Potentials of enhanced context awareness in wearable assistants for Parkinson’s disease patients with the freezing of gait syndrome

Marc Bächlin*, Daniel Roggen, Gerhard Tröster
Wearable Computing Lab.
Swiss Federal Institute of Technology Zürich
8092 Zürich, Switzerland
*Corresponding author: baechlin@ifc.ee.ethz.ch
http://www.ifc.ee.ethz.ch

Meir Plotnik, Noit Inbar, Inbal Meidan,
Talia Herman, Marina Brozgol, Eliya Shaviv,
Nir Giladi and Jeffrey M. Hausdorff
Laboratory for Gait and Neurodynamics
Tel Aviv Sourasky Medical Center, Israel
http://www.tasmc.org.il/e/

Abstract—Freezing of gait (FOG) is a common gait deficit in advanced Parkinson’s disease (PD). It is often a cause of falls, interferes with daily activities and significantly impairs quality of life. Gait deficits in PD patients are often resistant to pharmacologic treatment; therefore effective non-pharmacologic assistance is needed.

In this paper we show the potential of context aware assistance for PD patients with FOG and present our first results on start and turn FOG assistance using our modular wearable research platform. We developed a real-time FOG detection system which provides external acoustic cues when FOG is detected from on-body motion sensors, until the subject resumes walking. In an evaluation study, ten PD patients tested our device. We recorded over 8h of data. Eight patients experienced FOG during the study, and 237 FOG events have been identified by physiotherapists in a post video analysis. For the first time PD patients with the FOG syndrome were assisted by a context-aware wearable system. We report a high accuracy of freeze detection (73.1% sensitivity, 81.6% specificity, user independent). Based on subjective reports, the majority of patients indicated a benefit from the automatic cueing.

We discuss how additional sensor modalities can paint a more complete view of the user’s context and may increase the system’s accuracy, decrease its latency, and eventually allow going from freeze detection to freeze preemption.

I. INTRODUCTION

A. Parkinson’s disease

Parkinson’s disease (PD) is a common progressive neurological disorder of the central nervous system. It is caused by a progressive loss of dopaminergic and other sub-cortical neurons [1]. PD patients often suffer from impaired motor skills, speech, and other functions [2]. Four impaired motor skills are often grouped under the acronym TRAP, which stands for Tremor at rest, Rigidity, Akinesia (or bradykinesia) and Postural instability. Beside these, flexed posture and freezing (motor blocks) are classic features of PD. Freezing most commonly affects the legs during walking and is generally referred to as freezing of gait (FOG). However, also arms and eyelids can be involved.

B. Freezing of gait

Freezing of gait (FOG) is common in advanced PD and typically manifests as a sudden and transient inability to move. Five subtypes of freezing have been described by Schaafsma et al.: start hesitation, turn hesitation, hesitation in tight quarters, destination hesitation and open space hesitation [3].

Based on responses by 6620 patients to a questionnaire sent to 12000 members of the German Parkinson Association, 47% of patients reported freezing; it occurs more frequently in men than in women and less frequently in patients whose main symptom is tremor [4]. 10% of respondents with mild PD symptoms and 80% of those severely affected regularly experienced freezing.

Freezing is associated with substantial social and clinical consequences for patients. In particular, it is a common cause of falls [5], interferes with daily activities, and significantly impairs quality of life [6].

C. State of the art in pharmacological treatment of FOG

Pharmacological management of FOG is difficult and often ineffective. For over 40 years the most common form of treatment to manage the motor symptoms of PD is Levodopa (LD), the metabolic precursor to dopamine. Although FOG episodes appear in general more often in the OFF state (at no-effect level of medication), gait deficits in PD patients are often resistant to pharmacologic treatment [5]. Also Botulinum toxin injections, although effective for a variety of Parkinson symptoms such as tremors, dystonia and sialorrhoea, have not been found consistently effective in the treatment of freezing [7]. In addition, prolonged drug intake may also be associated with decreased responsiveness to medication [8]. Therefore effective non-pharmacologic treatments need to be developed as an adjunct therapy to relieve symptoms and improve mobility.

D. State of the art in non-pharmaceutical treatment of FOG

Some patients develop tricks to overcome freezing attacks. These tricks include marching to a command, stepping over
a walking stick or cracks in the floor, walking to music or a beat, and shifting body weight.

Several studies have shown that gait performance in PD can be improved by applying continuous external rhythmic auditory or visual cues [9], [10].

