Synchronized walking cadence for TUG in perturbed environments: using Earcon or Tacton cues ?

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***Abstract*—Audio and haptic cueing have proven their usability to assist gait for patients with Parkinson's disease. These cueings are used when a gait issue is classified in real-time by an artificial intelligent algorithm using wearable IMU signals located at the lower limb. Such gait issue could be freezing of gait (FOG) and Bradykinesia symptoms. This system detects freezing periods and plays a rhythmic pattern such as Tacton or Earcon in haptic or audio respectively. When prior training is done with an appropriate serious game, cueing could help to recover gait cadence and then help to avoid fall. Both types of cueing were used in different research works without prior analysis on the best stimulation to use in a perturbed environment. Since rhythmic auditory sound could be an issue in a real outdoor environment, this paper suggests evaluating rhythmic stimulation cueing with the Time Up and Go clinical assessment test used for mobility evaluation.**

Keywords—freezing of gait; cueing; Parkinson's disease

I. INTRODUCTION

Gait disorders associated with Parkinson's diseases have important consequence on the health of affected people, especially because of potential risk of fall that could result. Indeed, more than a third of people aged 65 years and older fall at least once a year, causing 65% of injuries in this age group and initiating psychological impact due to fear of falling.

Parkinson's disease (PD) is one of the most prevalent neurodegenerative diseases. Most people with PD have balance problems which worsen with disease progress [1]. Symptoms of this disease, in particular motor symptoms such as festination, freezing of gait, etc. increase risk of falling as compared to healthy individuals at the same age, but also in relation to people with other neurological disorders [2]. While people with Parkinson's disease (PD) represent 1% of the population aged 60 and over, 20% of those aged 80 years old or older have gait disorders which can lead to falls. These falls cause stress, pain and are the leading cause of death by injury in the elderly. Among these, 43% claims to have a fall last year [3].

Wherefore, locomotion assistance system was previously studied such as lower limb exoskeleton [4], instrumented shoe with powered ankle-foot orthosis [5], locomotion interface using virtual reality (electromechanical gait trainer) [6] and balance training system [7].

Recent research work suggest to use low cost wereable accelerometer or gyroscope located at the limb or force sensor located inside insole for the analysis of gait. Once the symptom is detected, a warning message is presented (displayed) to the user in order to reduce its impact. This method is often called biofeedback and uses different sensory modalities such as audio [8], vibrotactile and visual [9] cues. Cognitive aspect is related to this warning message and these cues should be learned [10]. These cues could be a rythmic pattern usually very simple such as a repetitive frequency due to the low cost technology used. However, ecological vibrotactile icon could be used or different waveforms with multi-frequency such as Tacton (structured vibrotactile message or Hapticon) or haptic icon. A Tacton uses different duration and rhythm in order to display a message [11] and is then a good candidate for stimulation of PD patients.

This paper suggest to evaluate an innovative wearable prototype located at the Achilles tendon using haptic biofeedback cueing considering the natural environment of PD patients. For the demonstration of the system, haptic and audio cueing are compared in a perturbed environement for daily usage. In order to evaluate and compare this setup, some clinical tests are available such as Time up and Go Test (TUG), Berg Balance Scaled (BBS) or the Tinetti assessment tool [12]. Since we evaluate the impact of environmental perturbations during walking and the use of biofeedback to correct the situation, an instrumented TUG is the most appropriate test as suggested in [13] for PD patients.

This paper is organized as following: In the second section, a brief presentation of the related works is presented with the contribution of this research work. The third section presents the proposed hardware system used for haptic stimulation and freezing of gait recognition. The fourth section presents the experimental methodology with some results and discussion related on rhythmic cues in perturbed environment.

II. RELATED WORK

Previous research work reveal both motor control and gait issues are progressing and cause a motor pattern characterized by certain symptoms such as: reduction of the step length and speed, appearance of festination and, as a final result, freezing of gait (kinetic jamming or blocking). From a cinematic point of view, it is a disorder in the rhythmic control of movements.

