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SYSTEMS-LEVEL QUALITY IMPROVEMENT

Finding Parameters around the Abdomen for a Vibrotactile System: Healthy and Patients with Parkinson's Disease

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Abstract

Freezing of Gait (FOG) is one of the most disabling gait disorders in Parkinson's Disease (PD), for which the efficacy of the medication is reduced, highlighting the use of non-pharmacological solutions. In particular, patients present less difficulties in overcoming FOG when using feedback and especially with Biofeedback Systems. In this study it is intended to detect the frequency threshold and the minimum interval of perception of the vibrotactile feedback, through a proposed wearable system, a waistband. Experimental tests were carried out that considered a temporal, spatial and spatiotemporal context, for which 15 healthy and 15 PD patients participated. It was detected as threshold frequency 180 Hz and for minimum interval of vibration perception 250 ms. The identification of this threshold frequency and this interval will allow us to select the frequency and the minimum interval of vibration to be used in a Vibrotactile Biofeedback Device for patients with PD, in order to help them to overcome FOG.

Keywords Freezing of gait · Biofeedback · Vibrotactile perception · Frequency

Introduction

One of the most disabling gait disorders in Parkinson Disease (PD) are the freezing episodes, denominated by Freezing of Gait (FOG), which corresponds to a temporary, sudden, transient, unpredictable and involuntary disability of performing gait [1].

To overcome FOG, two approaches can be considered: the pharmacological and non-pharmacological methods [2–4]. Regarding to the pharmacological methods, there have been no significant scientific advances and these methods do not alter the course of PD symptom, and consequently, do not prevent FOG. As a result, the patients' quality of life remains reduced [1, 2, 4, [5]. Thereby, this pharmacological barrier has encouraged new researches based on non-pharmacological approaches [5, 6]. In fact, the non-pharmacological methods are a non-invasive and efficient solution for patients to overcome FOG, with an increasingly innovative character. However, some non-pharmacological methods are more efficient than others and, in particular, patients present less difficulties in overcoming FOG when using external sensory cues through Biofeedback Systems, which allows a more goal-oriented type of motor control [5].

The use of sensory cues through Biofeedback Systems is based on the hypothesis that temporal deficits in PD are a major contributor to gait impairment. This hypothesis is supported by the fact that specific pharmacological therapies to improve gait performance, reduce time deficits in PD [7, 8].Accordingly, two fundamental modes of timing, which present distinct underlying neural networks, can be considered: *implicit* and *explicit timings* [8] .*Implicit timing* uses external cues and involves automatic and less self-aware timing systems such as serial prediction tasks, which require the subject to use a regularly timed stimulus to make temporal predictions about future stimuli. On the other hand, *explicit timing* is used to make deliberate estimates of duration. PD

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patients have more difficulty with *explicit timing* than with *implicit timing*, but even so, they still have the ability to make temporal predictions through implicit time [8]. In other words, patients can still use external cues to inform decisions based on time, e.g. when the next step should occur [7, 8]. In this way, the internal timing (*explicit timing*) impairments can be corrected and recalibrated through motor–sensory interaction with the world. Thus, Biofeedback Systems use the *implicit timing* abilities still present in PD patients to recalibrate the internal clock with external cues [7, 8]. Therefore, these systems can bypass the failure of nerve message during a FOG event by inducing motor–sensory feedback signals which can be integrated in the PD patients' sensory systems [8, 12, 13].

Three types of stimuli can be provided through Biofeedback Systems: visual, auditory and vibrotactile stimuli. A fourth system can be considered when joining two types of feedback. In particular, Vibrotactile Biofeedback can be perceived in any environment, address multitasking issues, not require too much cognitive and it is easily accepted by patients [9]. However, the current Vibrotactile Biofeedback Systems present some limitations: are not ergonomic or robust, constrain the freedom of movement, are uncomfortable and not easy to use [10–15]. Thus, it was highlighted the need to identify the best body zone to provide vibrotactile feedback, aiming to develop a wearable system more robust, functional, ergonomic and considering the patients' comfort and acceptability [16].

All body zones present different responses to the vibrotactile feedback and in [17] it was presented a study which discussed the vibrotactile sensitivity for different body areas. Indeed, it was verified that the areas of the skin without hair, the glabrous skin, are more sensitive to vibrations and thereby, the hands and the soles of the feet are the body areas with greater vibration sensitivity [17]. However, [18, 19] and [20] have shown that in order to develop a biofeedback system that provides vibrotactile information, it is necessary to consider the vibrotactile sensory discrimination in humans. Furthermore, if it is intended to design a wearable system able to address a multitasking requirement and the patients' freedom of movement, it was verified that the lower trunk, in particular the waist body zone, is an area capable of easily perceiving vibrotactile stimulus while respecting these constraints [18, 19].

In addition, in [20] the authors' studied the conditions for a precise location of the vibrotactile stimuli presented in the lower trunk. Overall, it was observed that by reducing the number of vibrotactile units, the subjects' perception increases since it involves lesser cognitive effort. Also, it is important to consider the use of the vibrotactile units in the reference areas, navel and spine, because these body zones are used as natural anatomic references [20].

Regarding to the interaction between the provided feedback and the patients' sensory system, in human skin, the cutaneous mechanoreceptors are responsible of perceiving the vibrotactile information that is provided. Many mechanoreceptors participate in the vibration sensitivity perception, depending primarily on the stimulus frequency [21]. These cutaneous mechanoreceptors have a vibration frequency range for perception and, in general, the vibration detection for skin ranges from 80 to 300 Hz [17, 21]. Furthermore, it is necessary to consider the pathways that lead the vibration information to the cerebral cortex [21]. Indeed, the vibrotactile information that is perceived in skin mechanoreceptors is deteriorated until it reaches the cerebral cortex, which, consequently, is able to discriminate a range of 80–250 Hz [17, 21, 22]. Therefore, it is concluded that the vibration frequency range that must be considered is 80–250 Hz [21].

