

Title: Structural Health Monitoring and Evaluation of Human Gait to Assist in the Diagnosis of Parkinson's Disease

Authors: Iris Tien
Steven D. Glaser

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ABSTRACT¹

The human body is a complex structure, and its structural health can be monitored using sensors. A system using wireless inertial measurement units for data acquisition and the monitoring of human gait is described. Gait analysis is used in the medical community to diagnose and evaluate patients with Parkinson's disease. Currently, such analysis is done subjectively. The system described quantifies gait analysis by making detailed and continuous measurements of foot motions during walking. Raw acceleration and rotation rate data is transformed into time histories of displacements and Euler angles, providing clinicians with precise numerical measurements of a multitude of gait parameters. A discussion of selected simple features with clear physical analogues shows the utility of our system to evaluate different damage states and distinguish between healthy and infirmed cohorts.

INTRODUCTION

Structural health monitoring (SHM) involves the observation of a structure over time using a sensor and evaluation system. The human body is perhaps the most complicated structure in existence, so structural health monitoring and evaluation (SHME) of the corporeal structure presents particularly difficult problems to the researcher. This paper presents our solution to some of the important problems found when applying SHME to understand human gait. The motivation behind the creation of our human health monitoring system is to assist clinicians in the diagnosis and evaluation of patients with Parkinson's disease (PD). Currently, 1.5 million Americans have PD, with an estimated 60,000 new cases diagnosed each year. As PD has a higher incidence among the elderly, the number of people with the disease will likely increase in the coming years as the U.S. population ages.

¹ Iris Tien and Steven D. Glaser, University of California, Berkeley, Center for Information Technology Research in the Interest of Society (CITRIS), and the Department of Civil and Environmental Engineering, 252 Hearst Memorial Mining Building, Berkeley, CA 94720, U.S.A.

Despite its prevalence, there are no objective tests for the presence or progression of the disease. Diagnoses and evaluations of PD are made based on the subjective judgments of a skilled and experienced clinician based on their observation of the patient's gait. This leaves the process open to variation among clinicians and even possible human errors in judgments. In addition, for patients in remote areas where experts in PD may not be available, it is difficult to receive accurate diagnoses and prognoses.

As an abstraction, measuring and distinguishing between different stages of PD in a patient is analogous to damage detection and state analysis of man-made structures. We have developed a SHME system that allows the absolute description of the foot through time, hence the quantification of gait, leading to the quantification of the diagnostic indicators, fine and gross, of PD. In the current state, clinicians use qualitative analysis of gait to diagnose a great many neuropathologies. The potential to impact the lives of an increasingly large segment of the population coupled with the opportunities of tele-medicine motivates our research.

GAIT ANALYSIS

The process of evaluating patients for PD includes the observation of a patient's gait. Previous studies have found that patients with PD exhibit increased cadence, as measured in steps per minute, and decreased stride length, which indicates how much distance is covered with each step [1]. PD patients also exhibit a decreased ability to maintain a steady gait, which increases the stride-to-stride variability in their gait cycle timing [2]. In the practical setting of patient evaluations, there is currently no easy-to-use technical equipment available to provide clinicians with precise numerical measurements of these, and perhaps finer, diagnostic parameters. Sensitivity is limited by the ability of the human eye to only discern relatively slow, and large, changes in movement. To move past the current state of practice, clinicians need to consider more than just cadence and stride length when evaluating patients for PD.

INERTIAL MEASUREMENT UNITS

A system most beneficial in assisting clinicians in the evaluation of PD will have the capabilities to measure beyond what the human eye can see. The measurement package must not interfere with the natural movements of the patients, especially the elderly and infirm. We have therefore chosen powerful, and still small, inertial measurement units (IMUs) as the sensors for our system. Our current IMUs, shown in Figure 1, is a custom-made device manufactured by MicroStrain, Inc., built off the 3DM-GX2 Gyro Enhanced Orientation Sensor model [3]. The unit includes a 50-g triaxial accelerometer, a 1200 deg/s triaxial rate gyroscope, and a 2-Gauss triaxial magnetometer. With the battery attached, the unit measures 60 mm x 38 mm x 18 mm and weighs 44 grams each. It communicates with a Nokia N810 hand-held computer via Bluetooth. The units are compact and lightweight enough not to interfere with natural human movements. Attached to the foot, the

IMUs capture the full, three-dimensional motions of the foot during walking, as accelerations and rate of rotations about the three Cartesian coordinates.



Figure 1. Scale of IMU and battery pack.

