Apkinson - the health "buddy" that helps in monitoring Parkinson's patients

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Structured abstract
Aim. This paper introduces *Apkinson*, a new mobile application that allows the motor evaluation and monitoring of Parkinson's disease patients. **Methods.** The App is based on previously reported methods to model different motor activities including speech production, movement of the arms, finger tapping, and gait. **Results.** Preliminary experiments with a small set of patients and healthy controls indicate that most of the measurements extracted using *Apkinson* are suitable to perform the automatic discrimination of patients and controls. Kruskal-Wallis tests indicate that most of the features extracted from speech signals, hand movements, and finger tapping are significantly different between Parkinson's patients and healthy controls. **Conclusions.** Although the reported results correspond to preliminary experiments, we think that *Apkinson* is a very useful App that can help patients, caregivers and clinicians, in performing a more accurate monitoring of the disease progression. Additionally, the mobile App can be a personal health assistant (i.e., a health buddy), such that motivates the patients to continue doing the exercises recommended by the doctor in their personal therapy.

Keywords: Parkinson's disease, mobile application, automatic monitoring, motor evaluation, speech, gait, hand movement, finger tapping.

1. Introduction

Parkinson's disease (PD) is a neurodegenerative disorder that affects about 2% of people older than 65 years, which represents more than six million of people in the world [1]. PD is caused by the progressive loss of dopaminergic neurons in the mid-brain. Among the most prominent symptoms exhibited by PD patients are bradykinesia, rigidity, tremor, postural instability, motor speech disorders, and others.
According to the Royal College of Physicians in London [2], in order to relieve the impact of PD, in addition to the pharmacological treatment typically administer by clinicians, PD patients should have access to specialized nursing care, physiotherapy, and speech and language therapy [3]. All of these PD-related treatment exceeds $US 4,072 only in USA (without including cases where ambulatory assistance is necessary). Although the population aging is already a real problem worldwide, it is estimated that the economic burden of PD could be significantly decreased if the disease progression is slowed down in at least 20% [4]. One possible strategy to help in slowing down the impact of PD is based on systematic and unobtrusive monitoring of patients. In order to contribute to this aim, the Pattern Recognition Lab from the University of Erlangen-Nuremberg (Erlangen, Germany), the Machine Learning and Data Analytics Lab also from the University of Erlangen-Nuremberg (Erlangen, Germany), and the GITA research Lab from the University of Antioquia (Medellín, Colombia) started

to work several years ago on the development of different technological tools based on Pattern Recognition and Signal Processing methods to help patients, caregivers, and clinicians in the process of monitoring the neurological state of PD patients. One of the most recent initiatives is the project "*Speech and Movement Analysis using your SMArt phone for neurological diseases - (SMA)^2*" which is financed by the Ministry of Education and Research in Germany (BMBF).

This paper provides details of *Apkinson*, a mobile application that was developed within the framework of the project with the aim of providing the patients, caregivers and clinicians with a technological tool that supports them in the process of following the disease progression. Although the App is not yet advertised and distributed among all potential users, this paper includes results of preliminary evaluations performed with a sample of participants by using *Apkinson* as the recording tool.

1.1. General description of Apkinson

It is a mobile application that records several signals using sensors embedded on the smartphone (microphone, accelerometer, and gyroscope) and performs different analyses with the aim of modeling the neurological progression of PD patients. The App includes information from the patient, medication intake, dose, etc. There is a set of 38 different exercises and the patient is requested to do between six and eight of them every day (in its current version the set of exercises is repeated every week). The set includes tasks of different nature like speech production, hands movement, gait, and finger tapping. The information from those signals is stored on the phone and processed such that the results are compared with previous recording sessions, which allows *Apkinson* to provide the patient with a direct and individual comparison. Those exercises that require more computation power due to more elaborated and complex algorithms are sent to a server. Once the process is performed, the result is sent back to *Apkinson* and included in the feedback that is provided to the patient. Details about the first cohort of patients that are being currently recorded and all of the measurements that are extracted from the collected signals are provided in the next sections.