These mechanoreceptors and their connection to the central pathways and target areas in the cerebral cortex constitute the vibrotactile human sensory system. This sensory system, when stimulated, transmits information such as location, intensity, duration, frequency and even the density of stimulated receptors. Thus, the specific characteristics of the vibrotactile stimulus, such as frequency and amplitude, are very important to decode sensory information [17]. Yet, the perception of somatosensory vibratory sensitivity depends basically on the frequency of the stimulus [21, 22]. Thus, it became imperative to study how patients discriminate frequencies and vibratory sites, so that the vibrotactile feedback can be adequately provided and transmitted from the mechanoreceptors to the cerebral cortex where it can be decoded. There are sites which are not, or are less, sensed, and as such should be avoided. In this way, the feedback can be incorporated into the patients' sensory system and replace the failure of the nerve message that occurs during a freezing episode [17, 21, 22].

Based on these findings, in this study it is intended to detect the frequency threshold, within the frequency range perceived by humans (80–250 Hz), and the minimum interval of perception of the vibrotactile feedback, through a proposed wearable system, a waistband, depicted in Fig. 1. The system provides vibrotactile stimulation in the lower trunk, more properly at the navel, right, spine and left zones, allowing the system to meet the previously mentioned requirements and overcome the limitations of the current Vibrotactile Biofeedback Systems. This work comprises the first steps in the implementation of a Vibrotactile Biofeedback System for patients with Parkinson's Disease.

Methods

System overview

The proposed system consisted in a processing unit, an actuation system (haptic drivers and vibrotactile units), a wireless communication system (Bluetooth Module), and Graphical Interfaces.

The processing unit consists in the Arduino Mega 2560, which is based on the microcontroller Atmega 2560. Concerning to the actuation system, the Adafruit Industries'

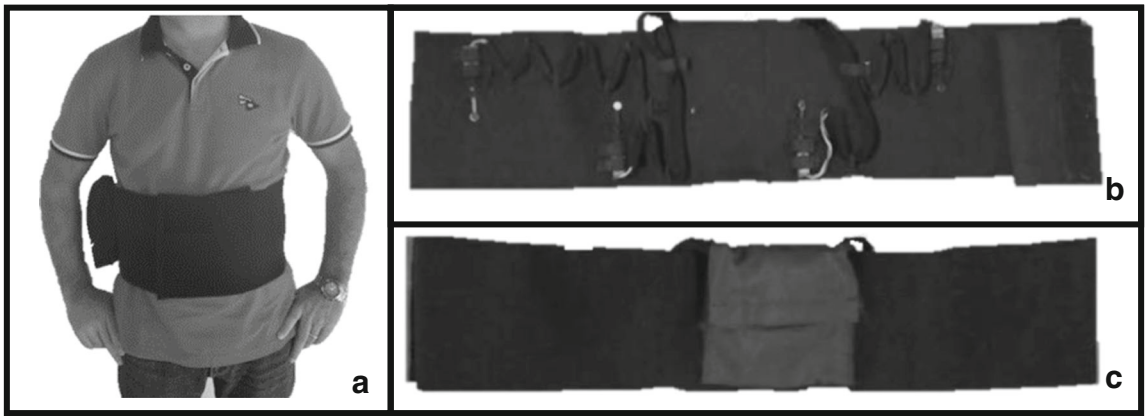

Fig. 1 A) Implemented system: The waistband: B) an inside view, with the vibrotactile units; and C) an outside view with the majority of the electronic components

DRV2605 were the used haptic drivers, which allowed an adjustable control of the actuators, the vibrotactile units - Eccentric Rotating Mass (ERM) - over a shared I2C-compatible bus. The vibrotactile units were mini vibration motors 2.0 mm (Seed Studio Electronic), a special type of ERM motors, coin vibration motor, also known as "pancake" vibrator motors. These motors allowed to provide the vibrotactile stimuli at a frequency range of 60–300 Hz, with an amplitude of 0,2–2,8 G. To obtain a Wireless Communication, it was used a Bluetooth Module, the HC-06 Itead Studio. This module uses Bluetooth 2.0 and allows a range of 10 m of wireless communication. Both mobile and desktop Graphical Interfaces were programed, in Android and MATLAB®, allowing the tester to select the test's parameters and send them to the processing unit aiming to control the experimental tests. The system was powered by a Lithium-Ion Researchable Covert Battery, 12 V.

Except for the actuation system (haptic drivers and vibrotactile motors), all systems were housed inside a bag on the outside of the waistband (Fig. 1.C). The actuation system was placed inside the waistband (Fig. 1.B): four haptic drivers/vibrotactile units were arranged with an equidistant spacing that allow reaching the minimum (76 cm)/maximum (110 cm) average waist of an adult and provide the stimulation to the specific areas of study [20]. Thus, these four actuator systems were placed with a minimum spacing of 15 cm, and to ensure universality of use, the connecting wires between the components of the inner waistband were zigzagged. The waistband was designed to be robust enough to support the electronics (overall weight of 458 g) and, at the same time, to be adaptable to different abdominal diameters, ensuring the provision of vibrotactile feedback in the areas of the navel, right side, lumbar spine and left side, regardless the user.

Validation

The validation of the proposed system involved 15 healthy subjects and 15 PD patients. All patients gave informed consent and study was granted ethical approval by the Hospital of Braga Ethical Commission. Table 1 presents the morphological features of the healthy subjects and PD patients. All patients had an autonomous gait and without dementia. All patients were in the ON phase, where the medication had the desired effect. These are the inclusion and exclusion criteria used in the experimental tests.

The parameters under analysis, frequency of vibration and minimum interval of perception, were selected in a Graphical Interface (Android or MATLAB®) and then sent by Bluetooth to the processing unit on the Waistband. Based on this information, the processing unit ordered to execute the experimental tests. After the execution of each experimental test, the obtained data were properly analyzed. Figure 2 represents the process described.

