Alleviating Freezing of Gait using phase-dependent tactile biofeedback*

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***Abstract*— In this feasibility study, we present a novel, wearable prototype of tactile biofeedback to alleviate gait disturbances, such as freezing of gait in Parkinson's disease. We designed and tested a phase-dependent tactile biofeedback system that can be easily worn on the feet, with a simple switch to turn it on or off. Preliminary validation was performed in 8 subjects with Parkinson's disease who show freezing during a turning in place test. A metronome, control condition was used to compare effectiveness in alleviating freezing. Promising results were obtained, both in term of acceptability of the device, and improving motor performance.**

I. Introduction

Gait disturbances in Parkinson's disease (PD) are the major cause for functional dependence and have recently been shown to be the largest risk factor for falls, institutionalization and death in PD [1]. Most research on parkinsonian gait has focused on their reduced gait speed, shorter stride length, increased double support time, and arrhythmicity; changes that occur continuously during gait. Less attention has been given to transient gait disturbances, such as freezing of gait (FoG) and festination [2, 3].

Over half of patients with PD develop FoG, an intermittent failure to initiate or maintain walking [2]. Although some of the gait changes in PD might be explainable by decreased dopamine in the nigro-striatal pathway, dopaminergic treatments and deep brain stimulation only partially improve gait or FoG, and sometimes produce a negative effect.

Although PD is primarily a motor disease, accumulating evidence suggests that inadequate integration of sensory inputs and defective proprioceptive internal maps underlie abnormal motor control in PD [4-6]. For instance, most patients with PD and FoG have no difficulties crawling or bicycling, and when seated or lying down, they usually have mild or little difficulties in mimicking stepping movements. This context-specific FoG suggests that FoG is not exclusively due to a defect in the central rhythmic stepping generators but occurs in specific conditions in which proprioception and postural adjustments are essential for the preparation and execution of locomotion [7, 8]. Interestingly, FoG most frequently occurs during tasks that require asymmetric motor control, such as turning when walking or when patients start walking, that depend heavily on task-specific changes in proprioceptive feedback [9]. For these reasons, augmenting somatosensory information by using a biofeedback approach during appropriate phases of gait cycle may improve gait disturbances.

A biofeedback approach has the potential to detect online gait abnormalities and feed back vibrotactile somatosensory signals as it is happening during normal walking activities. The use of a fixed, rhythmic, external somatosensory cue applied to the trunk has recently been shown to increase stride length, cadence and velocity in PD [10]. In addition, a recent study showed how the use of pressure switches to activate vibration in the sole of the feet, ie: step-sychnronized, improved gait in a small group of PD [7]. However, no studies have included patients with FoG or tested PD patients in the off levodopa state.

Our long-term goal is to develop a system that could be used during normal daily activities to automatically monitor and condition motor performance when needed. Our hypothesis is that phase-dependent vibrotactile biofeedback will be effective in overcoming FoG. Here, we present a new, wearable vibrotactile biofeedback prototype and its preliminary application in eight subjects with PD who experience FoG.

II. System Prototype

The system (Figure 1) consists of three parts: A) a sophisticated, inertial, movement monitor for collecting high resolution spatio-temporal gait parameters, B) a novel controller unit, C) a tactor unit to generate a vibration (in our case to the wrist, but tactor can be applied on the foot as well).

A. High-resolution, inertial movement monitor

The high-resolution, inertial movement monitor is an Emerald movement monitor from APDM. APDM is a small company that has recently developed and marketed the most advanced wearable inertial movement monitor (see http://apdm.com). Emeralds are unique in their ability to accurately wirelessly synchronize (≤10 μs) 3D accelerations (up to 6 g) and 3D angular velocities (up to 1500 deg/s) at 128 Hz across body segments. Each Emerald can store up to 8Gb of data (enough for over 30 days of continuous monitoring). Emeralds are extremely small and lightweight

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(20 g, like a wrist watch), have battery life over 18 hours, and easily uploads data with a docking station that also recharges the battery. The Emeralds record and store high-resolution data from its inertial sensors, and timestamps from when the tactor unit is triggered by the controller unit. The inertial data and time-stamped vibration data are analyzed offline to obtain spatio-temporal gait parameters.