2. Materials & methods

2.1. Participants

A total of 60 healthy control (HC) people (30 female) and 23 PD patients (12 female) are included in these preliminary evaluations. All of the patients are active members of Fundalianza Parkinson Colombia, which is the foundation for Parkinson's patients in Medellin, Colombia. The patients have an average age of 68.6 years (SD=11.3) with 13 (SD=3.8) years of education. For the case of the control group, they have an average age of 62.2 (SD=10.2) and 10.4 (SD=4.2) years of education. The two groups are matched by age [$t(59)=0.023$, $p<0.00001$] and education level [$t(59)=0.01075$, $p<0.0001$]. The matching of gender is guaranteed per class, i.e., there is a balanced number of female and male in each group (PD patients and healthy controls). The clinical diagnosis of the patients was performed by an expert neurologist in accordance with the United Kingdom PD Society Brain Bank Criteria [5]. At the moment of the pilot evaluation using *Apkinson*, the average time post diagnosis for the patients was 9.7 years (SD=9.3).

The motor evaluation of the patients was according to the section 3 of the Movement Disorder Society-sponsored revision of the Unified Parkinson's Disease Rating Scale (MDS-UPDRS-III) [6]. A total of 17 of the 23 patients were evaluated and the mean value of the MDS-UPDRS-III score was 37.05 (SD=14.5). The reason for the other six patients not to be evaluated is because the project that finances the cost of the neurological evaluation was not running for the time of those recordings. For the patients who were evaluated by the neurologist, our team extracted the values of partial items of the scale like those related with the evaluation of the lower limbs, upper limbs, and the specific item of speech. We believe that the analysis of information regarding these items provide specific insights regarding particular abnormalities in the upper or lower limbs and in speech. Further experiments considering this information will be performed in the near future. None of the participants in the healthy control group presented any neurological or movement disorder. Table 1 and Table 2 include details of clinical and demographic information of the healthy controls and the patients, respectively.

Healthy Controls		
Gender	**Age**	**Education**
F	56	16
M	59	18
F	64	11
F	69	11
F	61	11
F	64	11
F	62	13
F	58	13
F	71	5
F	57	5
F	74	11
F	71	11
F	62	11
F	57	16
F	55	13
F	61	7
F	74	5
F	76	5
F	67	11
F	60	11
F	72	11
F	64	11
F	63	11
F	60	3
F	64	5
F	54	5
F	61	11
F	72	11
F	55	11
F	63	7
F	60	5
M	80	11
M	72	16
M	62	11
M	70	10
M	69	5
M	69	5
M	61	8
M	66	16
M	62	12
M	54	11

M	70	18
M	62	11
M	64	18
M	59	11
M	54	13
M	52	5
M	56	8
M	64	18
M	62	16
M	64	16
M	56	16
M	60	5
M	58	5
M	8	13
M	61	9
M	60	9
M	56	11
M	89	1
M	48	11
Mean	62.2	10.4
SD	10.2	4.2

Table 1. Demographic information of the healthy control participants.

Parkinson’s Disease Patients							
Gender	**Age**	**Education**	**Y**	**MDS-UPDRS-III**	**Speech**	**Lower limbs**	**Upper limbs**
F	62	5	44	31	2	19	10
F	61	19	19	19	1	10	6
M	65	13	16	23	2	12	9
M	75	16	7	33	3	15	15
F	65	13	10	39	1	19	18
M	72	17	7	59	3	31	24
M	74	14	10	39	1	19	19
M	81	12	13	43	3	16	23
F	66	17	10	20	1	9	10
M	72	12	17	44	2	19	23
F	87	12	6	48	2	30	16
M	86	12	7	43	1	18	24
M	73	17	5	65	2	29	32
F	81	17	5	22	0	8	14
F	84	6	3	54	2	27	25
M	54	17	2	32	1	14	17
M	53	12	20	16	0	4	12
F	79	11	3				
F	68	11	1				
F	58	11	4				
F	47	15	3				
M	58	5	3				
F	57	15	8				
Mean	68.6	13	9.7	37.1	1.6	17.6	17.5
SD	11.3	3.9	9.3	14.5	0.9	7.9	6.9

Table 2. Clinical and demographic information of the PD patients. Y: years after the diagnosis. The column Speech indicates the value of the item that evaluates speech deficits in the MDS-UPDRS-III scale. Lower and upper limbs correspond to the sum of items in the scale that are related with the movement of lower and upper limbs, respectively.