A. Symptoms classification

One of the current challenges is the recognition of a deviation of gait parameters in order to adjust balance in real-time. Despite some success in this area, this recognition requires a lot of work for the differentiation between normal and abnormal movement during daily activities. In order to detect abnormalities in early PD, Zampieri et al [14] used body-worn sensors for mobility testing at home and to compare it to the laboratory instrumentation. They used five inertial sensors, which were attached to the dorsum of each wrist, to the anterior shank and to the chest on the sternum. Their results show that home testing is feasible but this work is still incomplete. Other approach uses mismatch between frequency and velocity for a first evaluation [15]. Although many parameters of gait were assessed in their various studies, they don't consider the influence of cueing for motor recovery.

B. *Biofeedback cueing*

A system producing an auditory rhythm (via headphones) has been used to reduce these symptoms [16]. This system is able to reduce the number of freezing of gait from 76% to 80% and to reduce duration of 70%. Nevertheless, this efficiency should be improved through a rehabilitation program [17]. However, several constraints impose limits to its daily usage such as: external auditory stimuli (ambient noise, discussion with other person, etc.), the constraints associated with urban walking wearing headphones may be considered too restrictive. Moreover, used frequently, it is confronted with the phenomenon of craving. A very recent study also suggests using it only when it detects through the sensors, a critical situation or freezing of gait [18]. Finally, no research demonstrates the long-term benefits of this system.

Vibrotactile [19] and audio [20] cueing were evaluated for reducing the impact of freezing of gait in daily activities. Some studies related the effect is limited especially when attention is overloaded. However, Nieuwboer suggest longer period of cued training may be beneficial [21]. Different rhythmic cueing modalities (audio, visual and somatosensory) was also evaluated and compared while turning [22]. This study shows there is no significant difference between each stimulation modality. Some recent applications such as PDShoe (vibrotactile cueing) [23] and GaitAssist (audio cueing) [18] was successfully implemented which are an integration of FOG real-time detection and rhythmic cueing stimulation. However, the impact of the waveform was not evaluated. Also, the natural environment was not considered. In fact, rhythmic cueing alone is perhaps not enough. For this reason, another approach is to synthesize realistic gravel-footstep sounds in order to improve gait and balance [24].

C. *Contributions*

The scientific contribution of this project is to eliminate many of these constraints coming from audio cueing by using a haptic system used in daily activities. Since both stimulation are a good candidate, the evaluation would ensure that its effectiveness remains similar between them. The haptic stimulation is located at the Achiles' tendon only on one leg while the auditory stimulation uses small piezo-speaker located at the same position. System evaluation is conducted in a realistic environment with obstacles on the ground and visual and auditory disturbances. Although the instrumented version of the TUG is used, mobility of participant could be evaluated using four daily activities: stand up, walk, turn and sit down while disturbances are applied. This system is evaluated for end-user, not for perception (psychophysics).

III. Proposed System

The proposed system is attached around the Achiles tendon labelled ACHILE system. It could also be implemented for an insole or at the hip. ACHILE stands for ACtive Human-Computer Interface for Locomotion Enhancement. This is an intelligent system, recently developed; it aims at preventing accidental falls related to conditions of the physical environment of the person or abnormalities of its gait. This device counts a set of non-invasive sensors such as accelerometers, force sensors, bending variable sensor [25].

The next sections present the signal processing and then present the actuator used for rhythmic cueing.

A. *Real-time signal processing*

The electronic board, shown in Fig. 1, is the core unit of the artificial intelligence module of the ACHILE system, with a printed circuit board dimension of 38 × 28 mm. Primary components on this unit include IMU sensors for posture and gesture sensing, a PIC24 microcontroller from Microchip, a wireless module, a SD card for data recording, and a USB connector for data reading and battery charge. Data could be saved into the SD card or be transmitted to Android smart phone via a Bluetooth module.

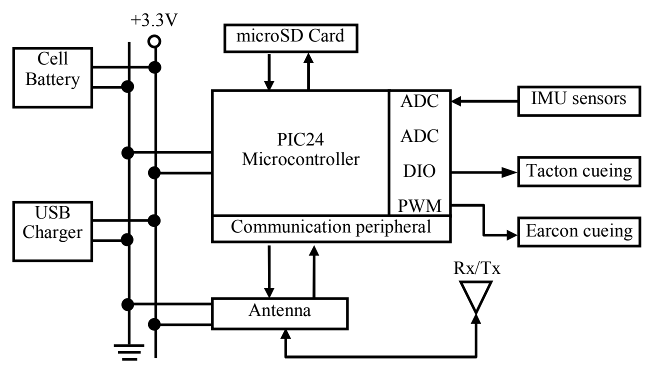

Figure 1. Diagram of electronic board

ACHILE monitors gait features and motion in order to characterize human activities and gait abnormalities in daily activities. Extraction of intelligible information from raw data is done by an artificial intelligence algorithm such as those used in [26-29]. When an anomalous gait parameter is detected, real-time assistance, as the first step, can be used to convey non-visual information to the user using audio and haptic biofeedback, such as vibration motor [30, 31] or using Haptuator.