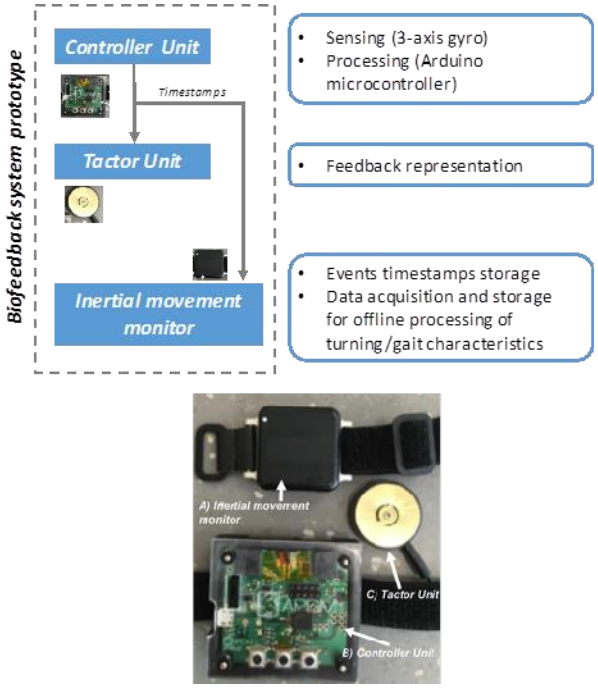

Figure 1: Biofeedback system prototype. Upper panel: system architecture. Lower panel: single components.

B. Controller Unit

The controller is housed in a small enclosure that can be worn comfortably on the foot, or on the leg just above the ankle. It consists of a very small, arduino compatible microcontroller (ATMega32u4, Atmel), with its own Lithium polymer battery pack. The microcontroller is connected to an ultra-accurate, low power 3-axis gyroscope (MAX21000, Maxim Integrated) via I2C. The controller unit also has the ability to interface with an APDM high-resolution inertial movement monitor. It can send a signal to the movement monitor to have it save timestamps of when the tactor unit is being triggered to vibrate.

The controller unit can operate in one of two modes: normal and metronome. In the normal mode, it uses readings from the gyroscope to detect when the user is in the stance phase of gait and vibrates the tactor by Pulse-Width Modulating (PWM) a sine-wave into it. When the unit triggers a vibration to the tactor it has the high-resolution inertial movement monitor record a timestamp. In metronome mode, it ignores the readings from the gyroscope and simply vibrates the tactor every 750ms for 250ms. There is also a third mode, the standby mode, in which only a battery check is performed.

There are also LEDs that correspond with what action the controller unit is taking. A green LED indicates the PWM sine-wave into the tactor. A blue LED indicates standby. A red LED indicates battery issues.

All firmware for the unit is written in C/C++ and utilizes several Arduino open-source libraries. The firmware allows for the customization of vibration amplitude, vibration frequency, angular velocity threshold, and start/stop delays.

C. Tactor Unit

The C-2 tactor is a miniature vibrotactile transducer that has been optimized to give a strong localized vibration in any preferred area of the body. It does this by incorporating a moving "contactor" that lightly touches the skin. When an PWM sine-wave is sent into the tactor, the "contactor" oscillates perpendicular to the skin. The skin around the "contactor" is shielded by a passive housing. This creates a "point-like sensation that is easily felt and localized" (C-2 tactor datasheet). The vibration intensity is similar to that of a cell phone operating in vibration mode. For optimum vibrotactile efficiency, the C-2 tactor is designed with a primary resonance in the 200-300Hz range (C-2 tactor datasheet). These units are small and reliable. They have a diameter of 1.17" and a thickness of 0.30". They have been used in a variety of applications in the past, and they have similar characteristics to the ones used for similar studies [11-13]. For this application, the tactor was applied to wrist.