Lim et al. have performed an extensive review study evaluating the effects of external rhythmical cueing on gait in patients with Parkinson’s disease on articles published from 1966 to January 2005 (159 screened studies) [10]. Best-evidence synthesis showed strong evidence for improving walking speed with the help of auditory cues. Insufficient evidence was found for the effectiveness of visual and somatosensory cueing.

These studies provide continuous cueing in controlled laboratory situations. Such a continuous cueing is not suitable for everyday life.

E. Paper Contribution

A wearable assistant for PD patients with FOG that can be used in daily life must identify when the patients needs help (i.e. when freeze occurs) and provide external cueing only under this condition. Detection of the freeze should have a short latency, and ideally the system should provide cueing before the onset of the freeze as a way to prevent it.

In this paper we present our first results on context aware assistance for FOG patients. After showing the results of an evaluation study, we discuss how additional sensor modalities paint a more complete view of the user’s context as a way to increase the system’s accuracy, decrease its latency, and eventually go from freeze detection to freeze preemption.

In detail the contributions are:

1) The development of a wearable system and algorithms to detect FOG online and provide automatically acoustic cueing;
2) The first study on start and turn FOG detection and online assistance by auditory feedback;
3) The subjective and objective evaluation of the study;
4) The discussion of additional sensor modalities to extend the wearable context aware system in order to further improve the assistance provided to PD patients.

II. CONTEXT AWARE WEARABLE SYSTEM ASSISTANT

A. Wearable hardware devices

Our wearable device for online FOG detection and auditory cueing consists out of miniaturized motion sensors including 3D accelerometer and 3D gyroscope, and a light computing system. The motion sensors, including a rechargeable 300mAh Li-ion battery, are 22x41x12 mm$^3$ in size (with packaging: 25x44x17 mm$^3$) and weight less than 22 gram, with 6h battery life [11] (figure 1).

The acceleration data (64 Hz) are transmitted over a wireless Bluetooth link to a light wearable computing system for the online data processing (figure 2). The wearable computing system is a research platform based on an Intel XScale family processor and a Linux operating system, designed for rapid prototyping. It offers processing power comparable to an ultra portable PC. The computing system is kept modular in order to realize different feedback and sensing modalities. The system offers by default USB and Bluetooth as extension interfaces, allowing connections to a diversity of physiological and non-physiological sensors [11]. The system can be simply extended by Zigbee or ANT wireless interfaces with USB dongles. In order to avoid outstanding parts and unintended disconnection of these dongles, we provide an internal USB bay within the system’s housing. Furthermore there is a space and interconnection possibilities for an internal PCB extension board. This extension board is interfaced to a frontal 3.5mm jack and is meant to prototype various signal acquisition and conditioning hardware (e.g. for ECG or galvanic skin response sensing), or to provide user feedback. In the current version for our start and turn FOG assistant we extended the system with an auditory feedback module and earphones are connected to the frontal jack.

Figure 1. Packaged sensor with 3-axis accelerometer, 2-axis gyroscope, 300mAh battery and Bluetooth radio.

Figure 2. Modular research platform.
elastically strap and Velcro. A third sensor is attached to the belt of the patient. Also the computing system is attached to the belt placed on the trunk. Earphones placed around the subject’s neck and connected to the computing system produce a 1 Hz ticking sound whenever an FOG episode is identified and last until the subject resumes walking. Figure 3 shows the system and the sensors as worn by a patient.

B. Online FOG detection algorithm

A phenomenological study of Schaafsma et al. using video analysis has shown that FOG is often associated with a ‘trembling’ of the legs in an effort to overcome the block [3]. Although the underlying pathology of FOG is still unknown, Schaafsma speculated that FOG is an atypical form of action legs dystonia or dystonic tremor.

Moore et al. analyzed the power spectra of the vertical linear acceleration of the left shank of 11 PD patients [13]. They found out that high-frequency components of leg movement during FOG in the 3-8 Hz band were not apparent during volitional standing or during walking. For an objective method to identify FOG offline, Moore introduced a freeze index (FI) defined as the power in the ‘freeze’ band divided by the power in the ‘locomotor’ band (0.5-3 Hz). FOG can be detected using a ‘freeze’ threshold. FI values above this threshold are identified as FOG.