B. *Haptic actuators*

According to Hayward et MacLean, multiple haptic devices can act as rhythmic stimulation interface [32]. As one who produces vibrations in cell phones, the eccentric motor (also labelled linear resonnant actuator or LRA) is retained here because it is small and is applied to a small area of the skin. This technology has been used for warning car driver [33], for training pilots [34] or to stimulate the movement of the fingers in the PD patients [35]. According to these applications, it fits well in clothing and is still discreet.

IV. Methodology

Rhythmic haptic cueing is applied at the Achilles tendon of the participants in order to produce an easily perceptible stimuli as suggested in [36]. Comparative effectiveness of audio system (labelled 'A') and haptic system (labelled 'H'), in the presence of sensory disturbance, is measured in a standardized clinical test (*Time set Up and Go* or the [TUG] firstly presented in [37]) over a distance of 6 meters. In the presence of a stimulation 'A' or 'H' of same frequency and rhythm, the instruction given to the participant is trying to synchronize his cadence with the suggested rhythm. Two sensory disturbances are also used during testing: 1- cataract simulation glasses (sight reduction of visual perception) and 2- sound out ear muffs (reduction of hearing). These types of '1' and '2' disturbances are common among the elderly, including the PD patients.

Environmental obstacles are simulated by four (3.8 x 8.9 cm) boards placed at unequal distances on the course. For each participant in the study, seven walking tests are required to achieve the following objectives: I) Training participant to the experimental situation, (II) comparison of both variables 'A' and 'H', each accompanied by a double disturbances '1' and '2 ', (III) desensitization of the participant to rhythmic stimulation between these two tests using the dual disturbance without stimulation system, (IV) comparison of the variables '1' and '2' then used independently with a single system of stimulation (H-1 and H-2), (V) comparison of the experimental situation with a reference test, or the audio system 'A' without disturbance. The study includes a microsampling of 15 healthy (11 females and 4 males). Participants are also asked to complete a questionnaire for a qualitative assessment of the experiences and to validate the consistency of the quantitative results.

The research work is therefore to demonstrate the relevance of using other sensory stimulation under disturbances. The research hypothesis is then the following: given the constraints that includes the audio rhythmic stimulation system in the presence of sensory disturbance, a vibrotactile device has a better performance in the gait cadence when walking with sensory disturbances.

A. *Qualitative measurements*

Characteristics of the participant are demanded: age, sex, length of legs, walking or balance issues, rhythmic experience such as dancer or musician. TUG time is assessed (only quantitative dependent variable). After each test, the subject describes how he felt and if he struggled with disturbances or with obstacle on the ground. At the end, he determines the easiest stimulation to follow (scale of 1 to 5), the level of agreeableness or level of awareness (scale of 1 to 6) and whether or not to use the haptic or audio system in daily activities.

B. *Quantitative measurements*

Each subject starts sitting on a chair. At the signal, he stands up and walks a distance of three meters, turned around a cone and returned to sit down at the same chair. The proposed study set contains seven different situations during TUG as described in Table I: (1) walking alone; (2) haptic and ear muffs; (3) audio, ear muffs and cataract simulation glasses; (4) no stimulation but with ear muffs and binding glasses to confuse the participant in rhythmic stimulation; (5) haptic; ear muffs and binding glasses; (6) audio alone and finally (7) haptic and binding glasses.