Data is sampled at 100 Hz, a fine sampling rate selected to capture minute details of motion. Continuous sampling allows measurements to be made during the flight of a foot step, as opposed to only when the foot hits the ground, as is the case for systems utilizing force-sensitive insoles placed in the patient's shoes [1]. Enabling clinicians to observe full pedal motion, at a very fine granularity, and continuously, during evaluation of a patient's gait, is a significant improvement over presently available systems [4].

Some sample signals of acceleration in the forward direction (a) and rate of rotation along the transverse plane in the sagittal direction (b) from the accelerometer and gyroscope, respectively, are shown in Figure 2, for the IMU attached to the top of the foot (connected by the shoelaces) during walking. Five gait cycles are shown. This detailed time-series data allows for continuous monitoring of foot motion.

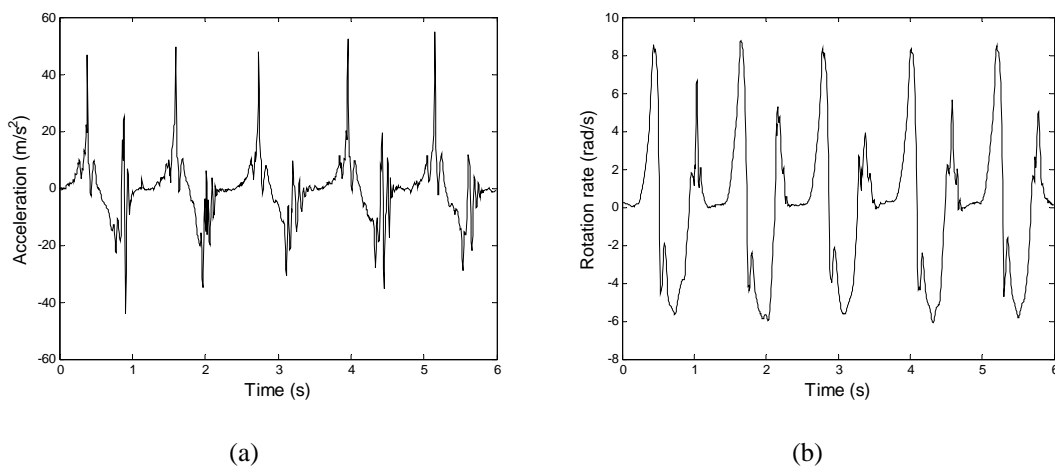


Figure 2. Time-series data for five gait cycles of acceleration in the forward direction (a) and rate of rotation along the transverse plane in the sagittal direction (b) from IMU attached to the foot.

DATA TRANSFORMATION

A clinician observing a patient's gait is not likely to be observing accelerations, as shown in Figure 2 (a), but rather, displacements. A direct double integration of acceleration to obtain displacement results in exponentially increasing error due to summation of sensor drift and noise. To transform the acceleration to the more intuitive displacement measurements requires a method known as zero velocity updating, or "zupting." This method has been utilized in inertial navigation applications [5], and is the method used here. The double integration can now be made for each single step, and from methods used to assess the drift at the end of every step, determined by when the foot velocity goes to zero, the error can be removed. Accurate values of displacement can then be calculated over longer periods of time, for example, thousands of individual steps [6].

Similarly, the rate of rotation, provided by MEMS-based rate gyros as shown in Figure 2 (b), is difficult to visualize. The rotation rate from the gyroscope is therefore integrated over time to produce a measure of total angle rotated as a function of time. In a three-dimensional space, multiplication of rotation is not commutative. However, in our application, we are calculating small changes in angle over small time steps of 1/100 s. Thus, a small angle approximation can be made so that any order of multiplication of rotation produces a unique solution, and integration of the gyroscope angle rate, providing measurements of the angle rotated.

As an example, Figure 3 shows the results of these data transformation methods for the raw data graphed in Figure 2. The forward displacement (a) is from the acceleration data, and the angle rotated (b) is from the rotation rate data. The clarity of these displacement signals provides an advantage over the accelerometry used in previous studies [7].