The studied frequencies belong to the range of human perception, 80 to 250 Hz, discriminated as: 80, 100, 120, 140, 160, 180, 200, 220 and 250 Hz. Further, all subjects repeat the experimental tests three times to obtain more reliable results. Between each test repetition, the waistband was removed and then replaced to assess test-retest repeatability. Lastly, the experimental tests had an average duration of about 20 min. During all the experimental tests, the subjects used headphones to ensure that they were unaffected by any external

Table 1 Morphological characteristics (number, gender, mean ± SD age, mean ± SD weight and mean ± SD height) of the involved healthy and PD subjects in the proposed experimental method

Subjects	Gender		Age	Weight	Height	UPDRS
	Female	Male	(years)	(Kg)	(cm)	scale
Healthy	6	9	44.02 ± 16.42	67.5 ± 16.06	172 ± 7.93	–
PD patients	7	8	64.00 ± 10.60	69.93 ± 11.41	165.93 ± 8.65	16.43 ± 7.91

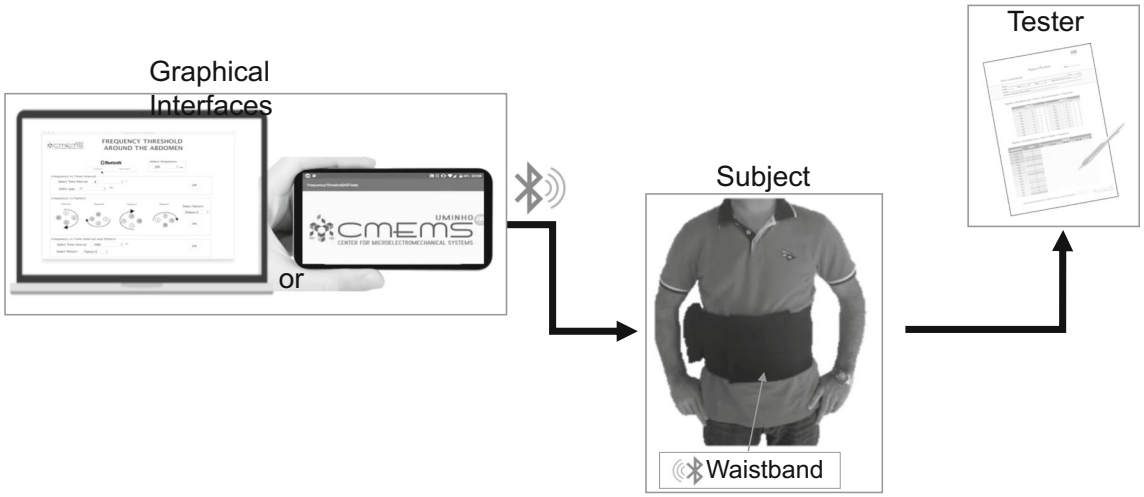

Fig. 2 Information flow during an experimental test: selection of test parameters under analysis; processing of ordered information and execution of the experimental test; and collection of the data obtained

influence of the surrounding environment or even some sound from the vibrotactile motors.

Experimental setup

The following sub-sections describe the methodology followed for each of the tests carried out: *Temporal perception* vs *Frequency* Test; *Spatial perception* vs *Frequency* Test; and *Spatiotemporal perception* vs *Frequency* Test. After the accomplishment of these tests, it was carried out a questionnaire for each participant.

Temporal perception vs frequency test

This test aims to detect the best perceived frequency in a short time, and for that, there is a trial capture interval where half of the interval is an OFF phase (without stimulation) and the other half is an ON phase (with stimulation). During the ON phase, vibrotactile stimulus are supplied at a randomly selected frequency among the possible values. In the graphical interface, the order of the ON/OFF phases is selected by the tester, for each trial capture. Also, the tester selected the duration of these phases, 4 s or 2 s. These phase intervals were chosen based on the literature in clinical protocols already performed [20]. All vibrotactile units vibrate at the same time and with the same frequency under analysis. The participant was warned of the beginning of each trial capture and, at the end, she/he only indicated in which of the phases the stimulation was perceived. The participants repeated the tests three times for each time interval of capture (4 and 2 s) at the selected frequency.

Figure 3 represents an example of this test for a trial capture interval with 2 s to each phase, where the dashed line corresponds to the OFF-phase and the solid line to the ON-phase. The capture intervals should never be too close, with a minimum of 20 s between each test.

Spatial perception vs frequency test

In this test, four vibratory patterns were provided (pattern N, R, S and L), as disclosed in Fig. 4. The test aims to verify if the vibrotactile feedback is perceived for each frequency in the four considered body zones (navel, right, spine and left) where the vibrotactile units were placed.

In [11] it is claimed that, in order to study the spatial perception, the provided sensory information must not be complex, but simple and preferably, encoded as short structured vibrating patterns. Thus, it was used these patterns, since with a simple and previously known pattern, the cognitive requirements are smaller, and easier to recognize and evaluate the stimulation zones where the motors are placed. Through the graphical

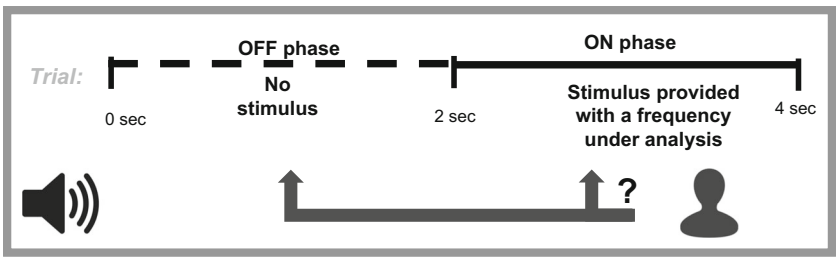

Fig. 3 Representation of the Temporal perception vs Frequency Test, for a trial capture interval with 2 s of each phases. Dashed line corresponds to the OFF phase and solid line to the ON phase