2.2. Registration to use the App, metadata, and settings

When the patient uses the App for the first time, it requests the patient to introduce several metadata including the birth date, gender, dominant hand, education level, years of diagnosis, medication name, dose and intake time, weight, height, and others. When the patient has been using *Apkinson* for several sessions, s(he) can see the progress in the performed exercises, and move to the different modules of the App, including access to exercises, results, and other settings. From this module the patient can also start to do the exercise session of the day. Figure 1 shows these options. The name ‘Camilo’ is a reference that corresponds to the name of the patient.

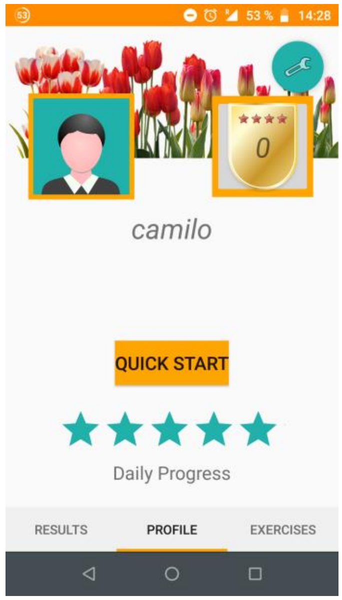


Figure 1. Starting interface after registration.

Apart from the registration and the metadata information, *Apkinson* incorporates a settings module where the patient can manage general aspects of the App like updates of the demographics or medication information, or to change the time of the notifications to remind the patients to do their daily exercises. In addition, when the patient attends a medical appointment, *Apkinson* allows the medical examiner to export the information from the patients' smartphone, and also to update exercises that the patient has to perform. A screenshot of the settings module is shown in Figure 2.

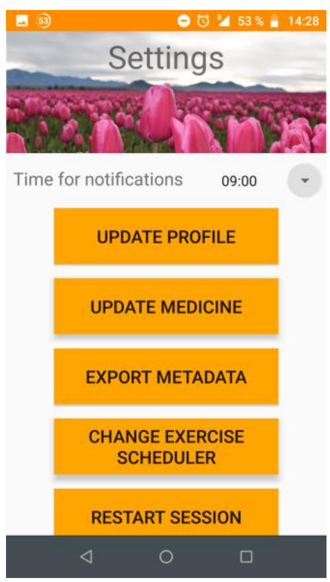


Figure 2. Settings module.

2.3. Exercises included in the current version of *Apkinson*

When the patients press the *quick start* button (see Figure 1), they are moved to the module with the exercises that should be performed on a daily basis. There is a total of 38 exercises, every day within a week the patient will be asked to perform between 6 and 8 different exercises. The patient will receive a daily notification as a reminder to do the exercises. There are three groups of exercises, the first group has a total of 21 speech tasks including the sustained phonation of the vowels /a/, /i/, and /u/, 6 diadochokinetic (DDK) evaluation (e.g., the rapid repetition of syllables like /pa-ta-ka/ and /pe-ta-ka/), 10 different sentences that the patient has to read, and the description of images that appear on the screen. The speech tasks are thought to evaluate phonation, articulation, and prosody impairments in the speech of the patients. The other two groups of exercises contain a total of 17 tasks that are captured using the inertial sensors of the smartphone. The aim is to evaluate different abnormal aspects in movements including postural tremor, kinetic tremor, finger tapping, gait deficits, among others. The patient can access the instructions via video, voice and text on the App. Those instructions guide the patient to perform the exercises correctly. Figure 3 shows different screens that the patient will see when selecting the exercises to perform. For instance, Figure 3(a) indicates a list of exercises to perform in the current session; Figure 3(b) shows an example (text and audio) to explain the patient how to perform the rapid repetition of the syllables /pa-ta-ka/, i.e., DDK exercise; Figure 3(c) shows the screen that the patient can see when is about to start one of the walking tasks. Figure 3(d) shows the example that the patient sees when doing one of the movement tasks which consists in moving the hand (while holding the mobile) from the front to the nose; Figure 3(e) shows the example of how to do the hand tremor exercise; and Figure 3(f) shows the screen of the task where the patient has to touch the lady-bugs alternating between the two fingers. Note that on each exercise the patient can see a video with the example and can also read the instruction that is written below the video screen.