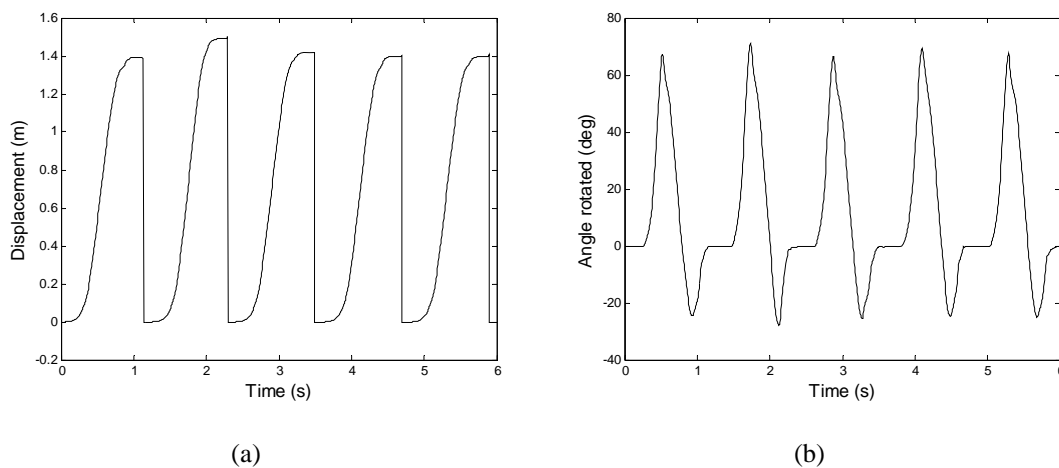


Figure 3. Recorded time-series data transformed into displacement in the forward direction (a) and angle rotated along the transverse plane in the sagittal direction (b).

DISCUSSION OF FEATURES

A major feature of a SHME system is the ability to identify features that distinguish between different states. Through proper experimental design, our diagnostic space is divided into the control (well) and damaged states, or non-PD and PD states. Data has been collected from both cohorts, and an example of the results obtained for a single control subject compared to a subject with advanced PD is presented in Figure 4. There is a clear visual difference between the signals for the two subjects, both in horizontal vector displacement (a) and rotation along the transverse plane in the sagittal direction (b) time histories. From these signals, physically-based features can be extracted to quantify the differences. The numerical values of some selected physical features for this data set are given in Table I. These simple features were selected based on their clear physical analogues that can be easily understood by the medical community. While more data needs to be analyzed to find additional, as well as the most significant, features to distinguish between non-PD and PD patients, it is clear that patients from these two groups have markedly different characteristics for even these simple features. The PD patient exhibits higher cadence, shorter stride length, decreased velocity, lower maximum vertical displacement, and decreased angle of rotation of the foot during walking, both in the plantar flexion and dorsiflexion directions.

The higher cadence, shorter stride length, and decreased velocity are consistent with previous findings [1]. These parameters describe the short, shuffling gait characteristic of parkinsonian patients. Patients with PD also have difficulty regulating their gait to adapt to their environment [8]. Decreased vertical displacement represents an especially increased difficulty in adjusting gait to match changing terrain, leading to gait instability and an increased rate of falls. Decreased foot rotation may also contribute to an increased rate of falls as the less flexible movement at the ankle of a PD patient results in a decreased ability for the subject to easily adjust body weight when compensating for the instabilities associated with normal walking.

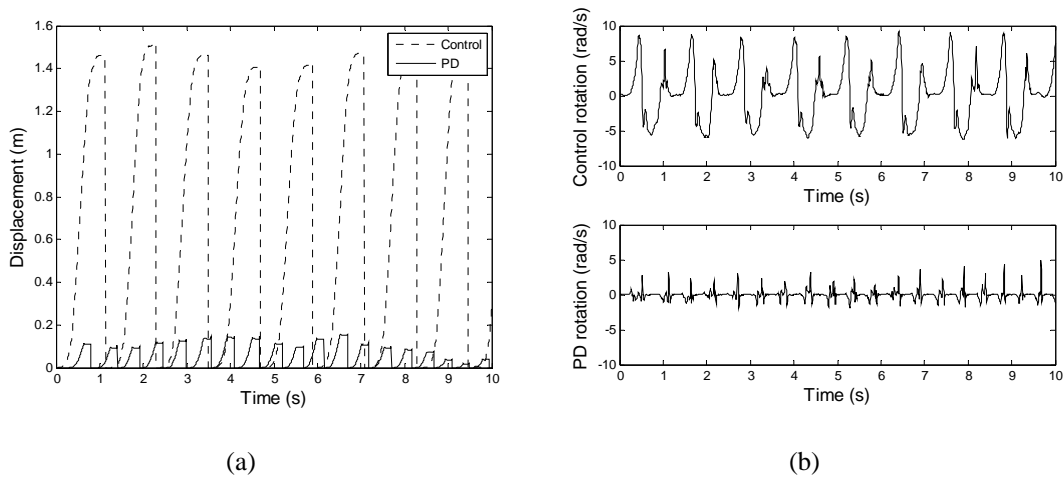
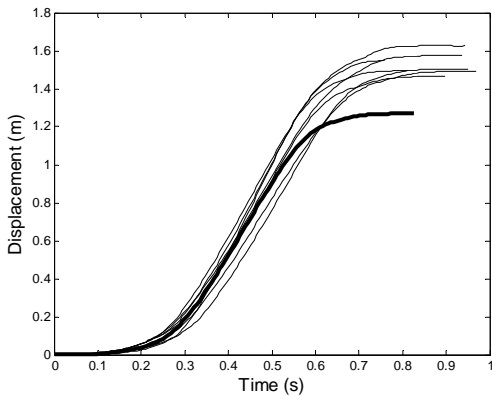


