Poster Abstract: Gait Health Monitoring Through Footstep-Induced Floor Vibrations

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ABSTRACT

Gait health monitoring is critical for condition diagnosis and fall prediction in elderly populations. Existing methods for gait health monitoring (e.g. direct observation and sensing) are not suitable for non-clinical environments due to qualitative assessments or operational limitations. Our method utilizes footstep-induced floor vibration sensing to provide a passive gait health monitoring platform that can be used in non-clinical environments (e.g. home settings) to provide gait health information in a timely manner. We decompose vibration responses to obtain signal peaks that correspond to temporal gait information and leverage foot dominance to learn a signal amplitude-footstep ground reaction force transfer function. Preliminary results show that temporal gait parameters can be estimated with up to 99% accuracy and gait balance symmetry can be estimated with as low as 10.4% error.

KEYWORDS

Gait Health, Footstep Ground Reaction Forces, Temporal Gait Parameters, Structural Vibrations

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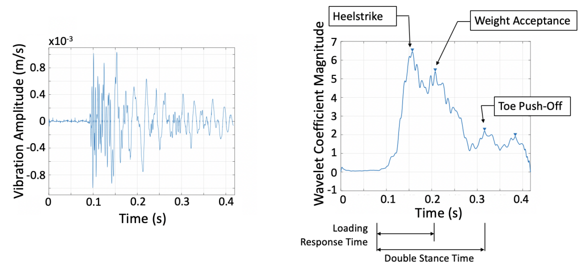

(a) Raw Footstep Signal (b) Decomposed Signal

Figure 1: Gait Health Monitoring System. (a) shows the raw footstep-induced floor vibration signal, (b) shows the decomposed signal and identified gait information.

1 INTRODUCTION

Gait health monitoring is a critical component of occupant health assessment across various healthcare applications. For example, it has be used for diagnosis of joint problems, neurodegenerative diseases, and elderly fall risk [1]. Gait health monitoring typically involves assessment of gait parameters (e.g. loading response time, step time, stride time, double stance time) as well as footstep ground reaction forces and balance symmetry. Current methods include direct observation by medical personnel and various sensing modalities. Direct observation approaches require specially trained medical staff while sensing approaches including pressure-, vision-, acoustic-, and wearable-based methods are limited in non-clinical settings due to operational requirements such as dense sensor deployment, perceived lack of privacy, sensitivity to background noise, and requiring persons to always wear a device [7].

To overcome the limitations of these existing approaches, our method uses footstep-induced floor vibration sensing to monitor gait. The use of vibration sensing enables passive gait monitoring with sparse sensing configurations (up to 20m sensing range) that is suitable for non-clinical applications (i.e. home health monitoring). Prior work using vibration sensing has been successful for person identification, localization, monitoring gait balance, and gait temporal parameter estimation [2, 3, 6, 8]. The research challenge addressed in this work is that the vibration signals contain a mixture of responses from each aspect of the foot interaction with the floor (e.g. heel strike, flat foot, toe push-off, etc.) and is influenced by foot dominance, making it difficult to extract the individual signal components that correspond to gait parameters. We address the challenge by decomposing the signal in the temporal-spectral domain to isolate individual phases of gait, and then by clustering the raw signal into dominate and non-dominate footsteps based on trace-level walking direction and relative step locations, and independently train for each foot. We evaluate our system with real-world walking experiments in an elder care facility and in a campus building.

2 SYSTEM OVERVIEW

Our approach for gait health monitoring includes 3 primary modules: 1) footstep detection and signal extraction, 2) temporal gait parameter estimation, and 3) footstep ground reaction force and balance symmetry estimation.

