A Wearable System to Assist Walking of Parkinson´s Disease Patients

Benefits and Challenges of Context-triggered Acoustic Cueing

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Summary
Background: About 50% of the patients with advanced Parkinson's disease (PD) suffer from freezing of gait (FOG), which is a sudden and transient inability to walk. It often causes falls, interferes with daily activities and significantly impairs quality of life. Because gait deficits in PD patients are often resistant to pharmacologic treatment, effective non-pharmacologic treatments are of special interest.
Objectives: The goal of our study is to evaluate the concept of a wearable device that can obtain real-time gait data, processes them and provides asistance based on pre-determined specifications.
Methods: We developed a real-time wearable FOG detection system that automatically provides a cueing sound when FOG is detected and which stays until the subject resumes walking. We evaluated our wearable assistive technology in a study with 10 PD patients. Over eight hours of data was recorded and a questionnaire was filled out by each patient.
Results: Two hundred and thirty-seven FOG events have been identified by professional physiotherapists in a post-hoc video analysis. The device detected the FOG events online with a sensitivity of 73.1% and a specificity of 81.6% on a 0.5 sec frame-based evaluation.
Conclusions: With this study we show that online assistive feedback for PD patients is possible. We present and discuss the patients' and physiotherapists' perspectives on wearabilty and performance of the wearable assistant as well as their gait performance when using the assistant and point out the next research steps. Our results demonstrate the benefit of such a context-aware system and motivate further studies.

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1. Introduction

1.1 Parkinson's Disease and Freezing of Gait

Parkinson's disease (PD) is a common neurological disorder caused by a progressive loss of dopaminergic and other sub-cortical neurons [1]. PD includes impaired motor skills as part of its symptoms [2]. Beside a flexed posture, tremor at rest, rigidity, akinesia (or bradykinesia) and postural instability, motor blocks, i.e., complete inability to move, are a common negative effect of PD. Symptoms of PD progress are commonly described by the Hoehn and Yahr (H&Y) scale[a].

About 50% of patients in the advanced stages of the PD are affected by the freezing of gait (FOG) symptom [3]. Patients, who experience FOG, report that during the freezing episode their feet are inexplicably glued to the ground [4].

Schaafsma et al. divided FOG into subtypes, i.e., start hesitation, turn hesitation, hesitation in tight quarters, destination hesitation and open space hesitation [4]. A survey among the 12,000 members of the

[a] The H&Y scale uses five stages to indicate the relative level of disability. Stage 1: Symptoms on one side of the body only. Stage 2: Symptoms on both sides of the body; no impairment of balance. Stage 3: Balance impairment; mild to moderate disease; physically independent. Stage 4: Severe disability, but still able to walk or stand unassisted. Stage 5: Wheelchair-bound or bedridden unless assisted.

German Parkinson Association, which was answered by 6620 patients, has shown that 47% of the patients experience FOG. FOG occurs more frequently in men than in women and less frequently in patients whose main motor symptom is tremor [5]. 10% of respondents with mild PD symptoms and 80% of those severely affected regularly experience freezing.

FOG is associated with substantial social and clinical consequences for patients. In particular, it commonly causes falls [6], interferes with daily activities, and significantly impairs quality of life [7].

1.2 Limits of Pharmacological Treatment of FOG

The most common form of treatment to manage the motor symptoms of PD is Levodopa (LD). LD is the metabolic precursor to dopamine and is used to replace endogenous dopamine at the striatum. However, only 1–5% of LD enters the dopaminergic neurons. The remaining LD is often metabolized to dopamine elsewhere, causing a wide variety of side effects.

The medication cycle between two consecutive intakes is roughly divided into two periods, the *ON* period in which the LD is effective, and the *OFF* period in which the influence of the medicine has subsided. Dosing is challenging: the clinicians attempt to maximize the *ON* periods and to minimize the *OFF* period by optimizing dosage and frequency of daily LD consumption. As the disease advances more frequent LD administration is necessary [8]. In addition, the development of involuntary movements and the *ON/OFF* phenomenon (motor response fluctuations uncorrelated with the expectation from the daily medications intake schedule) can limit mobility and complicate dosing.

Gait deficits and FOG are often resistant to pharmacologic treatment [6]. Therefore, effective non-pharmacologic treatments are needed as an adjunct therapy to relieve symptoms and improve mobility.