III. Case Study

A. Participants

Eight subjects with idiopathic PD with FoG (Unified Parkinson Disease Rating Scale, Motor Part, [14, 15] MDS-UPDRS III: 41±14 and new FoG-questionnaire [16] score: 20±5) participated in the study. Subjects did not have any neurological disorders other than PD, or any orthopedic disorders or other impairments that could interfere with gait, and all patients had to be able to walk independently.

All participants provided informed consent approved by the Oregon Health & Science University Institutional Review Board.

B. Protocol and data analysis

All participants underwent a 3-hour mobility assessment, which included clinical assessments, questionnaires, and quantitative assessments of balance and gait. Subjects with PD were tested OFF their antiparkinson medication in the morning (after at least 12-hour washout).

In this study we focused our analysis on the turning in place task. For this task, subjects performed a turning test consisting of turning in place for one minute (changing turning direction after each full turn) while wearing three inertial sensors mounted on the posterior trunk and on each shank, see Figure 2.

Turning was compared across 3 randomized conditions: i) turning without any external cue (baseline condition), ii) turning to the beat of a metronome (control condition), and iii) turning with phase-dependent tactile biofeedback via light

vibration to the wrists every time the ipsilateral foot was in stance phase (biofeedback condition).

The following measures were extracted to objectively characterize turning for each conditions: 1) FoG ratio as index of freezing severity, [17] calculated as the power spectral density ratio between high (3-8 Hz) and low (0-3 Hz) frequencies of antero-posterior shank accelerations, 2) the percentage of time spent freezing during the task were measured, 3) average turn peak velocity, from the yaw angular velocity of the sensor on the posterior trunk, and 4) average turn jerkiness from the lateral acceleration of the sensor on the posterior trunk.

A non-parametric Mann-Whitney test was used for both parameters to determine whether differences existed between the metronome and baseline condition and between the biofeedback and baseline condition.

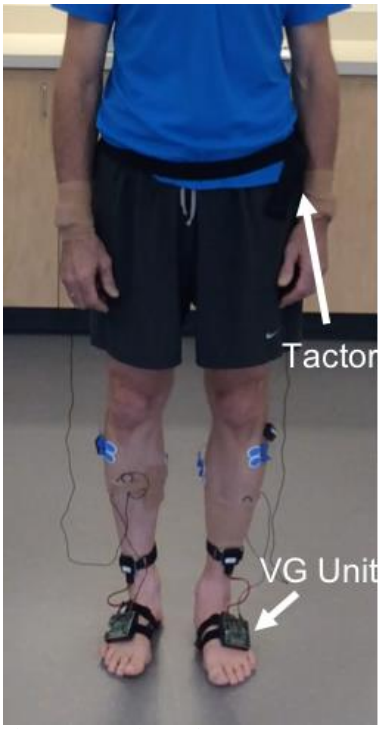

Figure 2: Experimental Setup.

C. *Preliminary Results*

All subjects showed mild-to-moderate FoG during the assessment. We observed a significant decrease in the freezing in both the metronome condition and the biofeedback condition. Figure 3 shows the PSD and the FoG Ratio in a representative subject in the baseline, metronome and biofeedback conditions. Note how the power in the "freezing bandwidth" (light grey area) is decreasing from the baseline condition to the metronome and biofeedback conditions, together with an increase in the "movement bandwidth" (dark grey area). The FoG Ratio is decreasing from 6.7 in the baseline condition to 0.9 in the metronome and 1.1 in the biofeedback condition.

The group mean FoG ratio in the baseline turning condition was 2.5±0.7 and it significantly reduced to 1.4±0.6 in the metronome condition (p=0.03) and to 1±0.3 to the tactile-biofeedback condition (p=0.008).

