, analogous to epicenter localization, infer loading and human–structure interaction from ambient data [26, 27, 28, 29, 30]; underfloor accelerometer networks resolve footstep activity [31, 32]; and full-scale arrays (e.g., Goodwin Hall) demonstrate in situ localization with seismic-grade sensors [33, 34, 35, 36, 37, 38, 39, 40]. In this context, our premise is to exploit floor-vibration signatures to separate nominal gait from *reactive-balance* events and to treat the emergence of reactive signatures as an early indicator of instability—aligning modal analysis with proactive fall-risk detection in operational environments [41, 42, 43, 44, 45, 46].

Reactive balance denotes the rapid, unplanned stepping response that stabilizes the center of mass (COM) relative to the base of support (BOS) following an external perturbation, and it is dynamically distinct from volitional (pre-planned) gait that executes an intended COM–BOS trajectory [47, 48]. In reactive events, the control objective switches from trajectory tracking to immediate recovery: step initiation latency shortens, swing-leg unloading accelerates, and step velocity increases, yielding spatiotemporal patterns (step time, stance/swing durations, double support, stride/step length, and step speed) that diverge from steady walking [49, 50, 51, 52]. From a modal-analysis perspective, these control shifts imprint measurable differences in floor-response signatures: reactive steps tend to excite broader-band content, altered mode participation (including antisymmetric/torsional components), and higher peak ground-reaction impulses that modify the amplitude and phase of the operating-deflection shape relative to nominal gait. Because such compensatory postural reactions are a primary line of defense against balance loss and strongly tied to fall risk in older adults [53, 54], their early detection is clinically meaningful. This work therefore exploits contact-free floor-vibration sensing as a system-identification channel to separate reactive balance from nominal gait in situ, leveraging the building’s dynamics as the sensing medium and avoiding the deployment burdens of cameras or wearables [55, 56, 57, 58]. We treat the presence of reactive-balance signatures as a precursor for fall detection and a trigger for targeted monitoring, enabling a pathway to scalable, privacy-preserving, building-integrated surveillance of instability [59, 60, 61].

Current solutions for gait tracking span clinic-and home-based modalities with varied fidelity and scalability: structured monitoring and early intervention improve balance, reduce fall risk, enhance mobility, and support quality of life [50, 54, 62, 63, 64, 65, 66], yet population aging ($\sim$ 1.5 billion $\geq$65 by 2050) [67] and access barriers in rural/underserved settings constrain clinic-centric care [68, 69]. Affordable modalities include wearables, marker-based/markerless 3D motion capture, video analytics, and remote supervised monitoring [70, 71, 72], but each exhibits domain-specific limitations: augmented-reality devices are sensitive to lighting/sensor interference and narrow fields of view that under-sample whole-body kinematics; wearables suffer from placement variability, motion artifacts, partial-state observability, and user-compliance drift in older adults [73]; and video systems pose persistent privacy/security risks and observer effects that bias natural
gait [74, 75].

To address these limitations, this study introduces a contact-free framework that treats the floor itself as a distributed sensing medium. By analyzing vibration responses induced by footfalls, the system identifies distinct *reactive-balance* signatures that differentiate them from nominal gait. Within this framework, floor vibrations are modeled as structure-borne excitations whose spatiotemporal features reveal balance recovery dynamics. The approach enables continuous, in situ monitoring capable of detecting early signs of instability—without the need for wearable devices or cameras. Through cost-effective signal processing and vibration-based system identification, the proposed method offers a scalable, privacy-preserving pathway for telehealth integration and fall-risk assessment in real architectural environments [76, 77, 78].

Methods

Experiments were conducted in Michigan Tech’s H-STEM Functional Mobility Laboratory on a reinforced-concrete floor bay with a clear span of approximately $9\ \mathrm{m}$. Eight seismic accelerometers were surface-mounted within a single-bay grid and oriented to capture the vertical vibration response. The array included five PCB 393B04 sensors (sensitivity $10^3\ \mathrm{mV\,g^{-1}}$) for broadband measurements and three high-sensitivity PCB 393B31 units ($10^4\ \mathrm{mV\,g^{-1}}$) positioned near midspan and antinodal regions to enhance the signal-to-noise ratio during low-amplitude footfall excitation. All sensors were bonded to the slab using a low-creep adhesive, gravity-leveled, and powered as IEPE channels. Data acquisition was performed using Siemens Testlab, equipped with per-channel anti-aliasing filters, at a sampling rate of $10.24\ \mathrm{kHz}$. Each trial consisted of a $20\ \mathrm{s}$ time record initiated by a common hardware trigger to ensure phase coherence across all channels. A pilot study was conducted with a single participant to evaluate structural and human response under two surface conditions: one covered with an anti-slip mat and the other with a low-pile carpet. On each surface, both nominal gait and reactive-balance tests were performed to examine differences in foot–floor interaction, traction behavior, and vibration response characteristics.

