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# An Untethered Shoe with Vibratory Feedback for Improving Gait of Parkinson's Patients: The PDShoe

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***Abstract*— Subjects with Parkinson's disease (PD) often have trouble with ambulation. Some research has shown that auxiliary cueing in the form of vision, audio, or vibration can improve the gait of PD patients. We have developed a new vibratory feedback shoe, known as the PDShoe, which builds on existing research. This device can modulate both frequency and amplitude of feedback for the wearer. It is untethered, and thus can be worn during daily activities. Pressure and tactor status data are transmitted wirelessly over a personal area network to a notebook computer. This computer can also control the tactor actuation and stimulation frequency. This paper describes the details of design and construction of the PDShoe. A preliminary evaluation with four Parkinson's disease subjects and two healthy subjects is included to show the usability of the device.**

## I. INTRODUCTION

Parkinson's disease is an idiopathic condition, often characterized by gait impairments, arising from progressive degeneration of the central nervous system. Some research has shown that external cues in the form of vision, audio, or vibration can help in motor planning and execution.

Behrman[1], Del Olmo[3], and Khudados et al[5] have each shown that visual, auditory, and vibration respectively can improve the gait of Parkinson's patients. More recently, King et al[6] showed that whole body vibration can improve Unified Parkinson's Disease Rating Scale measures for tremor and rigidity. De Nunzio et al[2] demonstrated an increased stride length, cadence, and consequently velocity in Parkinson's patients exposed to trunk vibratory stimulus. Protas et al[8] showed a positive benefit to gait training at a higher than overground treadmill speed. Such training was found to reduce fall incidence and improve both dynamic balance and gait speed. Ghoseiri et al[4] found that vibration applied to the posterior lumbar region of Parkinson's patients improved balance. In 2007, Novak and Novak[7] performed a pilot study assessing the short term effects of step synchronized vibration stimulation to the plantar region of the feet of Parkinson's patients and age matched healthy subjects. They showed improvements of walking speed, stride period, stride length, cadence, and consistency of gait. The healthy subject control group also showed improvements in walking speed and consistency of gait. This was demonstrated with eccentric mass motors embedded in a shoe insole that were activated when applied pressure was higher than a minimum threshold. These motors vibrated at a fixed frequency of 70 Hz with a fixed amplitude. log data on use and provided feedback.

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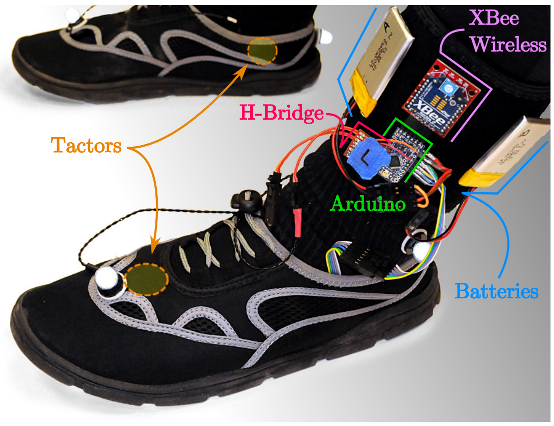


Fig. 1: The PDShoe as worn by a participating subject.

The PDShoe advances the current state-of-the-art through (a) the use of tactors capable of modulating both frequency and amplitude of vibration independently, (b) untethered portability of the device - it can be worn almost anywhere by the patient, and (c) on board data collection - providing the tools for clinical staff to analyze therapeutic efficacy.

This paper covers the mechanical, and electronic design and construction of the PDShoe. Results from a training protocol, evaluated with two measures of gait, are discussed as well.

## II. DESIGN

Prototype components were chosen based on performance of desired function and ease of rapid construction. For example, the shoes were chosen because of their elastic nature, i.e., a single pair of shoes can be used for subjects with shoe sizes within a large range. The microprocessor platform within the shoe is inherently designed as a rapid development platform.