1.3 State of the Art in Non-pharmaceutical Treatment of FOG

In terms of non-pharmaceutical treatment, previous work has shown that gait performance in PD can be improved by applying continuous external rhythmic auditory, visual or somatosensory cues [9–11].

An extensive review study by Lim et al. on articles published from 1966 to January 2005 on external rhythmical cueing to support PD patients (159 screened studies) has shown best-evidence for improving walking speed with the help of rhythmic auditory stimulation (RAS) [11]. Insufficient evidence was found for the effectiveness of visual and somatosensory cueing. Gait speed and gait variability were best improved (i.e., improvement in gait stability) when RAS was applied as a regular metronome ticking sound at a rate of 110% of the natural walking rate of the tested patient [12]. There was no relative advantage using this method to improve the gait of PD patients who suffer from FOG (PD + FOG) compared to PD patients who do not suffer from FOG (PD-FOG).

However, it is unclear whether positive effects which are identified in the laboratory will remain so during activities of daily living and reduce the frequency of falls in the community. In particular, it is important to clarify how strong the carry-over effect is after a RAS intervention. Nieuwboer et al. evaluated the effect of cueing training in PD patients at home. Hundred and fifty-three patients with PD participated in a three-week home-based cueing intervention, with a total of nine treatment sessions of 30 min each. They observed positive effects on gait, freezing and balance, which decreased with time after the conclusion of the intervention. This decline in effectiveness underscores the idea that permanent cueing schemes are needed rather than single time intervention treatments [13]. In another study of Cubo et al., nine PD + FOG patients used RAS for cueing training at home, but no significant alleviation in the freezing symptoms was detected [14]. Taken together these results lead us to propose a paradigm shift: instead of providing a continuous cueing intervention, we suggest to provide the RAS only in the crucial time during episodic gait disturbances (i.e., FOG).

1.4 Paper Contribution

The main limitations of the previous external cueing approach are the continuous nature of the cueing intervention, manually triggered cueing or provided only during training sessions, but not provided at the time of episodic gait disturbances. In order to overcome these limitations, our objective is to develop and evaluate a system that provides cueing automatically only in the context of impaired performance, i.e., only when most needed. In our study we focused on the actual FOG episodes and the perception of the patients and physiotherapists. In detail the contributions are:

1. a personal wearable system together with algorithms to detect FOG online and provide automatically RAS;
2. the evaluation of our system in a study with 10 PD patients and the analysis of real-time freezing recognition in terms of accuracy and latency;
3. the discussion of the PD patients' and physiotherapists' perceptions on the wearable, context aware technology.

2. Evaluation Study

2.1 Wearable FOG Detection System

►Figure 1 shows a patient wearing our wearable FOG detection system. Two acceleration sensors are attached to the shank (just above the ankle) and the thigh (just above the knee) using an elasticized strap and Velcro.

A third sensor is attached to the belt of the patient. Each packed acceleration sensor, including a rechargeable Li-ion battery, is $25 \times 44 \times 17$ mm^3 in size and weights ≈ 22 grams [15]. The wearable computer ($132 \times 82 \times 30$ mm^3, 231 grams) is also attached to the belt, placed around the trunk.

The acceleration data (64 Hz) are transmitted over a wireless Bluetooth link to the wearable computer for real-time identification of FOG. Our online FOG detection algorithm is based on the principle described by Moore [16]. The novelties in comparison to Moore's algorithm are the reduced freeze detection latency, the enhanced robustness by preliminary segmentation of walking and