Similarly, the % time spent freezing in the one minute turning task significantly decreased from 48%±10 at baseline to 25%±10 in the metronome condition (p=0.01) and to 19%±7 in the tactile biofeedback condition (p=0.005).

The average turn peak velocity and jerkiness didn't show a significant difference among the three conditions (p>0.05), although the values are slightly lower for the metronome and tactile biofeedback conditions compared to baseline (average peak velocity: baseline, 95.2±8.5 degrees/s; metronome, 80.3±8.6 degrees/s; biofeedback, 84.2±5.7 degrees/s; average jerkiness: baseline, 0.58±0.1 m^2/s^5; metronome, 0.73±0.08 m^2/s^5; biofeedback, 0.41±0.07 m^2/s^5).

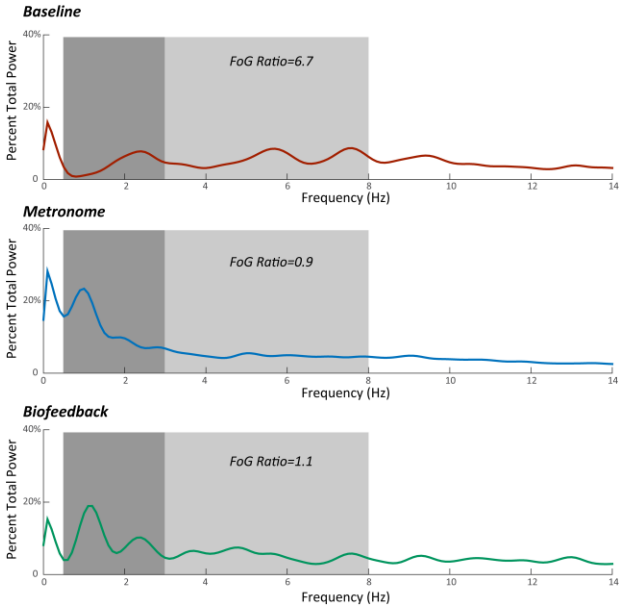

Figure 3: Representative examples of PSDs and Frequency Ratios in a subject with PD and freezing of gait in the three different turning conditions (baseline, metronome, and biofeedback).

IV. Conclusion

In this feasibility study, all the eight subjects with PD found the system easy-to-use, and they were able to correctly follow the vibration information to overcome their FoG during a turning in place task.

In fact, we observed a significant decrease in freezing of gait while turning for both an externally-cued open-loop condition (metronome) and closed-loop biofeedback condition. Due to the feasibility nature of this study, here we didn't make comparison between the metronome (control condition) and the biofeedback condition, but we limited our analysis to investigate that our biofeedback prototype was as effective as a metronome in reducing FoG.

Our results, although preliminary, suggest that augmenting somatosensory information with a phase-dependent biofeedback system, relying on a very unobtrusive modality may be very helpful in reducing FoG in everyday life.

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OHSU, Drs. McNames, Holmstrom, and Horak have significant financial interests or are employees in APDM, a company that may have a commercial interest in the results of this research. This potential conflict of interest has been reviewed and managed by OHSU and the Integrity Oversight Council.