We have developed an online FOG detection algorithm based on the principle described by Moore with emphasis on low latency. The Context Recognition Network (CRN) Toolbox (see [14] for details) was used for the data processing. Only the shank sensor data has been used for the online FOG detection. Sensor data coming from the acceleration sensor with 64 Hz are windowed by a 256 sample window (4 sec). The windowing is done in steps of 32 samples (0.5 sec). On each window block the first 32 frequency components (0-8 Hz) of the power spectrum of a 256 point FFT are calculated. The FFT calculation is the main computational part in the whole algorithm.

The energy in the low frequency part between 0.5 and 3 Hz is summed up as well as the energy in the higher frequency part between 3 and 8 Hz. Furthermore the complete energy between 0.5 and 8 Hz is calculated by the addition of both parts. If the power content of the signal between 0.5-8 Hz is above the power-threshold (PowerTH), the freezing index (FI) is calculated by dividing the energy in the freeze band by the energy in the locomotor band. For signal parts with a power content below PowerTH (standing parts), FI is set to zero. Finally FOG is detected whenever the FI exceeds the ‘freeze’ threshold (FreezeTH). A signal extract together with the online calculated FI and the FOG detection signal is depicted in figure 4.

III. THE FEASIBILITY STUDY

A. Participants

For our study ten idiopathic PD patients with a history of FOG, able to walk un-assisted in “OFF” period were
recruited by the specialists at the Movement Disorders Unit, Department of Neurology at the Tel Aviv Sourasky Medical Center (TAMSC). Patients unable to walk un-assisted in “OFF” period have been excluded as well as patients with severe vision or hearing loss, dementia or presence of other neurological/orthopedic diseases which might affect gait. The study was approved by the local Human Subjects Review Committee, and was performed in accordance with the ethical standards of the 1964 Declaration of Helsinki. All participants were free of signs of dementia and willing and able to sign a consent form for participation. A detailed characteristic of the participants is given in [15].

B. Protocol

Subjects were asked to come for an experimental session that took about 1h. Patients arrived at 8:00 and 9:30am (two recording per day) at the TASMC without having taken their usual morning PD medications in an “OFF” state (except for two patients who regularly experience FOG in “ON” state). First, patients were instructed on the experiment and explained how they may take advantage of the auditory cue in case of freezing.

The study protocol had two sessions. During the first session the device recorded all the necessary data and performed online the FOG detection, however the metronome was deactivated. The second session is the repetition of the first session with the metronome activated (feedback system activated). Both sessions had three walking tasks and have been designed to represent normal daily walking. The three walking tasks consisted out of: (a) straight baseline walking in the lab hallway, including several 180 degrees turns; (b) random walking in a reception hall space that included a series of initiated stops and several 360 degrees turns - the examiner spontaneously instructed the subject to turn in different directions, at least six turns, three to each direction; (c) walking related to activities of daily living (ADL) - the ADL task included entering and exiting rooms, going to the lab kitchen, getting something to drink and going back with the cup of water to the starting room. Figure 5 depicts a sketch of the path taken by the patients for each walking task. Each single walking task has been performed for about 5-10 min. Participants walked without assistance, but with a therapist close by for safety reasons, at their own natural pace.

At the end of the study patients returned to the examining room, took their medication, had a debriefing with the therapist and filled out a standardized self-report of patient satisfaction and a questionnaires to qualify the systems operation.

C. Annotation of Ground Truth

Figure 6 shows a snapshot of the study with two physiotherapist and two assistants, who were running and observing the study. Each subject was watched closely by an assistant who real time annotated the patients’ current activity (standing, walking, turning and freezing). In addition all walking trials were recorded on a digital video camera. Synchronization of leg movement data with the video recordings was achieved by recording three synchronization steps at the beginning and end of the recording sessions. These results in characteristic and easy to find peaks in the acceleration signal and allow aligning the timestamps with the video camera recordings. In a post process professional physiotherapists analyzed the video recordings to identify the FOG events and determine the exact start times, durations and end times.

IV. RESULTS

Ten PD patients (7 males) diagnosed with idiopathic PD (66.4 ± 4.8 years; Hoehn-Yahr score (H&Y) in “ON”;

Figure 6. Snapshot of the study, depicting one PD patient, the therapist (near the subject for safety reasons) and the research assistants (more remotely from the patient) who were documenting the trials.
2.6 ± 0.65) have taken part at this study. Eight patients were examined in the “OFF” state (more than 12h after their last medication) and 2 patients, who regularly experience “ON” FOG, were examined in the “ON” state. The diversity of the participating patients covered a wide spectrum of PD patients. It included PD patients difficult to differentiate from healthy people by their gait performance when they do not have an FOG event, as well as a PD patient not able to walk distances > 15m, and therefore is often using a wheel chair in normal life. The walking distance and number of turns depended on the subjects’ gait speed. One patient could not perform the ADL part.