TABLE I. INSTRUMENTED TUG TIMING WITH DISTURBANCES AND STIMULATIONS

	Walking evaluation						
Participants	O-3	H-1	A-1-2	O-1-2	H-1-2	A-3	H-2
	(sec.)	(sec.)	(sec.)	(sec.)	(sec.)	(sec.)	(sec.)
1	7	8,75	7,71	7,6	6,37	8,51	7,56
2	9,31	11,14	9,23		11,16	9,97	13,2
3	7,81	7,34	7,48	9,9	10,64	7,65	9,47
4	6,89	7,62	9,66	8,64	9,25	8,36	9,39
5	8,33	7,14	8,94	9,8	10,09	8,37	8,72
6	9,04	8,76	7,82	9,11	9,41	7,22	9,07
7	7,74	8,62	9,46	11,29	10,29	6,08	8,86
8	9,5	10,5	10,11	9,83	9,77	8,16	11,96
9	8,74	10,5	7,51	7,08	7,79	7,07	8,22
10	8,47	7,27	8,47	7,82	7,12	6,94	6,66
11	9,9	8,57	8,87	8,48	7,51	7,24	7,07
12	8,01	9,75	8,41	11,72	8,71	8,13	9,29
13	8,19	10,24	10,27	11,6	7,56	7,49	9,1
14	8,06	10,2	9,31	10,38	12,73	6,74	8,6
15	10,41	10,42	10,6	10,08	10,78	7,5	11,79
Mean	**8,493**	**9,121**	**8,923**	**9,524**	**9,279**	**7,695**	**9,264**

Standard deviation	1,002	1,362	1,012	1,473	1,757	0,931	1,808
Minimum	7,49	7,76	7,91	8,05	7,52	6,76	7,46
Maximum	9,50	10,48	9,94	11,00	11,04	8,63	11,07

A: Audio biofeedback system
H: Haptic biofeedback system
O- Without stimulation

1- Sound out ear muffs
2- Cataract simulation glasses
3- Without perturbation

V. RESULTS AND DISCUSSION

An analysis using the "t" hypothesis test for comparison of matched pairs has demonstrated that both systems H and A used in the presence of disturbances produce very similar results (reduced difference t = 0,8007 < 2,976 with $\alpha = 0.01$). With the same level of significance, the audio system has produced significantly different results depending on whether it is accompanied or not with disturbance (t = - 3,530 <-2,9768). These preliminary results have motivated the realization of a more complete analysis.

The choice of analysis of variance (ANOVA) with a factor of Freidman and hypothesis testing 'F' available on SPSS, is justified by the nature of the variables involved and because it is a non-parametric situation (small size of the sample and many samples related to compare). First, it is necessary to verify the impact of sensory disturbances on the experience.

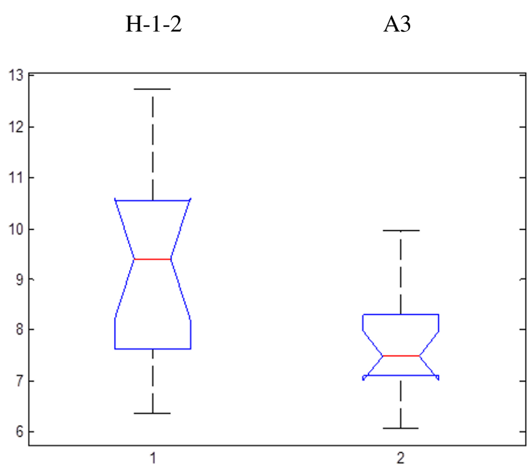

Figure 2. ANOVA analysis between H-1-2 and A-3

Comparison between the results of H with sensory disturbances (H-1-2) and the A-3 reference test without disturbances, confirms a clearly significant difference (F = 9.51 > p-value = 0.0046) as shown in Fig. 2. Thus the sensory disturbance produce a clearly measurable effect.

Now, in their presence, is both stimulation systems has the same effect? Four experimental situations of rhythmic stimulation with sensory constraints are compared (H-1-2, A-1-2, H-1 and H-2). Beyond doubt, the difference between the results of these four tests is not significant (F = 0.18 < p-value = 0.91). Therefore, both stimulation systems produce the same results in the presence of sensory disturbance, regardless their combination (see Fig. 3).