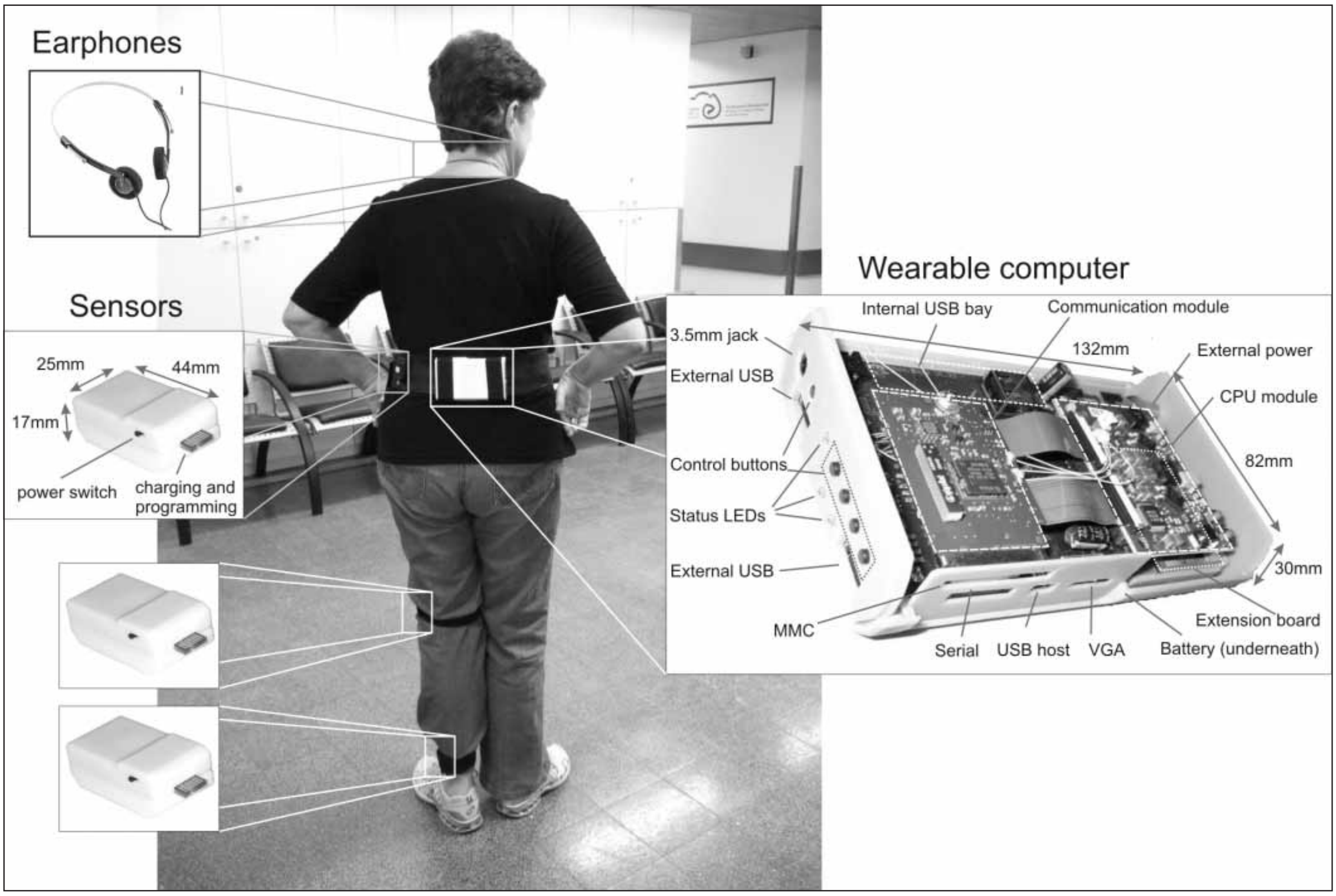

Fig. 1 FOG detection and feedback system worn by a patient. The system consists of a wearable computer, a set of acceleration sensors, and headphones. Acceleration sensors are attached to the shank and the thigh using an elasticized strap and Velcro. A third sensor and the wearable computer are attached to the belt. The sensors are wirelessly connected to the wearable computer; the headphones are connected by a cable to the computer.

standing periods and the real-time online operation. We have described the algorithm in detail in [17]. Earphones placed around the subject's neck and connected to the computing system produce a 1 Hz ticking sound whenever a FOG episode is identified and last until the subject resumes walking.

2.2 Participants

We recruited idiopathic PD patients with a history of FOG, able to walk un-assisted in the OFF period of the medication cycle. Patients unable to walk unassisted 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. Each subject signed an informed consent prior to entering the study.

Ten patients diagnosed with idiopathic PD (7 males, 3 females; 66.5 ± 4.8 years; 2.7 ± 0.6 H&Y score in *ON*) have taken part at this study. Motor performance among PD patients is generally characterized by large variability. So was the case among the group of patients which participated in this study. For example, some patients, when not encounter freezing episodes, maintained regular effective gait, while others had slowed and unstable gait. The detailed patients' characteristics are listed in ▶Table 1.