REFERENCES

1. M. E. Morris, F. E. Huxham, J. McGinley, and R. Iansek "Gait disorders and gait rehabilitation in Parkinson's disease," *Advances in neurology*, 87: pp, 347-61,2001
2. N. Giladi, T. A. Treves, E. S. Simon, H. Shabtai, Y. Orlov, B. Kandinov*, et al.* "Freezing of gait in patients with advanced Parkinson's disease," *J Neural Transm*, 108: pp, 53-61,2001
3. J. G. Nutt, B. R. Bloem, N. Giladi, M. Hallett, F. B. Horak, and A. Nieuwboer "Freezing of gait: moving forward on a mysterious clinical phenomenon," *Lancet Neurol*, 10: pp, 734-44,2011
4. W. G. Wright, V. S. Gurfinkel, L. A. King, J. G. Nutt, P. J. Cordo, and F. B. Horak "Axial kinesthesia is impaired in Parkinson's disease: effects of levodopa," *Experimental neurology*, 225: pp, 202-9,
5. W. G. Wright, V. Gurfinkel, L. King, and F. Horak "Parkinson's disease shows perceptuomotor asymmetry unrelated to motor symptoms," *Neuroscience letters*, 417: pp, 10-5,2007
6. Q. J. Almeida and C. A. Lebold "Freezing of gait in Parkinson's disease: a perceptual cause for a motor impairment?," *J Neurol Neurosurg Psychiatry*, 81: pp, 513-8,2010
7. P. Novak and V. Novak "Effect of step-synchronized vibration stimulation of soles on gait in Parkinson's disease: a pilot study," *J Neuroeng Rehabil*, 3: p 9,2006
8. J. V. Jacobs, J. G. Nutt, P. Carlson-Kuhta, M. Stephens, and F. B. Horak "Knee trembling during freezing of gait represents multiple anticipatory postural adjustments," *Exp Neurol*, 215: pp, 334-41,2009
9. J. D. Schaafsma, Y. Balash, T. Gurevich, A. L. Bartels, J. M. Hausdorff, and N. Giladi "Characterization of freezing of gait subtypes and the response of each to levodopa in Parkinson's disease," *Eur J Neurol*, 10: pp, 391-8,2003
10. A. M. De Nunzio, M. Grasso, A. Nardone, M. Godi, and M. Schieppati "Alternate rhythmic vibratory stimulation of trunk muscles affects walking cadence and velocity in Parkinson's disease," *Clinical neurophysiology : official journal of the International Federation of Clinical Neurophysiology*, 121: pp, 240-7,2010
11. C. Wall, 3rd, N. D. Lyford, K. H. Sienko, and M. D. Balkwill "The design and development of a production prototype balance belt," *Conf Proc IEEE Eng Med Biol Soc*, 2011: pp, 3524-8,2011
12. C. Wall, 3rd, L. I. Oddsson, N. Patronik, K. Sienko, and E. Kentala "Recovery trajectories of vestibulopathic subjects after perturbations during locomotion," *J Vestib Res*, 12: pp, 239-53,2002
13. K. N. Winfree, I. Pretzer-Aboff, D. Hilgart, R. Aggarwal, M. Behari, and S. K. Agrawal "The effect of step-synchronized vibration on patients with Parkinson's disease: case studies on subjects with freezing of gait or an implanted deep brain stimulator," *IEEE Trans Neural Syst Rehabil Eng*, 21: pp, 806-11,2013
14. "The Unified Parkinson's Disease Rating Scale (UPDRS): status and recommendations," *Mov Disord*, 18: pp, 738-50,2003
15. C. G. Goetz, S. Fahn, P. Martinez-Martin, W. Poewe, C. Sampaio, G. T. Stebbins*, et al.* "Movement Disorder Society-sponsored revision of the Unified Parkinson's Disease Rating Scale (MDS-UPDRS): Process, format, and clinimetric testing plan," *Mov Disord*, 22: pp, 41-7,2007
16. A. Nieuwboer, L. Rochester, T. Herman, W. Vandenberghe, G. E. Emil, T. Thomaes*, et al.* "Reliability of the new freezing of gait questionnaire: agreement between patients with Parkinson's disease and their carers," *Gait Posture*, 30: pp, 459-63,2009
17. M. Mancini, K. C. Priest, J. G. Nutt, and F. B. Horak "Quantifying freezing of gait in Parkinson's disease during the instrumented timed up and go test," *Conf Proc IEEE Eng Med Biol Soc*, 2012: pp, 1198-201,2012