## A. The Shoe

Building on the design presented by Novak and Novak[7], a pair of water shoes, shown in Figure 1, was used as a platform to house the actuators and electronics. The water shoes provide many prototyping advantages over athletic shoes. First, the shoes are designed to be one-size-fits-most. This flexibility reduces the need for multiple shoes. Second, the vamp and quarter walls of the shoe are constructed from a thin material that is highly conductive to vibratory actuation. Three sizes of shoes were used. The small size corresponded to an American men's shoe size of 6 to 8, medium was 9 to 11, and large was 12 to 13.

## B. Sensing

Three sensors are used in each shoe, placed at the heel, ball, and toe of the foot[1]. These are force sensing variable resistors. These sensors are flexible, durable, and able to measure the phases of gait if placed between the foot and shoe. The force sensing variable resistors are connected to the microprocessor in a voltage divider circuit; the voltage across the fixed resistor in the circuit is measured by the on-board 10 bit ADC built into the Arduino microprocessor. The sensors were assumed to follow the calibration information provided by the supplier.

## C. Actuation

Vibration stimulation was provided via two or three (depending on the subject) Engineering Acoustics Inc.[2] C-2 tactors. These actuators are fundamentally different from the eccentric mass vibratory motors often used in many haptic applications. The magnitude and frequency of the eccentric mass motors is coupled and modulated by varying the direct current input voltage to the motor. Conversely, the tactors are designed such that frequency and amplitude are independent. These tactors function like an audio speaker. Like speakers and unlike eccentric mass motors, tactors must be driven with an AC input. The microprocessor used on the PDShoe is capable of providing this AC signal. The heel tactor is placed on the medial side of the calcaneus, where the heel pressure pad is located. One subject (PD013) required two tactors on his heel, lateral and medial. These two tactors were wired in series to distribute the voltage between the two and prevent the tactors from warming up. The toe tactor was placed on the anterior distal side of the metatarsals, on top of the foot and between the ball and toe pressure pads.

## D. Processing and Logging

The central processor of the shoe is an Arduino[3] Mini Pro. This microprocessor has six analog inputs, three of which are used for the pressure sensors, and fourteen available digital IO. Two of these digital IO are used for wireless communication between each shoe and the computer. A schematic of the circuit is shown in Figure 2. Upon command from the computer, several parameters can be changed in the shoe without the need to reprogram or reconnect via USB; this is all done via the wireless XBee network. The voltage from the pressure sensors as well as the logical output state are transmitted from each shoe to the computer using this same wireless link. The on-shoe software samples inputs, updates outputs, and transmits to the computer at better than 20 Hz. The shoes are synchronized to each other, wirelessly, before data collection begins.

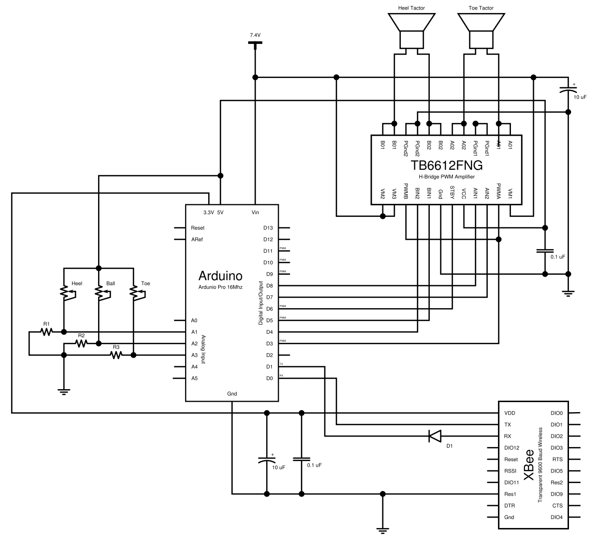


Fig. 2: A schematic representation of the PDShoe electronics. Note that the amplitude of the tactors is fixed, but does not vary while the vibratory frequency is changed.