2.3 Protocol

The patients arrived at the Tel Aviv Sourasky Medical Center (TAMSC) in the morning without having taken their usual morning PD medications. Eight patients were examined in the *OFF* state (more than 12 h after their last medication) and two patients, who regularly experience *ON* FOG, were examined in the *ON* state. Before the recordings, patients were instructed on the experiment and explained how they may take advantage of the auditory cues by synchronizing the movement of the leg to the sound in case of freezing.

The study protocol consisted of two sessions and was designed to represent normal daily walking. Each sessions had three walking tasks: a) straight baseline walking in the lab hallway, including several 180-degree turns; b) random walking in a reception hall space that included a series of initiated stops and several 360-degree 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 from the kitchenette to the examination room. Each single walking task lasted about 5–10 min. Patients walked without assistance at their own natural pace, but with a therapist close by for safety reasons (▶Fig. 2).

During the first session the device recorded all the necessary data and performed online the FOG detection, however the RAS was deactivated. The second session is a repetition of the first session with the RAS activated.

At the end of the study patients returned to the examining room, took their medication, underwent a debriefing with the therapist and filled out a standardized self-report of patient satisfaction and a questionnaire to qualify the system's operation.

2.4 Evaluation Methods

▶Figure 2 shows a snapshot of the experimental trial depicting two physiotherapists and two assistants, who were observing the study. Each patient was watched closely by an assistant who annotated in real-time the patient's current activity, identifying four major performances: standing, walking, turning, and freezing.

In addition, all walking trials were recorded on a digital video camera. In a post-hoc process, professional physiotherapists analyzed the video recordings to identify the FOG events and determined their exact start times, durations and end times.

After the recordings the patients filled out a questionnaire to evaluate the systems' operation, their gait performance during the study and their satisfaction with the system. For the questions where patients had to give a self-assessment, the visual analogue scale (VAS) [18] and the Clinical Global Impression Change scale (CGIC) [19] were used.

Before starting the recordings the patients graded their current walking performance on a VAS. In the post-study questionnaire we asked again how they graded their walking during the study. Furthermore, participants had to answer questions about the comfort and the disturbance of the belt with the computing device and the sensors at the leg. The VAS with anchor points *did disturb 'not at all'/'very much' while walking* was used for these questions. Finally we used the VAS to ask the patients if they think such a system could increase their Quality of Life (QoL) on a scale from '*not at all*' to '*very much*'.

For questions concerning relative changes the CGIC scale was used. Questions addressed:

- the relative occurrence of freezing events with the device compared to before ('*less*'/'*no change*'/'*more*');

Table 1 Detailed patient characteristics of age, disease duration and H&Y rating

Subject ID	Gender	Age [years]	Disease duration [years]	H&Y in ON	Tested in
01	M	66	16	3	OFF
02	M	67	7	2	ON
03	M	59	30	2.5	OFF
04	M	62	3	3	OFF
05	M	75	6	2	OFF
06	F	63	22	2	OFF
07	M	66	2	2.5	OFF
08	F	68	18	4	ON
09	M	73	9	2	OFF
10	F	65	24	3	OFF
Mean ± STD		**66.4 ± 4.8**	**13.7 ± 9.67**	**2.6 ± 0.65**	

Fig. 2 Snapshot of the experimental trial, depicting one PD patient, the therapist (near the subject for safety reasons) and the research assistants (further away from the patient) who were documenting the trials (i.e., video and written annotations).

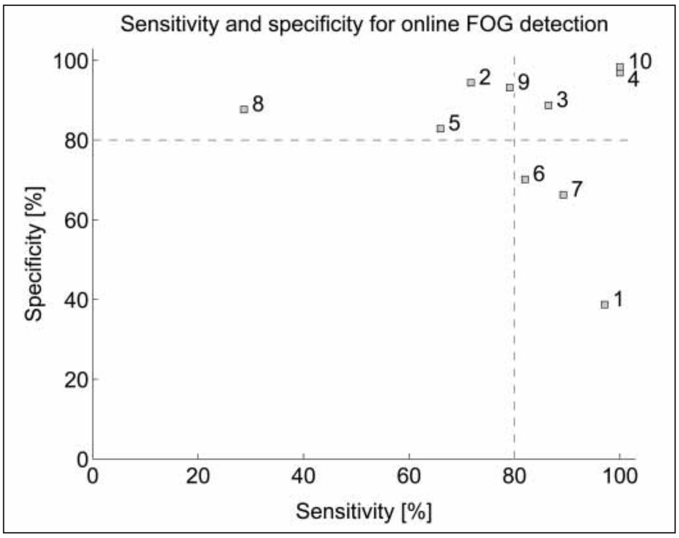

Fig. 3 Sensitivity and specificity distribution for the online detection accuracy using the ankle sensor. Numbers correspond to the patients ID.