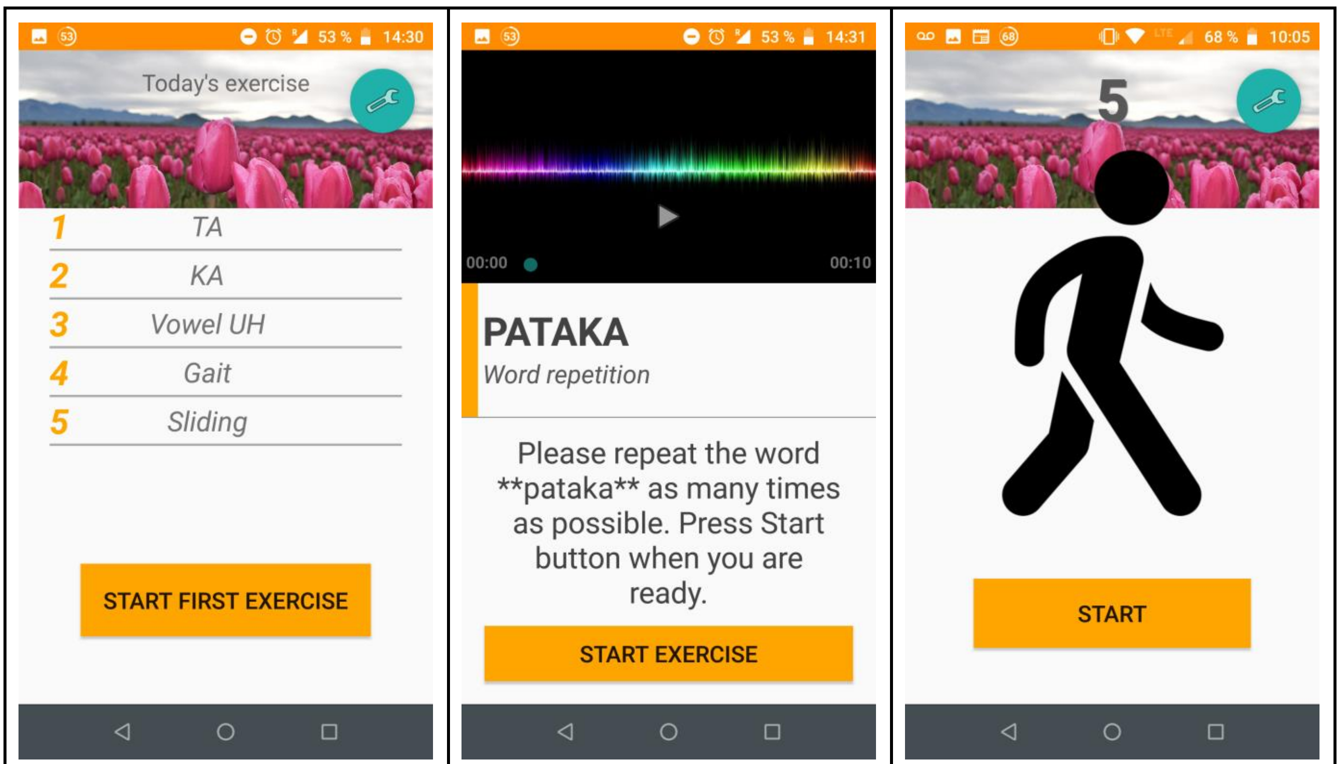
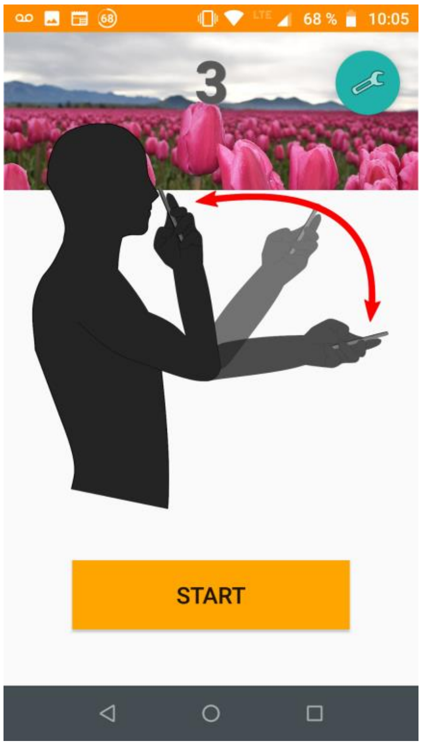
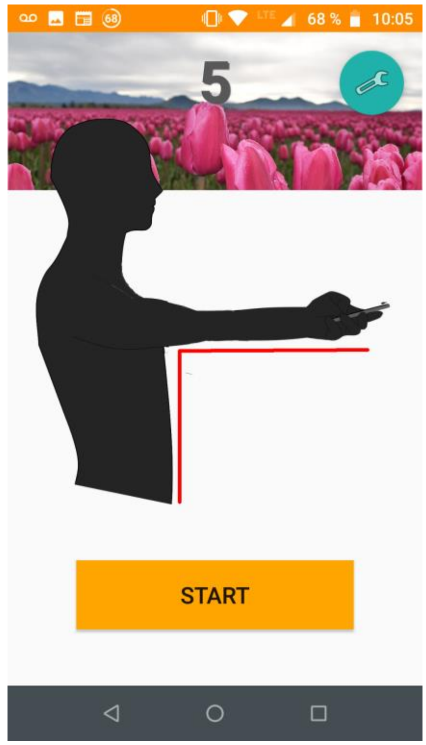