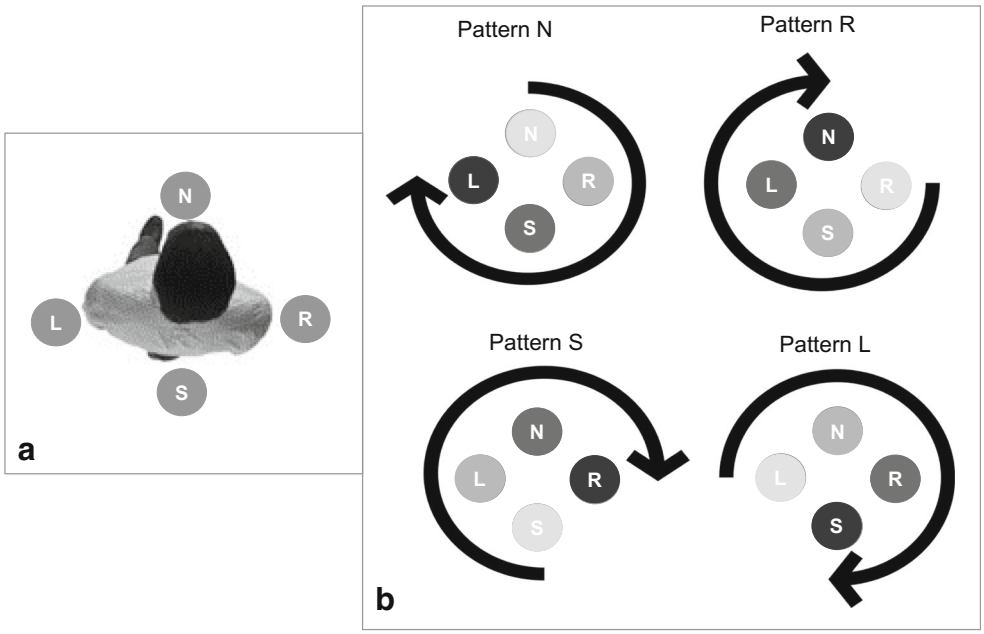

Fig. 4 Representation of the Spatial perception vs Frequency Test: A) Human top view, whit specification of the placement of the vibrotactile units: N - navel; R - right; S - spine; and L – left; and B) Visual representation of vibratory patterns: arrows and colors represent the order of vibration for a given pattern. The arrows represent the spatial order and the colors represent the order of activation of the vibrotactile units (clearest first, darkest last)

interface, the tester selected the pattern, which allowed to evaluate if the participant correctly perceived the first zone stimulated by the provided pattern. To this end, the participants indicated which pattern they perceived, stating the first place (navel, right, back or left side) at which they felt the vibration. During the test, each vibrotactile unit vibrated for 2 s, according to the respective pattern order, at the frequency of the test.

Spatiotemporal perception vs frequency test

The goal of this test was to ascertain the frequencies' perception in a short time interval, on a scale of milliseconds, for all the vibrotactile units. Thus, it was detected the best perceived frequency according to the spatiotemporal context. For such, it was used vibrating patterns in short interval times. The patterns represented in Fig. 4 were used and the vibrotactile units vibrate during different five intervals of study – 100, 250, 500, 750 and 1000 ms – according to the pattern's order, at the frequency of the test. At each test, the subjects had to indicate the pattern perceived similarly to the previous test, by indicating the first place they felt to vibrate (navel, right, back or left side). These time intervals were chosen considering that a normal gait cycle is approximately 1.15 s and the minimum duration for gait events is 115 ms [23]. It was important to identify these test time intervals, since, in a future context, these biofeedback systems should provide the vibrotactile feedback in accordance with the patients' gait. It is important to highlight that in this test, it was only tested the frequencies of 200, 220 and 250 Hz, since for frequencies below 200 Hz, the vibrotactile motors cannot effectively vibrate for the lower time intervals of 100 and 250 ms. Finally, the subjects had to fill in a questionnaire as depicted in Fig. 5.

Results

Temporal perception vs frequency test

Table 2 shows the results obtained for the *Temporal perception* vs *Frequency* Test, where the mean ± SD percentage of healthy and pathological subjects that correctly identified the stimulation interval is highlighted.

Figure 6 discloses the mean percentage of correct identification during the three test sessions.

Spatial perception vs frequency test

Table 3 depicts the results for the *Spatial perception* vs *Frequency* test, discriminating the mean ± SD percentage of

Questions	Scores (1 - Nothing, 2-Little, 3-Moderate, 4 – High and 5 – Very High)
Frequencies perception	
Time Interval perception	
Vibrotactile unit perception at navel	
Vibrotactile unit perception at right	
Vibrotactile unit perception at spine	
Vibrotactile unit perception at left	
Comfort	

Fig. 5 Self-assessment questionnaires performed

Table 2 Percentage (mean ± SD) of healthy subjects and PD patients who correctly identified the stimulated interval for each of the frequencies tested to the phases intervals of 2 and 4 s

Time interval (s)	Frequency (Hz)	Percentage (%)	
		Healthy subjects	PD patients
4	80	81.25 ± 10.83	56.25 ± 51.23
	100	81.25 ± 10.83	56.25 ± 51.23
	120	87.50 ± 12.50	81.25 ± 40.31
	140	93.75 ± 10.83	93.75 ± 25.00
	160	100.00 ± 0.00	97.88 ± 8.50
	180	100.00 ± 0.00	100.00 ± 0.00
	200	100.00 ± 0.00	100.00 ± 0.00
	220	100.00 ± 0.00	100.00 ± 0.00
	250	100.00 ± 0.00	100.00 ± 0.00
2	80	75.00 ± 44.72	46.67 ± 51.64
	100	81.25 ± 40.31	53.33 ± 51.64
	120	87.50 ± 34.15	53.33 ± 51.64
	140	93.75 ± 25.00	53.33 ± 51.64
	160	98.44 ± 6.25	66.67 ± 48.80
	180	100.00 ± 0.00	93.33 ± 25.82
	200	100.00 ± 0.00	100.00 ± 0.00
	220	100.00 ± 0.00	100.00 ± 0.00
	250	100.00 ± 0.00	100.00 ± 0.00

healthy subjects and PD patients that correctly identified the provided pattern.

Figure 7 discriminates the mean percentages of correct identification of the different provided patterns, for the three experimental sessions, through a polar graphic that illustrates a top view of the human body for better visualization.

Figures 8 presents the participants' performance during the three sessions of the experimental tests, highlighting the mean percentage of correct identification for all provided patterns (Pattern-N, Pattern-R, Pattern-S and Pattern-E) in each session.

Table 4 shows a confusion matrix which describes the indicated the responses (percentage) by healthy subjects and PD patients for each of the patterns provided, regardless the frequency in analysis, during the three experimental sessions.