- the relative length of freezing events with the device compared to before (‘*shorter*’/‘*no change*’/‘*longer*’);
- the preferred occurrence of the metronome assistance relative to the experience in the study (‘*less often*’/‘*no change*’/‘*more often*’).

In all cases there was the opportunity to give additional comments to the ratings. Within the questionnaire we also asked the patients if they would wear the system a complete day and if they would like to change something (e.g. place of attachment, kind of feedback, ...). A more detailed description of the questionnaire is given in [20] and in ►Table 2.

In order to get a second evaluation from another perspective, the physiotherapists answered a complementary questionnaire at the end of the complete study.

3. Results

Eight out of the ten patients exhibited FOG during the study; two patients did not have any FOG event. The walking distance and number of turns depended on the patients’ gait speed. One patient could not perform the ADL part. Overall, 8 h 20 min of data have been recorded. Two hundred and thirty-seven FOG events (range 0–66 per patient; mean 23.7 [S.D. 20.7]) have been identified from the video recordings by the physiotherapists.

The length of the FOG events ranged from 0.5 sec to 40.5 sec (mean 7.3 sec (S.D. 6.7 sec)). Over 50% of the FOG episodes lasted longer than 5 sec, and 93.2% of FOG events were shorter than 20 sec.

No technical malfunctions occurred during the recordings. 96.2% of the identified FOG episodes (n = 237) were detected online by the wearable device. The user-independent frame-based sensitivity and specificity of the online detected FOG using the ankle sensor were 73.1% and 81.6%, respectively. The evaluation is based on 0.5 sec frames [17]. ►Figure 3 depicts the detection accuracy of our system. For each patient sensitivity value (abscissa) and specificity value (ordinate) is plotted. These are the online detection accuracy results with one global algorithm parameter set for all patients. As we did not have any patient’s data beforehand, there is no patient-specific algorithm calibration. We calibrated the algorithm beforehand based on data recorded on ourselves and colleagues imitating FOG after watching video recordings of previous studies.

It can be seen that the system did not work equally well for all patients. Worst results in terms of specificity performance were obtained for patient 01. Only 39.7% specificity was achieved (with 99.1% sensitivity). Worst results in terms of sensitivity were obtained for patient 08. Only a sensitivity of 34.1% (with specificity of 88.9%) was achieved. In [17], we describe an offline analysis we performed after the recordings in order to evaluate the benefits of a personalized calibration. We showed that the detection accuracy could be improved up to 87% sensitivity and specificity with a better algorithm calibration (analysis performed with a leave-one-person-out cross validation).

►Table 2 shows the detailed survey questions and their results. The evaluation of the questionnaire showed that the sensors as physical objects with volume and weight were unobtrusive and did not interfere with the locomotion of patients. Only one rated slightly above ‘*not at all disturbing*’ for the sensor at the leg and mentioned that he was feeling the elastic strap (sensor) at his leg. He reported feeling observed, and this called his attention to concentrate on his walking performance.

All ten patients expressed their willingness to wear the sensors during everyday life. None had any privacy concerns of collecting their gait data. One patient said he would wear it even for months if necessary for further research. This are positive preliminary results as a follow-up study with the system worn over a longer time is required for a clear assessment of the effectiveness and wearability in daily life.

Although the computing system is still quite big, there was only one comment that it should be miniaturized. The belt seemed to be the most preferable place to carry such a device. Nobody wanted to wear it somewhere else. Also two of the physiotherapists thought that the wearable system is already suitable for day long at home recordings with minor drawbacks. The other two have seen it less suitable, especially due to the size and the attachment method to the belt. The sensor attachment at the ankle is an acceptable place for all patients, especially because it can be worn below the pants. The sensor position just above the knee was not accepted.