## E. Logic Control

The Arduino microprocessor has been programmed such that upon heel contact, determined when the heel pressure sensor reports a value that exceeds a threshold of 22.5 N, the heel actuator begins to vibrate at a predetermined frequency. If the ball or toe of the foot are in contact with the ground, the toe actuator vibrates. When both the heel and ball or toe are concurrently in contact, both tactors vibrate. This condition is met during stance phase of ambulation. However, in the event that these pressure sensors report simultaneous contact for greater than one second, both actuators are disabled. This one second window was empirically found to be long enough for stance in the healthy individual, but short enough to reject suspected motionless standing. Once ambulation is resumed, the pressures on the three sensors vary enough that normal operation is resumed. The threshold was found to best judge if the foot was in contact with the ground while rejecting pressure caused by fit of the shoe and is the same for all three sensors.

## F. Power

Two 3.7 V, 1000 mAH lithium polymer batteries are used to power each shoe. These are similar to the battery found in many mobile phones. They are used in series to provide 7.4 V for use by the microprocessor and h-bridge amplifier used for the tactors. In a typical training session, the batteries last about 70 minutes. If the tactors are disabled for evaluation sessions, they can last several hours.

[1]Interlink Electronics, 546 Flynn Road, Camarillo, CA 93012
[2]Engineering Acoustics, Inc., 406 Live Oaks Blvd, Casselberry, FL 32707
[3]Arduino available from SparkFun.com in Boulder, CO

| Subject | Sex (M:F) | Age (Years) | Symptoms (Years) | Stage (HY) | MMSE |
|---|---|---|---|---|---|
| **PD** | | | | | |
| PD006 | F | 67 | 11 | 3 | 30 |
| PD007 | M | 73 | 6 | 3 | 30 |
| PD009 | M | 52 | 11 | 2.5 | 30 |
| PD013 | M | 57 | 4 | 1.5 | 30 |
| **Group** | **3:1** | **62.25±9.5** | **8±3.6** | **2.5±0.7** | **30** |
| **Healthy Subjects** | | | | | |
| HS011 | F | 58 | | | |
| HS014 | M | 59 | | | |
| **Group** | **1:1** | **58.5±0.7** | | | |

TABLE I: Subject Demographics for initial PDShoe study.

## III. DEVICE EVALUATION AND FINDINGS

Six subjects were included in this study. Four of these subjects had been diagnosed with Parkinson's disease (PD) and the two others were healthy controls. Those with PD were included if their Hoehn and Yahr stage of the disease score was greater than one and less than four (indicating mild to moderate disease), a Mini Mental State Exam (MMSE) score greater than 24 (absent of dementia), they were self ambulatory (use of cane okay), and they could follow directions from the researchers in either English or Hindi language. Subjects were excluded if they exhibited other neurological impairments or physical disabilities, or used a walker. Healthy subjects were included if they were between the ages of 50 and 70 years. Potential healthy subjects were excluded if they exhibited any neurological disorders or physical impairments. University of Delaware (UD), Newark, DE, USA. Subject demographics are given in Table I. All IRB protocols were followed.

### A. Protocol

Subjects chose an appropriate shoe size, after which the tactors and other electronics were placed as described above. The vibration frequency was set to 175 Hz, a frequency found to be low enough that it wasn't loud yet high enough that it was easily sensed. Before each session began, the sensation of vibration feedback was verified. Subjects attended nine sessions (morning and afternoon Monday-Thursday and morning of Friday). Each session started with a two minute walking bout (vibration off), followed by three six minute walking bouts (vibration on), and ended with a two minute walking bout (vibration off). All subjects were asked to rest for two minutes between walking bouts. During each walking bout, subjects walked 30 meter laps in a wide, clear hallway. They were asked to walk at a self-selected comfortable pace. A researcher monitored the subjects gait and signaled the start and stop times during all sessions.