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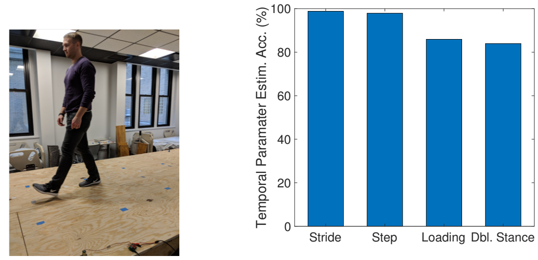
Footstep Detection: In the footstep detection module, our system extracts individual footstep responses from the overall vibration response. We first collect the vibration response of the floor structure using a SM-24 geophone sensor, and amplify the vibration signal 10-1000X to increase signal resolution. We then use an anomaly detection algorithm based on our prior work to isolate individual footsteps from the total vibration response [6]. This approach is based on the insight that footsteps represent impulsive events and their signal variance exceeds that of ambient vibration levels (i.e. when no footstep is present).

Temporal Gait Parameter Estimation: Once a detected footstep is isolated from the vibration signal, we estimate temporal gait parameters by transforming the signal to the temporal-spectral domain using a continuous wavelet transform (CWT). With the transformed signal, we decompose it into the scale that contains the most information about the individual components of gait by selecting the one with the most signal energy [3]. We then use the decomposed signal to identify peaks that correspond to foot interactions with the floor, as shown in Figure 1b. Using the isolated peaks, we estimate the gait temporal parameters (stride time, step time, loading response time, and double stance time).

Footstep Force and Gait Balance Estimation: In the final module our method considers the amplitude of the isolated footstep responses and trains a function mapping it to footstep ground reaction forces (GRFs). To accomplish this, we normalize the footstep signal amplitude by a distance attenuation factor, which is based on the rate at which vibration signals attenuate with distance [2]. Then we cluster the footsteps into dominate/non-dominate groups based on relative footstep locations and walking direction across the footstep trace (a series of consecutive footsteps). Finally we train a function to map normalized amplitudes to GRFs and use this function to estimate GRFs and balance symmetry. Balance symmetry is estimated based on a metric known as the Symmetry Index (SI), where asymmetric gait occurs when the SI exceeds 10% [4, 5].

3 PRELIMINARY RESULTS

We evaluated our gait health monitoring platform by conducting real-world walking experiments in two experimental locations: Vincentian Homes (an elder care facility) and Porter Hall at Carnegie Mellon University. To ensure sensor synchronization we use a directly powered wired system with six sensors at two meter spacing. The sensors are more densely spaced in order to understand information quality for different sensing configurations. In Vincentian Homes, 310 footsteps were recorded across 3 walking speeds (slow, normal, fast), and 3 balance conditions (normal, lean right/left). Footstep ground reaction forces and gait balance symmetry were compared to a baseline approach (which does not consider signal attenuation or foot dominance). Figure 2a shows one of the experimental locations. Preliminary results show an average estimation accuracy of 89% for GRFs and an average SI error of 10.4%, corresponding to 1.6X error reduction from the baseline for SI estimation, and is on the same order of magnitude as the threshold for asymmetric gait [5]. In Porter Hall, our method achieved average accuracy of 99%, 98%, 86%, and 84% for stride time, step time, loading response time, and double stance time estimation across 540 footsteps for 2 participants and 3 walking speeds, as shown in Figure 2b.



(a) Experimental Location **(b) Temporal Parameter Results**

Figure 2: Evaluation Results. (a) Porter Hall experimental location, and (b) accuracy for estimating temporal gait parameters using our approach.

4 CONCLUSIONS AND FUTURE WORK

In this work we utilize footstep-induced vibration sensing to monitor gait health. Our preliminary results are promising and indicate parameter estimation accuracies of up to 99%, footstep force estimation accuracy of up to 89%, and balance symmetry estimation error of 10.4%. In our future work, we plan to explore the robustness of our system to multiple concurrent walkers, varying persons, locations, and body sizes to understand its limitations. Further, we plan to explore the heel and toe interactions during gait in order to identify inter-foot pressure distributions while walking.

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