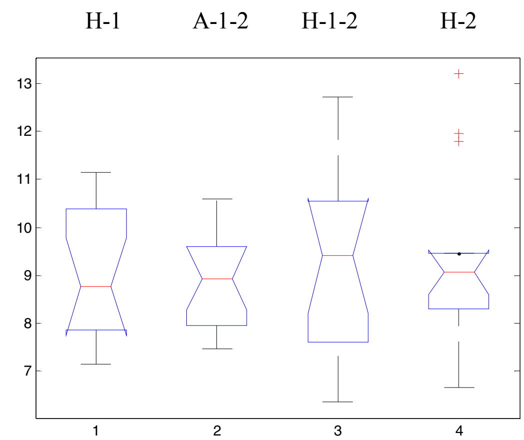

Figure 3. ANOVA analysis between four walking evaluations

Perception of the participants as to the ease and the awareness of each TUG evaluation, ordered from easiest to difficult and from more to less pleasant, reveals two linear trends (R^2 = 0,9631, 0,9248) and two perfectly correlated ordinal qualitative variables ($r_s = 1$) as shown in Fig. 4. Participants have experienced difficulties when walking with visual and auditory disturbances (H-1-2 and A-1-2). We note that with binding glasses, TUG situations are more difficult and variances results types increase. The results are less aggregated because the skill of each participant becomes a new important factor. Finally, between two disturbances, twice more participants were considered glasses (n = 10) more binding that ear muffs (n = 5).

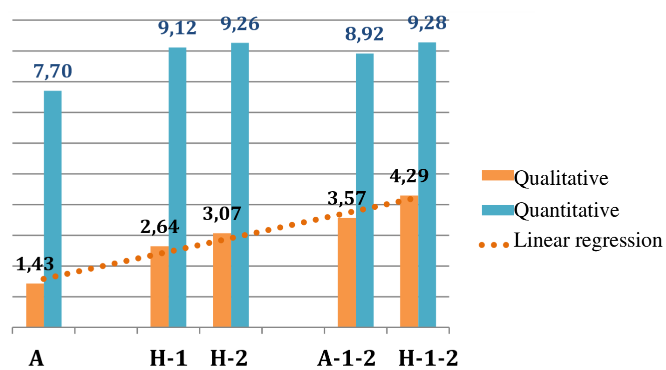

Figure 4. TUG timing compared to qualitative measurement

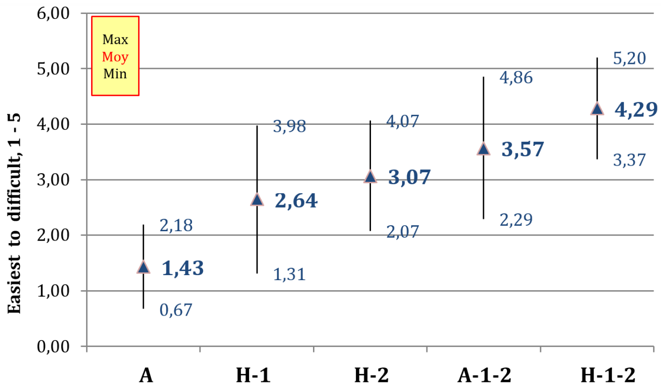

Figure 5. Qualitative measurement for each TUG evaluation

In conclusion, the ear muffs are easier and more pleasant to use than glasses as suggested by the results in Fig. 5. When weared both together, they are less easy and less pleasant. This agreed to the fact that 66% of subjects perceived glasses more restrictive than ear muffs. Moreover, in the presence of a double perturbation, the audio system seems easier and more pleasant than the haptic system. Note that the correlation between the facility and the TUG timing is less significant (r_s= 0.6) but we cannot draw conclusion since the TUG are similar in 4 of the 5 situations referred. Finally, 93% of participants consider the haptic system used discreet enough to be worn on a daily basis and the audio stimulation should not be used.

VI. Conclusion

The performance of the haptic system is comparable to audio system: so it's likely to produce the same positive effects for the reduction of motor symptoms in the PD patients. It was demonstrated an haptic system is able to impose a rhythm despite sensory disturbances and despite the fact that it is perceived less easy to use and less pleasant than an audio system.

However, it has a better potential to daily usage because it is: unperturbed by ambient noises, discreet (non intrusive and non invasive) and non-irritating. The perception that it is harder and less pleasant is probably influenced by the fact that the vibrotactile stimulus is a new phenomenon for the participants, while the response to a rhythmic hearing has been acquired from a while. This perception is also more determined by the nature of the sensory constraints by the type of system. The glasses appear stricter probably because this modality remains a sense more important than hearing in walking (spatial perception, appreciation of distance and direction related to the movement of the body). This experience does not allow to draw conclusion on the effectiveness of the haptic rehabilitation system or its long-term effect. Its accessibility and effectiveness remain however the benefits under a possible therapeutic use. In this regard, other analyses must be carried out.

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