Figure 4. Comparison of foot horizontal vector displacement (a) and rotation along the transverse plane in the sagittal direction (b) for control and PD subjects.

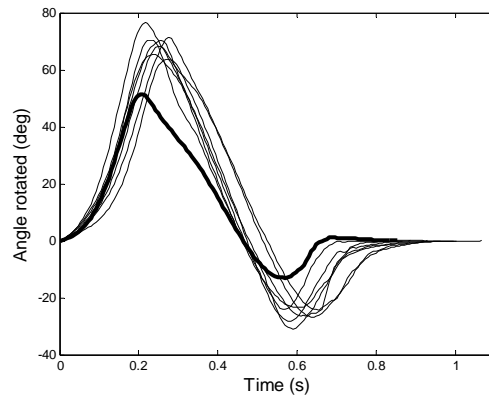
TABLE I. SELECTED GAIT METRICS FOR A CONTROL AND A PD SUBJECT

	Control	PD
Cadence (steps/min)		
Mean	50.1	117.5
Standard deviation	1.2	13.0
Stride length (m)		
Mean	1.462	0.103
Standard deviation	0.036	0.038
Velocity (m/s)		
Mean	1.221	0.201
Standard deviation	0.054	0.063
Maximum vertical displacement (m)		
Mean	0.111	0.0081
Standard deviation	0.016	0.0025
Maximum angle of plantar flexion (deg)		
Mean	68.9	12.1
Standard deviation	1.6	4.7
Maximum angle of dorsiflexion (deg)		
Mean	26.4	1.8
Standard deviation	1.7	0.5

The data presented in Figure 5 shows that more subtle differences between subjects can be detected as well. Each line represents the results of horizontal vector displacement (a) and angle rotated along the transverse plane in the sagittal direction (b) for the average step for each control subject – all males over the age of 50. The results show a strong consistency across multiple subjects. In contrast, the bold line in both (a) and (b) indicate the average step of a subject who was subjectively noted to be walking with a stiff right arm. Limb stiffness can be an indicator of the presence of neurological disease. Using our system, the qualitative observation is seen to correspond with a quantitative difference in gait that was not observable with the naked eye. It is this ability to make detailed and precise measurements of displacement and angular displacement, and interpret the data in physical terms, that makes our system an asset to the practice of neurology.



(a)



(b)

Figure 5. Horizontal vector displacement (a) and rotation along the transverse plane in the sagittal direction (b) results for the average step for multiple subjects. The bold line indicates the gait of a subject with observed limb stiffness.

CONCLUSIONS AND FUTURE WORK

The human body is a highly complex structure, and its state of structural health monitored using sensors. The state can then be evaluated using direct physical models. In this work, IMUs are used to make detailed and continuous measurements of foot motions during walking, with zuping-based recursive updating algorithms transforming the measured accelerations and angular rate changes into displacements and Euler angles through time. While gait characteristics are a diagnostic for a variety of neuropathologies, we focus our analysis to providing a clinical tool to help the clinician make the diagnosis of Parkinson's disease. Our quantitative gait SHME system provides clinicians with access to precise numerical measurements of a multitude of gait parameters, which allows for a simple differentiation between non-PD and PD cohorts.

To improve measurement reliability, the recursive updating algorithms are being improved so that the easily-biased magnetometer can be dispensed with. We are incorporating accelerometers and rate gyros with an order-of-magnitude reduction of the noise floor compared with the current devices, to improve signal-to-noise ratio, sensitivity, and reliability. We are also currently investigating more, and better, features with which to discern between members of healthy and infirmed cohorts, ranging from non-PD to mild PD to advanced PD. The selected discriminant features will then be used in a classification framework, which in turn will assist clinicians in their classification of patients with unknown conditions.

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