In the first phase, corresponding to the nominal gait condition, the participant walked across the instrumented span at a self-selected, comfortable pace, generating steady and periodic footfall excitations representative of natural walking dynamics. This dataset provided a consistent baseline for gait-related loading patterns and served as a reference for comparison with reactive-balance trials.

Reactive balance performance was evaluated using a lean-and-release (tether-release) apparatus [78, 79]. At the start of each trial, the participant adopted a standardized stance for balance assessment [80]. While secured to a posterior wall-mounted tether, the participant leaned forward by rotating about the ankle joints in a controlled, plank-like posture until the tether became taut Figure 1. Tether length was adjusted to achieve the desired shank inclination, measured as the angle between the shank and the vertical using a handheld goniometer aligned with the lateral malleolus. Two lean conditions, 10° and 18° from vertical, were tested. Shank orientation was determined using anatomical landmarks at the lateral malleolus and lateral femoral epicondyle, with all measurements collected by a trained researcher experienced in landmark identification and goniometric assessment.

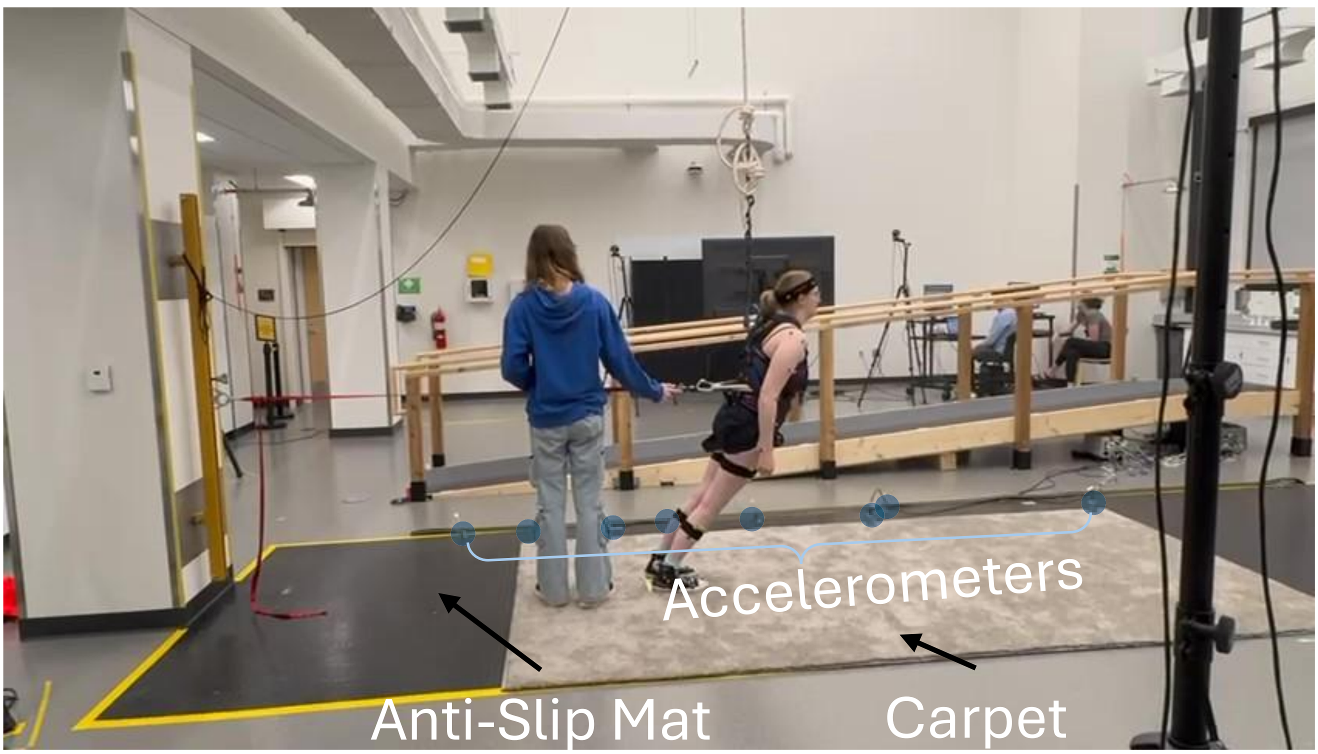
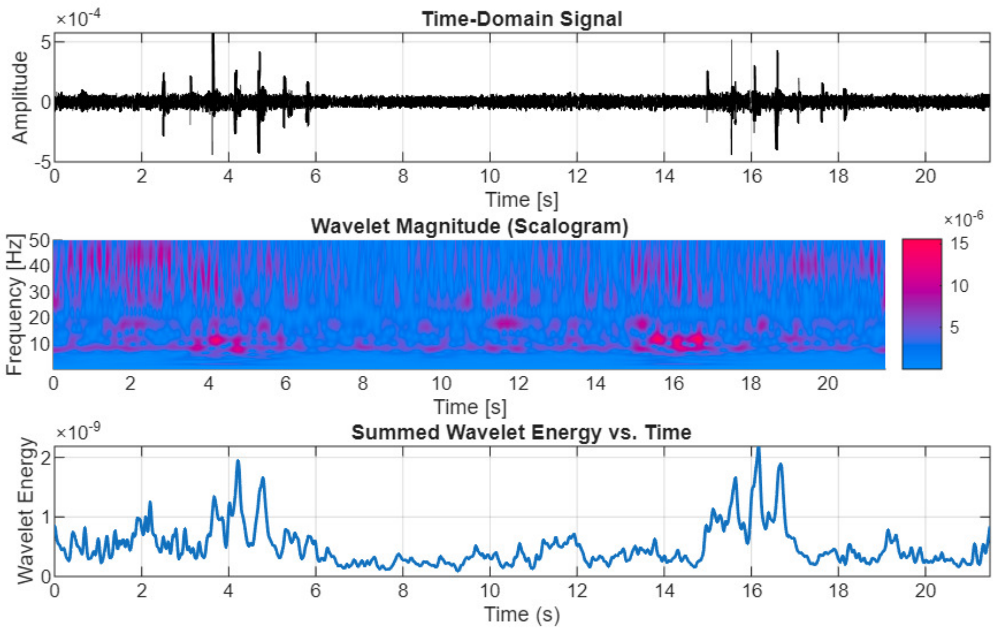