Further considerations

Table 5 summarizes results from *Temporal perception* vs *Frequency* and *Spatial perception* vs *Frequency* Tests and depicts a mean threshold value for the best perceived frequency, considering the values obtained between the healthy subjects and PD patients.

Spatiotemporal perception vs frequency test

Table 6 presents the percentages of correct identification for the *Time Interval and Spatial perception* vs *Frequency* Test, considering the time interval of vibration and pattern provided, for the healthy subjects and PD patients.

Self-assessment

The questionnaires allowed to subjectively evaluate the participants' opinions on all the parameters analyzed in the experimental tests. The scores obtained are pointed out in the Table 7.

Discussion

Temporal perception vs frequency test

By analyzing Table 2, it is verified that as the vibration frequency decreases, the number of subjects who correctly identified the stimulation intervals also decrease, both for the healthy subjects and patients with PD. However, the greatest decrease in the percentages of correct identification was obtained for the PD patients

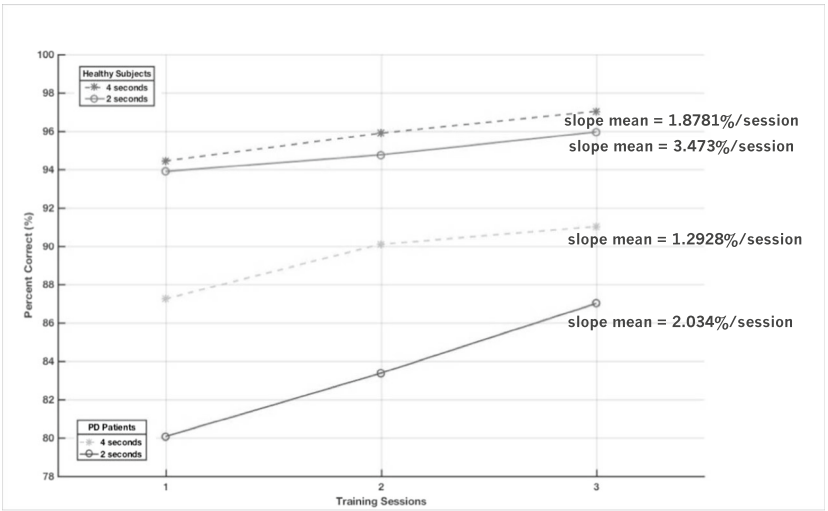

Fig. 6 Mean percentage of correct identification of Healthy subjects (solid and dashed line from above) and PD Patients (solid and dashed line from above), for the 4 (solid lines) and 2 s (dashed lines) time phases, during the three test experimental sessions. MATLAB® plot

Table 3 Percentage(mean ± SD) of healthy subjects and PD patients who correctly identified the provided pattern for each of the frequencies tested in the four patterns (N, R, S and L)

Pattern	Frequency (Hz)	Percentage (%)	
		Healthy subjects	PD patients
N	80 and 100	100.00 ± 0.00	73.33 ± 45.77
	120, 140, 160	100.00 ± 0.00	77.73 ± 41.16
	180 and 200	100.00 ± 0.00	100.00 ± 0.00
	220 and 250	100.00 ± 0.00	100.00 ± 0.00
R	80 and 100	98.33 ± 6.45	62.20 ± 48.59
	120, 140, 160	100.00 ± 0.00	83.29 ± 36.42
	180 and 200	100.00 ± 0.00	100.00 ± 0.00
	220 and 250	100.00 ± 0.00	100.00 ± 0.00
S	80 and 100	93.33 ± 25.81	66.67 ± 48.80
	120, 140, 160	98.33 ± 6.45	73.33 ± 45.77
	180 and 200	100.00 ± 0.00	100.00 ± 0.00
	220 and 250	100.00 ± 0.00	100.00 ± 0.00
L	80 and 100	95.00 ± 19.36	60.00 ± 50.71
	120, 140, 160	100.00 ± 0.00	73.33 ± 45.77
	180 and 200	100.00 ± 0.00	93.33 ± 25.82
	220 and 250	100.00 ± 0.00	100.00 ± 0.00

group. In fact, regardless of the stimulation time (2 or 4 s): the higher the vibration frequency, better the frequency perception. Even so, the percentages of correct identification declined more for a shorter stimulus interval. For the 4 s and 2 s stimulation intervals, the frequency at which all the healthy subjects start to correctly respond to the stimulation interval, was 160 and 180 Hz, respectively. Likewise, for the PD patients the frequency was 180 and 200 Hz. Nevertheless, the frequency value for which all participants correctly began to identify the stimulation interval did not differ significantly between healthy and pathological subjects, as well as between the phase intervals tested, 4 or 2 s.

Figure 6 analyzes the performance of the participants during the three sessions of this test. In general, the percentage of correct identification increases throughout the sessions, allowing us to verify that both groups of participants began to better understand the pacing time interval, regardless of the frequency of vibration used. However, it should be noted that the mean percentages of correct identification, for both healthy subjects (1st session: 94.44%; 2nd session: 95.89%; and 3rd session: 91.02%) and PD patients (1st session: 87.26%; 2nd session: 90.09%; and 3rd session: 91.02%), were obtained for the experimental test whose pacing interval corresponded to 4 s. Further, the values were higher in the sessions with healthy subjects. These higher percentages obtained during the experimental sessions for the 4-s pacing interval tests, are probably due to the fact that the pacing time interval was higher, which allowed the subjects to have more time to perceive with certainty the stimulus provided. On the other hand, for a 2-s pacing interval, because a stimulus was given in a shorter time interval, subjects could confuse the ON/OFF intervals. Even so, by analyzing the mean slope of the obtained percentages during the three sessions, it is possible to confirm that the mean percentages of correct identification per session had a greater increase in the experimental tests with 2 s stimulation intervals, for both PD patients (3.473%/sessions) and healthy subjects (2.034%/session).