We used headphones placed around the patient’s neck as loudspeaker to know directly during the study when the auditory feedback was activated. This is not the optimal configuration for everyday usage. Unsurprisingly the patients commented most on this issue. The patients would like to have the earphones less visible. In particular, people in the surroundings should not notice they are wearing such a system,

Table 2 Detailed survey questions and their results

Question	Patient ID									
	01	02	03	04	05	06	07	08	09	10
How do you grade your walking now? (1 = worst walking / 10 = best walking)	5	8	3	7	5	8	5	5	3.5	7.5
How do you grade your walking during the experiment? (1 = worst walking / 10 = best walking)	6	6	5.5	6	5.5	9	5	5	6.5	7.5
Did the belt with the computing device disturb you while walking? (1 = not at all / 10 = very much)	1	1	1	1	1	1	1	1	1	1
Did the sensor at the leg disturb you while walking? (1 = not at all / 10 = very much)	2	1	1	1	1	1	1	1	1	1
Did you have less/more freezing events with the device? (–3 = much less / 0 = no change / +3 = much more)	0	–1	–1	_	0	–2	0	–1	–2	_
Did you have longer/shorter freezing episodes with the device? (–3 = much shorter / 0 = no change / +3 = much longer)	0	–1	–1	_	0	–2	–2	+1	–1	_
Would you prefer to have the assisting RAS more or less often? (–3 = much less often / 0 = no change / +3 = much more often)	–2	+2	+2	_	+1	0	0	–2	0	0
Would you be able to trigger the assistant yourself by pressing a button on your wristwatch? (**N**o / **S**ometimes / **Y**es)	N	Y	Y	Y	Y	Y	S	N	Y	N
Do you think such a system could increase your qualtity of life? (1 = not at all / 10 = very much)	7	5	8	_	9	5	_	_	8	5
Would you accept to wear an acceleration sensor during your every day life? (**Y**es / **N**o)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Would you accept to wear EMG or ECG sensors glued to your skin during your every day life? (**Y**es / **N**o)	Y	Y	Y	Y	Y	N	N	N	Y	Y

either by seeing it or by hearing the ticking sound. One patient expressed his desire for a visual feedback. He suggested such a visual feedback could be lines projected on the floor.

The responses about the effectiveness of the system and the occurrence of the RAS were more heterogeneous. Five out of the eight patients, who experienced FOG during the study, thought they had less freezing events with the device. The remaining three could not see any change. Also five patients had the impression their freezing episodes have been shorter with the device. Only one thought his episodes have been longer as normal, and two could not determine any change.

Two patients clearly expressed their preference to hear the metronome less often. On the other hand, three patients expressed their preference to have the metronome sound more, or even much more often. For three patients the performance was just right. By looking at the sensitivity/specificity we could see that there is a correlation with the reports. People wanting the sound more often had the system not sensitive enough, people wanting the sound less often had the system too sensitive. This is calling for user-specific adaptation, which was shown to improve performance of FOG detection [17]. One mentioned that the beep sound and rhythm always was the same and he got used to it. He suggested bringing in some variations, because he thought that it would help him even more. Similarly the physiotherapists commented that the device should adjust the tempo according the walking speed of the patient.

Six patients and two physiotherapists rated the potential of our system to increase their QoL positive between 50% and 90% on the scale from 0% = '*not at all*' to 100% = '*very much*'. For the remaining four patients the trial was too short, and they cannot really judge. One physiotherapist was more skeptical and rated only 30%, because she thinks it depends very much on the patient. However, she thinks that for PD patients which have long FOG events and are aware, attentive and capable to adapt to the rhythm, automatic cueing will improve their QoL.

4. Discussion

Overall we consider these results as promising. The large variations in the detection performance of the system result from the different walking styles of the patients. For example, patient 01 suffered from foot drop while walking and the system was often 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 responsible for the sensitivity and specificity. For patient 08, best results of 76.1% sensitivity and 78.1% specificity were achieved with a better parameter setting. A detailed performance characterization based on the parameter setting is presented and discussed in [17]. There, we also showed that if such a system becomes a 'consumer appliance', already a rough segmentation of smooth and saccadic walking with two corresponding sensitivity settings (e.g. easily adjusted by a medical doctor or the patient himself on the device with a switch) are enough to increase the performance to 85.9% sensitivity and 90.9% specificity.