Eight patients out of the ten exhibited FOG during our study; two patients did not have any freeze event. 237 FOG events (range 0-66 per subject; mean 23.7 [S.D. 20.7]) have been identified from the video recordings by the physiotherapists. The detailed distribution of number of FOG per patient is given in figure 7.

The length of the FOG events ranged from 0.5 sec to 40.5 sec. (mean 7.3 sec [S.D. 6.7 sec]). 50% of the FOG episodes lasted less than 5.4 sec, and the majority of 93.2% of FOG events had a duration of less than 20 sec. The detailed distribution of number of FOG events within 1 sec bins is given in figure 8.

Our ambulatory system worked fine throughout all trials and 8h 20min of data have been recorded. The stride monitor was unobtrusive and did not interfere with the locomotion of the patients. All participants responded in the questionnaire that the computing device and the sensors at the leg did not disturb them while walking. Only one mentioned that he was feeling the elastic strap (sensor) at his leg and that it called his attention.

The frame based sensitivity and specificity of the online detected FOG were 73.1% and 81.6%, respectively. The evaluation is based on 0.5 sec frames. The reference for all our evaluations is the video annotation of the physiotherapists. A maximum detection delay of 2 sec is within the detection tolerance and evaluated as correct detected. The auditory cueing started properly whenever a FOG episode was detected, and stopped again when the patient managed to get out of the freeze and the system detected the normal gait.

Figure 9 depicts the detection accuracy of the device. For each patient sensitivity value (abscissa) and specificity value (ordinate) is plotted. It can be seen that the system did not work equally well for all patients. Worst result in terms of specificity performance was obtained for patient 01. Only 39.7% specificity was achieved (with 99.1% sensitivity). Worst result in terms of sensitivity was obtained for patient 08. Only a sensitivity of 34.1% (with specificity of 88.9%) was achieved.

These large variations result from the different walking styles of the patients. For example, patient 01 suffered from foot drop while walking. The system was most of the time not able to distinguish between walking periods and very short freezing events using the global algorithm parameter settings. Results of 95.9% sensitivity with 92.7% specificity could be achieved for patient 01 by adapting the two threshold parameters of the algorithm to a FreezeTH of 3.0
From the eight patients who had FOG events during the trials, six reported an improvement in gait and that the system provided them assistance when freezing. Two did not indicate any change.

V. FROM FREEZING DETECTION TO PREEMPTION

Currently, the external cueing is provided after the occurrence of the freeze, as it is detected from the motion of the patient’s limbs. Although we have minimized the system’s latency (theoretically 2 seconds worst case), the feedback ideally should occur with no latency at all, or even shortly before the onset of the freeze. In this section we discuss how domain specific knowledge and additional sensor modalities may be combined to reduce the system’s latency, increase the system’s accuracy, or even eventually allow to trigger cueing before the freeze.

Situational aspects: Schaafsma et al. analyzed the occurrence of freezing of gait depending on the type of walking situations [3]. This work led to a detailed characterization of the occurrence of freezing in the following conditions (in parenthesis prevalence of freezing episodes in percent for the corresponding situation): turns (63%), start of walk (23%), walking in narrow spaces (12%), upon reaching destination (9%), and walking in an open runway (3%). Further insights, although not quantified, show that freezing may also occur while crossing narrow spaces (e.g. entering an elevator), and that freezing is more common in crowded places [5]. By including additional sensors to detect the situation of the walk, these numbers may be used as domain specific knowledge and the prior probabilities of freezing may be adjusted in the freezing detection algorithm according to the situation of the user. Based upon user preferences, the acoustic feedback may even be automatically activated upon entering e.g. narrow passages as a preventive measure. Relevant sensors may include gyroscope to detect turns, or proximity sensors such as laser or ultrasound placed on the shank to scan around the user to detect tight quarter or open runway. Dense presence of people may be sensed by the same proximity sensors (i.e. a naive detection of the number of obstacles around the user at close distance).

Local aspects: Patients also report to experience FOG often at the same location in their every day surroundings. Therefore using the patient’s current location and his location history in conjunction with his previous instances of FOG will be a good way to predict the conditions of further FOG instances.

