# Characterizing Structural Changes to Estimate Walking Gait Balance

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**Abstract**

We present a method for improving left-right walking gait balance using structural floor vibration sensing by characterizing changes in structural properties in the sensing area. Understanding and measuring human gait balance can be used to assess overall health status, mobility, and rehabilitation progress. The key research challenge is that structural properties in the sensing area may differ from one footstep location to the next, resulting in inaccurate footstep force and balance estimations. To address this challenge, our method performs sensor selection using the insight that some sensors in the sensor network are in a similar structural region as the footstep location and, therefore, are not as effected by the observed variations in structural properties as the other sensors. We evaluate the performance of our method by conducting uncontrolled real-world walking experiments in a residential structure. This evaluation shows that our method achieves a 1.6X reduction in force estimation error and a 2.4X reduction in balance estimation as compared to the baseline approach.

**Keywords: Structural Vibrations, Footstep Ground Reaction Forces, Sensor Selection, Walking Gait Balance, Structural Identification**

## 1 Introduction

Walking gait balance is a critical component of health assessment in a number of fields such as physical therapy, elder care, and neurology [1, 2, 3]. Existing methods for monitoring gait balance involve visual observation, motion-tracking cameras, pressure sensors, and wearable devices (e.g. accelerometers), but have operational limitations such as specialized staff (observation), line of sight (cameras), dense sensor deployment requirement (pressure sensors), and requiring users to carry a device at all times (wearables) [3, 4, 5]. Recently, structural vibration sensing has been introduced to overcome many of the limitations of prior works [6], but may be limited in scenarios where local variations in structural properties (i.e. stiffness) result in increased footstep ground reaction force and walking balance estimation errors.

In this paper, we present a system to estimate walking left-right gait balance (referred to as balance) using structural floor vibrations that is robust to these local variations in structural properties. The primary research challenge addressed through this work is that variations in structural properties at one footstep location can significantly change the amplitude of the measured vibration response as compared to footsteps at adjacent locations, resulting in large footstep force and balance estimation errors.

Our approach utilizes the insight that there exist some sensors in the network that reside in a similar structural region as the footstep location and experience fewer structural effects than the other sensors in the network do. Therefore, we take this structural effect into account during the training phase to select the sensor that has the least training error for each location, thereby reducing the errors in footstep ground reaction force estimation and balance estimation. Our method contains three primary components: 1) a footstep detection module, 2) a force-amplitude-distance learning module, and 3) a structure-informed footstep force estimation module. We validate our approach using real-world walking experiments conducted in a residential apartment building.

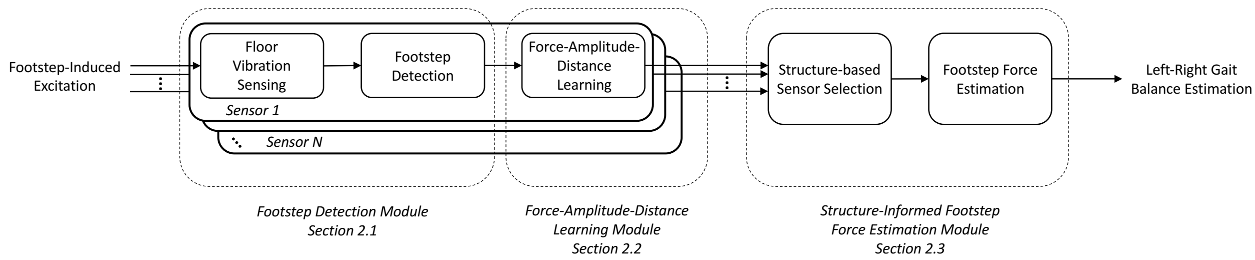


**Fig. 1** Gait Balance Estimation Approach Overview

## 2 Gait Balance Estimation Approach

Our balance estimation approach consists of three main modules: 1) a footstep detection module that isolates individual footstep responses, 2) a force-amplitude-distance learning module that maps footstep forces to signal amplitudes and distances, and 3) a structure-informed footstep force estimation module that selects the sensor with lowest training error to estimate footstep forces and balance. An overview of our system can be found in Figure 1.