The self-assessment indicates that the patients benefit from the system. Also the physiotherapists rated the influence of the automatic identification of the FOG events and the auditory feedback as beneficial, at least for those with severe freeze. Observations by the physiotherapists have shown that the patients used the cueing mainly in turning freeze which are longer than 3 sec, and in tight quarters (ADL part) after they were stuck. The RAS helped them to take small steps to come out of the freeze. One physiotherapist differentiated between patients that are usually stable during the freeze and patients that seem more at risk of falling in case of FOG. Patients that usually are stable during the freeze will use the cues more while freezing to get out again. In contrast, patients with lesser stable gait will try to use the cues to prevent falling. In the latter case, the RAS should already assist these people before freezing while they are walking so that they can use the rhythm to improve their walking abilities. In this context we also have to consider that one single system to address all the diversity of FOG is clearly not realistic – the goal of this work is to show that it may help segments of that population. From the feedback of the patients we learned that some would prefer visual feedback. Tajimi et al. have shown how such a visual feedback device could look like and how this hip-mounted projector can be stabilized to keep the projected image stable in the user's field of view [21]. Therefore, personalizing the feedback according to the patients' desires is possible by replacing the earphones with such a hip-mounted projector.

Looking at the performance of the system for the two patients which would like to have the metronome less often showed that it was too sensitive for these patients. A too sensitive system results in too many false alarms, which is annoying for the patients. It also shows that a continuous cueing is not acceptable for these people.

Also the answers of the three patients who expressed their preference to have the metronome sound more often are coherent with the observation of the system performance during the study. At least in two cases the sensitivity was relatively low, resulting in missed FOG events, and therefore the patients did not always get the auditory assistance when they experienced a FOG event. For the third patient we could not see such a clear indication (low sensitivity). Personal preferences are the most probable reason. However, their expression to hear the acoustic assistance more often compared to what they have experienced during the study indicates that they seem to have benefited from it.

One limitation of this study is the short time the patients experienced the system. Another limitation is the laboratory setup, where the system was tested, instead of a natural daily living surrounding. Despite the fact that all the patients reported on a history of FOG, two of them did not experience any FOG during the experiments. It is known that a laboratory setting can cause changes in attention and stress levels, which may result in reduction of FOG episodes. In addition, the controlled environment of the study and the physiotherapist nearby may have reduced the likelihood of FOG in these two patients. 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. A follow-up study will have to tackle the limitations of this first study.

Our data analysis has shown that a single sensor is sufficient to detect FOG satisfyingly, thus the obtrusiveness of the current system that used three sensors to compare FOG detection performance at several on-body locations can be reduced. In addition there are further possibilities for technical improvements. The whole miniaturized computing system with all its functionality can be integrated in the buckle of a belt [22]. A more specialized system, especially designed for this task, can even 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 the Fast Fourier Transformation (FFT), which is used in the online detection of FOG, can be processed with low power consumption on a device of the size of a button [23]. 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 could be given by a hearing aid-like device or even the hearing aid itself.

Furthermore the cueing speed can be adapted to the natural walking speed of the patient without any additional sensor. The natural walking speed can be extracted from the sensor recordings during normal walking.

For a long-time user study the system should be initially calibrated to the specific gait pattern of the patient as well as to his personal preferences. Finally new sensor modalities might be tested to go from FOG detection to prevention [24].

5. Conclusion

To our knowledge our study is the first where FOG has been automatically detected online by a wearable system and RAS was provided automatically at the onset of the freeze. The system detected the FOG events with a sensitivity of 73.1% and a specificity of 81.6%. The evaluations of the responses obtained from the patients were also rather positive, despite the fact that the first prototype is relatively bulky. This is promising for future utilization of this concept. Some patients expressed their motivation to wear it even for several weeks. Patient's comments regarding the influence and the effect of the automatic cueing were promising. At least half of the patients have seen a positive effect. The demand for more frequent auditory feedback of the patients for whom the system had a low sensitivity shows that these patients benefitted from the RAS. On the other hand, the demand for less auditory feedback of the patients for whom the system had a low specificity discloses that a continuous cueing is annoying. These results demonstrate the need for a context-aware system and motivate further studies.

Further investigations are necessary to analyze and prove the real-world performance. Remaining open questions are: i) How useful will the patients judge the system when using it for 2–3 hours for several days? ii) During constant use, can the patients learn to rely on the system the way they rely on other walking aids? iii) Can they even get used to it so much that taking advantage of the RAS becomes intuitive and unconscious?

Future studies shall take into account the feedback obtained from the patients and the physiotherapists, and especially consider: i) miniaturization and "professional" packaging and attachment, ii) user-specific calibration – even a simple 2-mode is sufficient to significantly increase performance, and iii) concealing the system so that it is invisible to the outside.

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