Spatial perception vs frequency test

The percentages of correct identification of the provided patterns declined to the lower vibration frequencies for the healthy

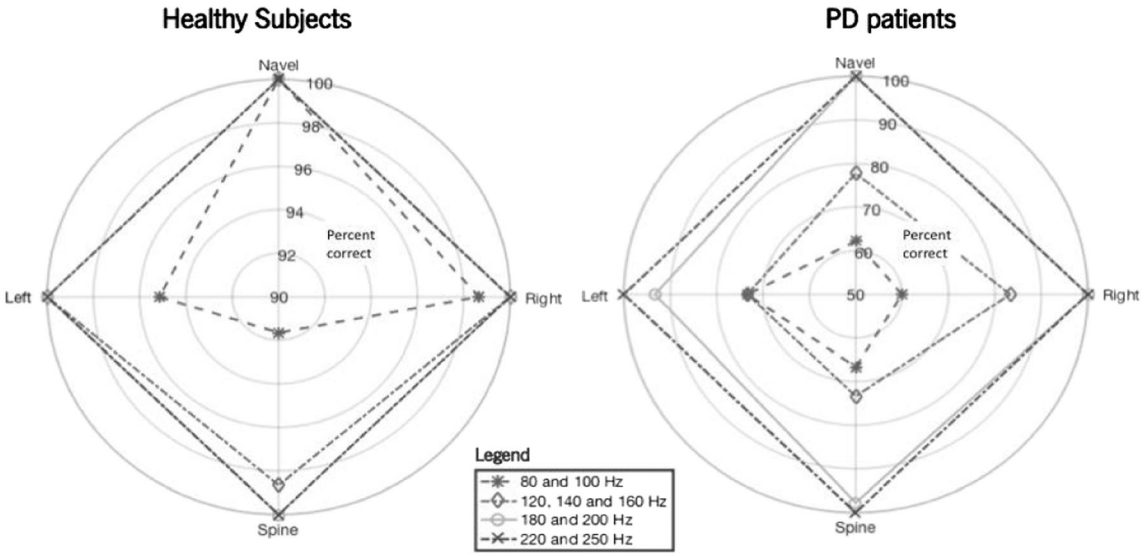

Fig. 7 Polar graph, illustrating a top view of the human body, with the mean percentages of correct identification for the different provided patterns for the healthy subjects (at left) and PD patients (at right). Patter-N: Navel, Pattern-R: Right, Pattern-S: Spine and Pattern-L: Left for the three experimental sessions. MATLAB® plot

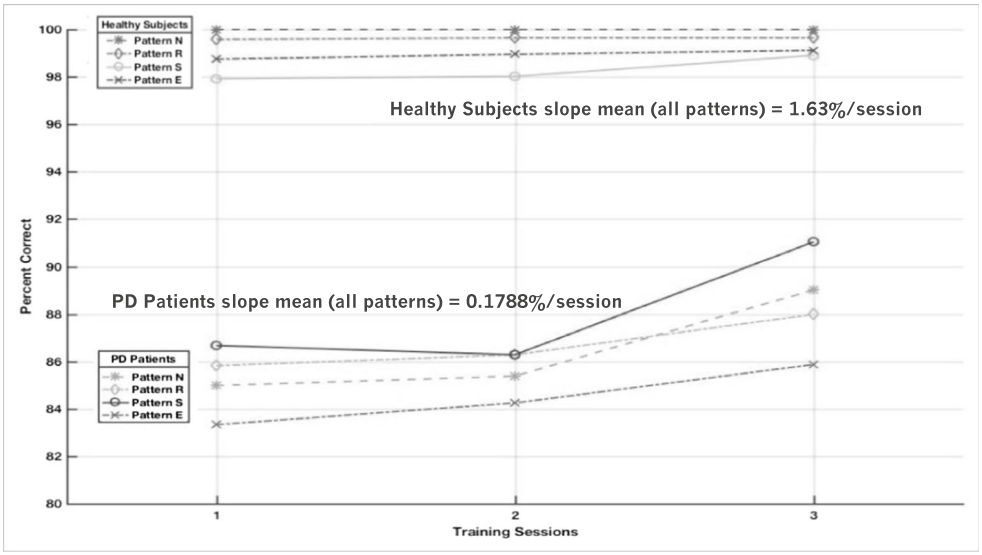

Fig. 8 Healthy subjects' and PD patients' mean percentage of correct identification, for all the provided patterns (Pattern-N, Pattern-R, Pattern-S and Pattern-E), during the three test experimental sessions. MATLAB® plot

and pathological subjects, although with greater accentuation for PD patients (except in the pattern-U), as shown in Table 3.

However, it is important to discriminate the mean percentages of correct identification for the different provided patterns. Figure 7 discloses this discrimination. Lower percentages of correct identification by healthy subjects and PD patients were obtained for pattern-S and pattern-L, respectively. Concerning to the lowest percentages of pattern-L, in PD patients, may be due to the fact that the left body side, at the waist level, is not an area which is used as a natural anatomical reference and thus may require some cognitive effort for its perception. Lastly, the frequency for which all subjects responded correctly to the provided pattern, and thus correctly identified the first body zone they felt the vibration, was 220 Hz for PD patients and 120 Hz for healthy subjects, as concluded through an analysis of Table 3.

In Fig. 8 it is possible to analyze the performance of the PD patients and the healthy subjects, during the three sessions of the *Spatial perception* vs *Frequency* Tests, for all the provided patterns. From session to session, the percentage of correct identification of the provided pattern increased, for all participants, with higher values (near to 100%) for healthy subjects. However, the mean slope of the obtained percentages during the three sessions presents a higher value for PD patients (1.63%/session), specially between the second to the third session for the Pattern-S and Pattern-N. In fact, the healthy subjects answered more correctly, during the three sessions, to the Pattern-N, regardless the frequency in analysis. On the other hand, the PD patients responded more correctly when the Pattern-S was provided. Note that these values agree with the expectations, taking into account that these zones are the zones that humans use as anatomical references (column and navel).