### Footstep Detection Module

In the first module of our approach, our system senses the floor vibration response due to a footstep-induced excitation using a SM-24 geophone vibration sensor [7] and isolates individual footstep signals. We utilize an anomaly detection algorithm to distinguish the footstep-induced excitations from the ambient noise [8]. Footsteps are identified as vibration responses that exceed an empirically-defined ambient noise threshold. Once identified, individual footstep responses are isolated from the total signal and used for subsequent modules.

### Force-Amplitude-Distance Learning Module

In this module, our system estimates the relationship between the input footstep forces, the measured signal amplitude, and the distance between the footstep and the sensor. This relationship is estimated using an adaptation of the method introduced in [6]. Using known footstep forces, peak footstep-induced signal amplitude values, and footstep-sensor distances, our system learns the relationship between footstep forces, amplitude, and distance. This process is completed independently for each sensor located in the region of the footstep.

### Structure-Informed Footstep Force Estimation Module

With the final module of our system, we utilize the structural insights described earlier to estimate footstep forces and left-right walking gait balance. With variations in structural properties, the force-amplitude-distance function from the second module may not adequately represent the structural response for effected sensors. Figure 2 shows an example of this structure effect. With Sensor 1, the fit curve at a distance of approx. 3.75m is considerably greater than the ground truth footstep data (actual footstep forces/amplitude). However, when the same step location is considered using Sensor 4, the structural effect is much smaller. Using this observation, this module selects one sensor for each step location that has the smallest training error and uses that sensor to estimate footstep forces for that location. Finally, with estimated footstep forces, we estimate balance by calculating the Symmetry Index (S.I.) which compares consecutive left-foot and right-foot footstep forces [9].

## 3 Evaluation

To evaluate the validity of our balance estimation approach, we conducted real-world walking experiments in a wood-framed residential apartment structure. For the evaluation, ground truth footstep forces were collected using FlexiForce A401 pressure sensors [10], and footstep locations were chosen based on the natural stride length of the participant. A total of 50 footsteps were recorded across 10 footstep locations using 4 evenly spaced geophone sensors. Of these 50 footsteps, 30 were randomly chosen for training and 20 were used for evaluation. Our method

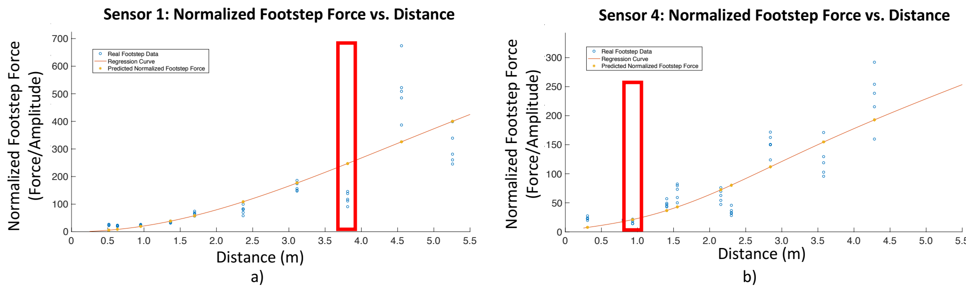


**Fig. 2** (a) at the highlighted location, structural differences result in low accuracy for Sensor 1. (b) For the same footstep location, Sensor 4 exhibits much higher accuracy

achieves a 1.6X reduction in footstep force estimation root mean squared error (RMSE) from a baseline approach that averages the force estimation from all four sensors (baseline: 66.5N (14.95 lbs.), our approach: 40.2N (9.04 lbs.)). Furthermore, for balance estimation our method achieves a 2.4X reduction in S.I. estimation RMSE from the baseline approach (baseline: 23.4%, our approach: 9.92%).

## 4 Conclusions

In this paper, we introduce a method for estimating left-right gait balance using structural vibrations that incorporates variations in structural properties. To reduce large errors associated with footstep locations where structural properties may have changed, our method selects the sensor that is least effected by these changes and uses it for estimating footstep forces and balance at that location. With this approach, our system achieves a 1.6X reduction in footstep force estimation RMSE and a 2.4X reduction in balance S.I. RMSE from the baseline approach.

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