### B. Measures and Processing

Descriptive measures included age, sex, years since PD symptoms appeared, and Hoehn & Yahr (HY) stage of disease. Additionally subjects were asked about comfort of shoe and vibration.

We used two measures to evaluate status and changes in gait. We evaluated the stride period, as determined by the time difference between heel strike and the subsequent heel strike on the same foot. We also evaluated stance to swing ratio, as determined by the relative ratio of time spent in stance to time spent in swing for each stride. Stance time is determined by the difference between toe off time and heel strike time of the same stride. All reported measures were taken from the first two minute walking bout (vibration off) of the session. The Pre measures thus represent status of the subject before any vibration therapy was administered. The Post measure reflects the status of the subject the day after the final vibration therapy, before the clinical evaluation. These samples were chosen to assess any carry over effects.

For each subject, the arithmetic mean and standard deviation for all gait measures were calculated. The arithmetic mean was used to combine the means of the healthy controls for all measures. A pooled standard deviation was calculated to describe the variability within the group of control subjects and within the group of PD subjects. Percent change was calculated to illustrate differences between sessions one and nine, pre and post therapy respectively. The difference was determined between the control group and PD group for both pre and post therapy sessions. A paired t-test was used to determine statistical significance of changes and differences within each PD subject shoe measure.

### C. Comparing PD to Healthy Subjects Before Therapy

As seen in Table II, there is a clear difference between the pooled measures of stride period in the healthy and PD subject groups. The healthy subjects took longer strides than the PD group (1.13 s for healthy, 1.09 s for PD on the dominant foot). This is as expected, as PD is characterized by short, shuffling steps. Both groups have approximately the same variability in this measure though (0.07 s for both on the dominant foot). The stance to swing ratio also shows a difference between the groups. On the dominant foot, the stance to swing ratio is nearly the same (1.83 for healthy, 1.77 for PD), but the between foot variability ($\delta_{foot}$) is notably different between the groups (0.04 for healthy, 0.14 for PD). The within foot variability is also larger in the PD group than in the healthy group (0.23 for healthy, 0.30 for PD on the dominant foot; 0.22 for healthy, 0.62 for PD on the non-dominant foot). This measure is as expected given that dyskinesia[4] is common among PD patients. Inspection of Table III reveals that the healthy subjects have similar measures of stance to swing ratio both within subject, between foot and between subject. The PD subjects measure of stance to swing ratio are visibly different between subjects and within subject, between foot.

### D. Comparing Differences Before and After Therapy

Table II shows that the stride period for the PD group decreased after the week of therapy (1.09 s to 1.05 s on the dominant foot). This decrease was approximately equal for each foot (-3.61% and -3.68%), but was not found to be significant ($p$ = .46). The absolute difference between the healthy group and the PD group increases (0.04 to 0.08

[4]Dyskinesia presents as diminished voluntary movements and the presence of involuntary movements.

TABLE II: Stride period (seconds) calculated from heel strike to subsequent heel strike on the same foot. Stance to swing ratio was calculated from the stride and stance duration, by inferring the swing duration.

| **Measure** Group | Pre Dominant | Pre non-Dominant | Pre $\lvert\delta_{foot}\rvert$ | Post Dominant | Post non-Dominant | Post $\lvert\delta_{foot}\rvert$ | Pre Post $\Delta$ Dominant | Pre Post $\Delta$ non-Dominant |
|---|---|---|---|---|---|---|---|---|
| **Stride Duration** | | | | | | | | |
| Healthy | 1.13±0.07 | 1.13±0.05 | 0.00 | | | | | |
| PD | 1.09±0.07 | 1.08±0.07 | 0.01 | 1.05±0.07 | 1.04±0.07 | 0.00 | -3.61% | -3.68% |
| $\delta_{PD-HS}$ | -0.04 | -0.05 | | -0.08 | -0.09 | | | |
| **Stance to Swing Ratio** | | | | | | | | |
| Healthy | 1.84±0.28 | 1.88±0.23 | 0.04 | | | | | |
| PD | 1.77±0.31 | 1.91±0.62 | 0.14 | 1.81±0.30 | 1.86±0.37 | 0.05 | 2.17% | -2.64% |
| $\delta_{PD-HS}$ | -0.07 | 0.03 | | -0.03 | -0.02 | | | |