By analyzing Table 4, it is possible to verify that all healthy subjects responded correctly to pattern-N. Although the PD Patients presented a higher percentage of correct response, when they failed, they affirmed to have firstly perceived the right side, inferring to Pattern-R (13.54%). When the Pattern-R was provided, in case of failure to correctly respond (PD patients – 13.4033% and healthy subjects- 0.3733%), the participants tended to respond that the provided pattern was the Patter-N, when they failed. The wrong responses to the tests when the Pattern-S was provided, diverged to the Pattern-R (PD patients – 11.01% and healthy subjects - 1.067%) and Pattern-L (PD patients – 0.9933% and healthy subjects - 0.3497%). Finally, when the Pattern-L was provided, the erroneous answers focused essentially on the Pattern-S for all participants (PD patients – 10.305% and healthy subjects - 1.06%), although there were some responses to the Pattern-

Table 4 -Pattern provided/ Response (percentages) for the H – Healthy subjects and PD – PD patients, from the three sessions for the second experimental test

		Response (percentages)							
		Pattern-N		Pattern-R		Pattern-S		Pattern-L	
		H	PD	H	PD	H	PD	H	PD
Pattern provided	Pattern-N	100	86.46	0	13.54	0	0	0	0
	Pattern-R	0.37	13.41	99.63	86.59	0	0	0	0
	Pattern-S	0	0	1.08	11.02	98.58	87.99	0.34	0.99
	Pattern-L	0	5.41	0	0	1.06	10.31	98.94	84.28

Table 5 Obtained mean vibratory frequency threshold around the waist zone with the experimental tests: Temporal perception vs Frequency and Spatial perception vs Frequency

	PD Patients	*Temporal perception* vs *Frequency*	>200
		Spatial perception vs *Frequency*	>180
	Healthy Subjects	*Temporal perception* vs *Frequency*	>180
		Spatial perception vs *Frequency*	>160
Mean ± SD			>180 ± 16.33

N (5.4117%) by the PD patients. Analyzing these values, when participants failed, tended to respond to the second zone to which the pattern was provided. Even when the wrong answers diverged, they had a greater incidence in these body areas, concluding that, when the participants do not correctly perceive the stimulated body zone, they recognize the nearest zones, where the vibrotactile units are placed.

Further considerations

Table 5 enables to conclude that the mean vibratory frequency threshold (frequency from which the response of all the group subjects under analysis was correctly identified) around the waist zone, considering both healthy and PD patients, and according to both tests is **180 Hz.** Also, it is possible to compare the threshold frequencies detected among the tests. Since the obtained threshold frequency was smaller for the *Spatial perception* vs *Frequency* Test, it is possible to conclude that all subjects have more spatial perception than temporal.

Time interval and spatial perception vs frequency test

In Table 6, it was observed that the subjects' perception decreases for lower stimulation time intervals and for pattern-L, regardless of the group of subjects (although lower percentages were obtained with PD patients). In general, only for the stimulation time interval of **250 ms**, both healthy subjects and PD patients detected all patterns for any frequency analyzed.

Self-assessment

As shown in Table 7, the healthy subjects evaluated the perception of frequencies and time intervals with high scores. For the perception of each vibrotactile unit, these values varied between healthy subjects and PD patients. Since the navel and the spine are considered natural anatomic references, it was expected that the vibrotactile units placed at these body zones were the best perceived. Indeed, the PD patients scored the vibrotactile units located at the navel and the spine with a higher score, being the

Table 6 Percentage (mean ± SD) of Healthy subjects and PD patients who correctly identified the provided pattern in a shorter time interval of vibration for each of the frequencies tested (200, 220 and 250 Hz)

Time interval of vibration (ms)	Pattern	Frequency (Hz)	Percentage (%)	
			Healthy subjects	PD patients
100	N	220 and 250	100.00 ± 0.00	69.23 ± 43.49
	R	200	100.00 ± 0.00	61.54 ± 50.67
	S	200 and 220	95.00 ± 19.36	79.87 ± 35.24
	L	200	91.66 ± 22.49	62.50 ± 43.30
250	N	200	100.00 ± 0.00	100.00 ± 0.00
	R	200, 220 and 250	100.00 ± 0.00	100.00 ± 0.00
	S	200	100.00 ± 0.00	100.00 ± 0.00
	L	220	100.00 ± 0.00	100.00 ± 0.00
500	N	200	100.00 ± 0.00	100.00 ± 0.00
	R	200	100.00 ± 0.00	100.00 ± 0.00
	S	200 and 220	100.00 ± 0.00	100.00 ± 0.00
	L	220 and 250	100.00 ± 0.00	100.00 ± 0.00
750	N	220	100.00 ± 0.00	100.00 ± 0.00
	R	200	100.00 ± 0.00	100.00 ± 0.00
	S	200 and 220	100.00 ± 0.00	100.00 ± 0.00
	L	220 and 250	100.00 ± 0.00	100.00 ± 0.00
1000	N	200	100.00 ± 0.00	100.00 ± 0.00
	R	200	100.00 ± 0.00	100.00 ± 0.00
	S	200, 220 and 250	100.00 ± 0.00	100.00 ± 0.00
	L	220	100.00 ± 0.00	100.00 ± 0.00

Table 7 Scores of the self-assessment questionnaires (mean ± SD)

Questions	Scores (1-Nothing, 2-Little, 3-Moderate, 4-High and 5-Very High)	
	Healthy subjects	PD Patients
Frequencies perception	4.79 ± 0.43	4.93 ± 0.26
Time interval perception	4.79 ± 0.43	5.00 ± 0.00
Vibrotactile unit perception at navel	4.79 ± 0.43	4.76 ± 0.43
Vibrotactile unit perception at right	4.79 ± 0.43	4.07 ± 0.83
Vibrotactile unit perception at spine	4.33 ± 1.05	4.57 ± 0.51
Vibrotactile unit perception at left	4.18 ± 1.22	4.36 ± 0.74
Comfort	4.93 ± 0.25	4.79 ± 0.43

vibrotactile unit placed on the left side evaluated with the lower score. However, the vibrotactile unit placed at the spine received lower scores from the healthy subjects.

According to qualitative data obtained through questionnaires, all subjects, healthy and PD patients, did not consider the use of the waistband uncomfortable, considering possible to perform their daily tasks while receiving vibrotactile feedback. Indeed, the PD patients and their families showed great interest and acceptability about the developed system.

Conclusions & future perspectives

Experimental tests were performed to detect the best vibratory frequency perceived by PD patients and healthy subjects. The detection of this frequency was carried out considering a spatial, temporal and spatiotemporal context. These tests allowed to detect the best perceived frequency around the waist body zone in a shorter time interval for all the body zones in which the vibrotactile units are placed.