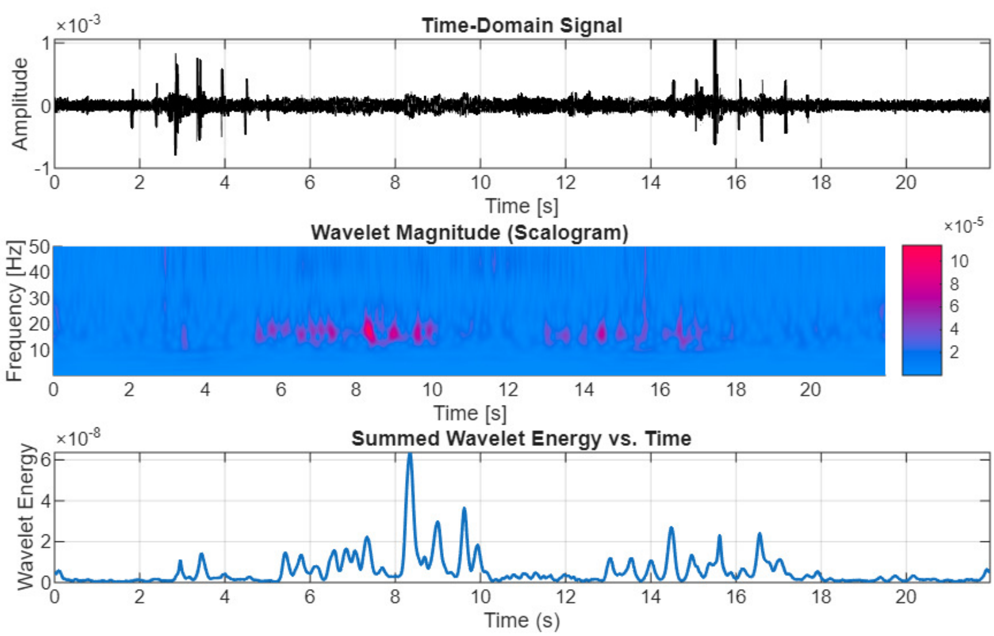
Fig. 1 Experimental setup showing the instrumentation and test configuration

Preliminary Results

Individual footfalls were successfully detected across all trials using the accelerometer array, with each event producing distinct vibration impulses consistent with heel-strike loading. Time–frequency analysis via continuous wavelet transformation (CWT) was then applied to the vertical acceleration signals to capture transient energy variations within the 0–50 Hz band Figure 2. The resulting wavelet scalograms will be used to get differences between nominal gait and reactive-balance events. Footstep segmentation will allow for the extraction of step-wise features, including dominant frequency content, temporal energy envelopes, and inter-sensor phase shifts. This classification pipeline will demonstrate a robust separation between nominal and reactive events, forming the basis for a real-time fall-risk indicator within building-integrated monitoring frameworks.



(a) Time Domain Analysis for the Anti-Slip Mat



(b) Time Domain Analysis for the Carpet

Fig. 2 Time Domain Analysis for the two surfaces

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Declaration of generative AI and AI-assisted technologies in the writing process

While preparing this work, the author(s) used ChatGPT to edit the language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publication’s content.

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