TABLE III: Stride period (seconds) calculated from heel strike to subsequent heel strike on the same foot. Stance to swing ratio was calculated from the stride and stance duration, by inferring the swing duration. $\star$ $p$ <.05, $\star\star$ $p$ <.001, statistical significance could be assessed per subject given that greater than 80 strides were measured for each subject and session. † dominant foot as determined by the longer stride period.

| **Measure** Subject | Pre Left | Pre Right | Pre $\lvert\delta_{foot}\rvert$ | Post Left | Post Right | Post $\lvert\delta_{foot}\rvert$ | Pre Post $\Delta$ Left | Pre Post $\Delta$ Right |
|---|---|---|---|---|---|---|---|---|
| **Stride Duration** | | | | | | | | |
| HS011 | 1.09±0.04† | 1.09±0.05 | 0.0007 | | | | | |
| HS014 | 1.15±0.05 | 1.16±0.12† | 0.01 | | | | | |
| PD006 | 1.01±0.06† | 1.00±0.05 | 0.01 | 0.99±0.05† | 0.99±0.05 | 0.00 | -1.48%$\star$ | -1.37%$\star$ |
| PD007 | 1.08±0.08† | 1.07±0.08 | 0.01 | 1.10±0.11† | 1.09±0.05 | 0.01 | +2.42% | +1.66% |
| PD009 | 1.12±0.05† | 1.12±0.05 | 0.00 | 1.05±0.03† | 1.04±0.04 | 0.01 | -7.09%$\star\star$ | -6.86%$\star\star$ |
| PD013 | 1.13±0.09 | 1.14±0.08† | 0.01 | 1.05±0.10 | 1.05±0.08† | 0.00 | -7.63%$\star\star$ | -7.75%$\star\star$ |
| **Stance to Swing Ratio** | | | | | | | | |
| HS011 | 1.84±0.15† | 1.88±0.24 | 0.04 | | | | | |
| HS014 | 1.87±0.22 | 1.84±0.35† | 0.03 | | | | | |
| PD006 | 1.62±0.23† | 1.66±0.22 | 0.04 | 1.62±0.24† | 1.71±0.33 | 0.09$\star$ | -0.05% | +3.20% |
| PD007 | 2.15±0.48† | 2.29±0.38 | 0.14$\star$ | 2.16±0.47† | 2.00±0.38 | 0.16$\star$ | +0.46% | -12.91%$\star\star$ |
| PD009 | 1.65±0.22† | 1.77±0.15 | 0.12$\star\star$ | 1.73±0.22† | 1.80±0.17 | 0.07$\star$ | +4.83%$\star$ | +1.60% |
| PD013 | 1.93±1.16 | 1.67±0.21† | 0.26$\star$ | 1.94±0.49 | 1.74±0.20† | 0.20$\star\star$ | +0.64% | +3.90%$\star$ |

on the dominant foot). The stance to swing ratio however shows a positive change. The absolute difference between healthy and PD stance to swing ratio as measured in each foot decreases after therapy (0.06 and 0.04 pre, 0.02 and 0.01 post). The between foot variability also dramatically decreases (0.14 pre, 0.05 post). The relative changes in each foot are of nearly the same magnitude, but the opposite direction (+2.17% and -2.64%).

## IV. CONCLUSION

The PDShoes were shown to be able to discern differences between healthy and PD subjects. A therapeutic effect is also visible after nine sessions of vibration therapy. A follow up study should include a larger subject pool, PD and healthy.

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