Regarding to the first two experimental tests, *Temporal perception* vs *Frequency*, *Spatial perception* vs *Frequency* Tests, it was verified that, for both case studies, the temporal and spatial perception is higher as the vibration frequency increases. Although, it has been observed that patients with PD present a lower perception than healthy subjects. Even so, it was possible to conclude that on average the frequency by which all subjects, healthy and PD patients, present a high vibration sensitivity at waist body level, was **180 Hz**.

The third test allowed to detect the minimum time interval that the vibrotactile feedback should be provided to be clearly perceived. Thus, it was observed that above **250 ms** of stimulation time interval, almost all PD patients and the healthy subjects detected all patterns for any frequency analyzed.

Taking all the obtained results into consideration, the first steps to implement a system to help PD patients were taken on. The identification of this threshold frequency and this interval will allow us to select the frequency and the minimum interval of vibration to be used in a Vibrotactile Biofeedback Device.

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Compliance with Ethical Standards

Conflict of Interest Helena Gonçalves, Rui Moreira, Ana Rodrigues and Cristina Santos declares that he/she has no conflict of interest.

Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent Informed consent was obtained from all individual participants included in the study.

References

1. Plotnik, M., Giladi, N., Balash, Y., Peretz, C., and Hausdorff, J. M., Is freezing of gait related to asymmetric rhythmic motor performance in patients with is freezing of gait in Parkinson ' s disease related to asymmetric motor function? *Mov. Disord.* 57:656–663, 2004.
2. Thomas, B., and Beal, M. F., Parkinson's disease. *Hum. Mol. Genet.* 16(2):183–194, 2007.
3. Davie, C. A., A review of Parkinson's disease. *Br. Med. Bull.* 86(1): 109–127, 2008.
4. National Institute of Neurological Disorders and Stroke, Parkinson's disease: Challenges, progess and promise. *Genetics*, 2004.
5. Šumec, R., Filip, P., Sheardová, K., and Bareš, M., Psychological benefits of nonpharmacological methods aimed for improving balance in Parkinson's disease: A systematic review. *Behav. Neurol.* 2015:620674, 2015.
6. Lammoglia, J. P., Designing for gait assistance in Parkinson's disease. Technische Universiteit Eindhoven, 2015.
7. Ginis, P., Nackaerts, E., Nieuwboer, A., and Heremans, E., Cueing for people with Parkinson's disease with freezing of gait: A narrative review of the state-of-the-art and novel perspectives. Ann. Phys. Rehabil. Med., 2017.

8. Ashoori, A., Eagleman, D. M., and Jankovic, J., Effects of auditory rhythm and music on gait disturbances in Parkinson's disease. *Front. Neurol.* 6, 2015.
9. Velik, R., Effect of on-demand cueing on freezing of gait in Parkinson ' s patients. *Int. J. Medical, Pharm. Sci. Eng.* 6(6):10–15, 2012.
10. Holland, S., Wright, R., Wing, A., Crevoisier, T., Hodl, O., and Canelli, M., A gait rehabilitation pilot study using tactile cueing following Hemiparetic stroke. *Proc. 8th Int. Conf. Pervasive Comput. Technol. Healthc*. 402–405, 2014.
11. Velázquez, R., Bazán, O., Alonso, C., and Delgado-Mata, C., Vibrating insoles for tactile communication with the feet. *IEEE 15th Int. Conf. Adv. Robot. New Boundaries Robot. ICAR* 2011. 118–123, 2011.
12. Nanhoe-Mahabier, W., Allum, J. H., Pasman, E. P., Overeem, S., and Bloem, B. R., The effects of vibrotactile biofeedback training on trunk sway in Parkinson's disease patients. *Park. Relat. Disord.* 18(9):1017–1021, 2012.
13. Rossi-Izquierdo, M. et al., Vibrotactile neurofeedback balance training in patients with Parkinson's disease: Reducing the number of falls. *Gait Post.* 37(2):195–200, 2013.
14. Winfree, K. N., Pretzer-Aboff, I., Hilgart, D., Aggarwal, R., Behari, M., and Agrawal, S. K., 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(5):806–811, 2013.
15. Ma, C. Z. H., Wan, A. H. P., Wong, D. W. C., Zheng, Y. P., and Lee, W. C. C., A vibrotactile and plantar force measurement-based biofeedback system: Paving the way towards wearable balance-improving devices. *Sensors (Switzerland)* 15(12):31709–31722, 2015.
16. Gonçalves, H., Minas, G., Rodrigues, A. and Santos, C., Literature review of vibrotactile systems addressing freezing of gait in Parkinsonians. *17th IEEE Int. Conf.Auton. Robot Syst. Compet.* 104–109, 2017.
17. Myles, K. and Binseel, M. S., The tactile modality : A review of tactile sensitivity and human tactile interfaces. *Army Res. Lab.* 1–27, 2007.
18. Szecsi, J., Schlick, C., Schiller, M., Pöllmann, W., Koenig, N., and Straube, A., Functional electrical stimulation-assisted cycling of patients with multiple sclerosis: Biomechanical and functional outcome–a pilot study. *J. Rehabil. Med.* 41(8):674–680, 2009.
19. Tsukada, K., and Yasumura, M., Activebelt: Belt-type wearable tactile display for directional navigation. *UbiComp* 2004 *Ubiquitous Comput.* 3205:384–399, 2004.
20. Cholewiak, R. W., Brill, J. C., and Schwab, A., Vibrotactile localization on the abdomen: Effects of place and space. *Percept. Psychophys.* 66(6):970–987, 2004.
21. Malamud-Kessler, C., Estañol-Vidal, B., Ayala-Anaya, S., Sentíes-Madrid, H., and Hernández-Camacho, M. A., Fisiología de la vibración. *Rev. Mex. Neurocienc.* 15(3):163–170, 2014.
22. White, T. L., Suitable body locations and vibrotactile cueing types for dismounted soldiers. 2010.
23. Central, P., Basic gait parameters : reference data for normal subjects 10–79 years of age. 1993.