Cognitive-affective aspects: Attention, which may be related in part to stress, as well as cognitive loading (e.g. dual-tasking) are also known to increase the likelihood of freezing. This is often used in clinical studies to artificially enhance the number of observed freezes [5]. Further factors affecting freezing include stress, anxiety, depression and cognitively challenging situations [17]. While the recognition of stress or cognitive load remains challenging, especially outside of the laboratory, a number of modalities are worth to investigate as a way to assess the cognitive-affective state of the user and eventually adjust prior probabilities of freezing. Eye movement and blink rate were shown to be related to cognitive load [18]. Our ongoing work towards wearable EOG goggles will eventually allow for long-term gazing tracking and blink recognition outside of the laboratory [19]. Stress and fear detection are known to be reflected in the physiology, such as galvanic skin response, blood pressure, or heart rate. We showed galvanic skin response related to fight-or-flight reflex can be sensed despite moderate levels of physical activities, which is a promising step towards eventually detecting fear in natural conditions [20]. Other work showed some success in deriving stress from multimodal sensors [21].

Physiological aspects: Offline analysis of the gait prior to freeze evidenced abnormal stride length and cadence during the three steps prior to freezing [22]. The online detection of such anomaly in the gait may eventually be used to trigger the cueing shortly before the freeze occurs. Bartsch et al. exhaustively reviewed methods to characterize gait in Parkinson’s disease patients, such as synchrony or fluctuation analysis [23]. Finally, preliminary insights suggest an increase in heart rate at the onset of freezing compared to 10 seconds before the freeze [24]. Ongoing analysés aim to identify up to which time prior to freezing the heart rate increases. The detection of heartbeat increase not correlated with physical activity increase during walking may thus suggest the onset of freeze.

Summary: While our work shows that acoustic cueing shortly after the onset of freeze is already positively evaluated by the patients and therapists, additional sensor modalities can paint a more complete view of the user’s context may allow to reduce the systems’ latency, increase accuracy, or even trigger cueing prior to the freeze. This last aspect may be especially important as a way to prevent falls. Often freezes occur as a surprise to the patients and may destabilize them. External cueing as a way to warn patients of the upcoming freeze may help them taking measures to limit falling risks.

VI. CONCLUSION

With our study we realized and evaluated the first context aware assistant for PD patients. To our knowledge it is the first time that FOG has been automatically detected online by a wearable device. Without any user adaptive training
our system had a sensitivity of 73.1% with a specificity of 81.6%. Given the large inter subject variation in the gait performance of the PD patients, at least a rough segmentation of the patients together with specific sensitivity already increases the detection performance to 85.9% sensitivity and 90.9% specificity.

With our study we could show first evidence that context aware assistance is beneficial for the patients. On the ‘human’ side we know that users have to be trained to use new assistive technologies to be able to take advantage of them. We did not instruct patients to use one specific strategy, rather gave them the freedom to find out a suitable personalized approach. For at least two patients we could clearly see visually how they used the metronome sound by balancing their body weight accordingly, to get back from FOG into a normal walking rhythm. Although we could not identify such clear signs for all patients, overall six out of the eight patients which experienced FOG during the study claimed that they benefited from the system.

There are further possibilities for improvements. We discussed several aspects where PD patients can benefit from additional sensor modalities. These additional sensor modalities may help to increase the system’s accuracy, decrease its latency, and eventually go from freeze detection to freeze preemption.

A complexity analysis shows that technically the system can be miniaturized to a size of a button with the FOG algorithms included in the sensor node itself. Roggen et al. have shown that even complex calculations such as FFT can be processed with low power consumption on a device of the size of a button [25]. Such a system could be entirely integrated into or attached to normal shoes of the patient, and only the trigger for the external cueing signal is transmitted to the feedback device. The external cueing signal can be given by a hearing-aid-like device or even included in future hearing aids.

Although all ten patients reporting a history of FOG, only eight experienced freezing during the experiment. Stress, attention and distractions are generally considered to have a negative effect on freezing; however it can also have a positive influence. The controlled environment of the study and the physiotherapist nearby may have reduced the likelihood of FOG in the two patients who did not experience any FOG event during our study. Both patients reported lots of freezing at home and could not explain why they did not have any FOG during the study. They expressed the motivation to test our device during their natural daily activities.

Further research will have to study the applicability of such an assistive system for every day usage. Additional sensing modalities to detect freeze remain to be investigated, such as electromyography to complement motion sensors. Furthermore taking into account additional contextual factors, such as localization, surroundings as well as physiological factors, and the study of gait characteristics shortly prior the onset of freezes, are research directions that may eventually allow to pre-empt freezing.

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