Figure 3(a)	Figure 3(b)	Figure 3(c)





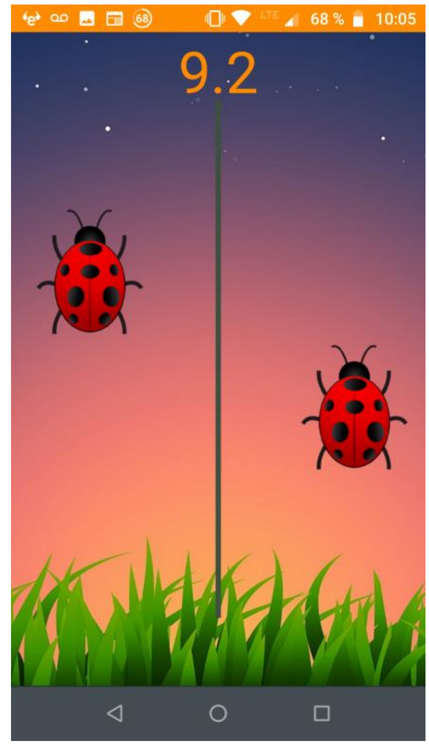


Figure 3(d)	Figure 3(e)	Figure 3(f)

Figure 3. Different exercises implemented in *Apkinson*.

2.4. Speech modeling

For the evaluation of speech, *Apkinson* focuses on the analysis of stability, speech rate, intonation, intelligibility, and pronunciation. The first three are computed directly on the phone and the last two are computed on the server. Further details of each feature are as follows:

Stability

The stability of the vocal folds vibration is measured by computing the jitter, which is defined as the temporal variation of the pitch period related to the frequency at which the vocal folds vibrate due to the airflow coming from the lungs during the production of voiced sounds such as the vowels. For the case of pathological speech, previous studies have shown that the jitter values are higher on PD patients with respect to people without any speech impairment or neurological disease [7-9]. In *Apkinson*, the Jitter is computed from the sustained phonation of the vowel /a/ using Equation 1, where N is the length of the pitch contour, F_0 is the pitch contour, and M_p is the maximum pitch value.

$$Jitter(\%) = \frac{100}{N*M_p} \sum_{k=1}^{N} \left|F_0(k) - M_p\right| \quad \text{Equation 1.}$$

Figure 4 shows an example of the pitch contour for the sustained phonation of vowel /a/ for an HC subject and a PD patient. Note how the pitch contour is more unstable for the PD patient, which is modeled with a higher value of jitter, compared to an HC speaker.

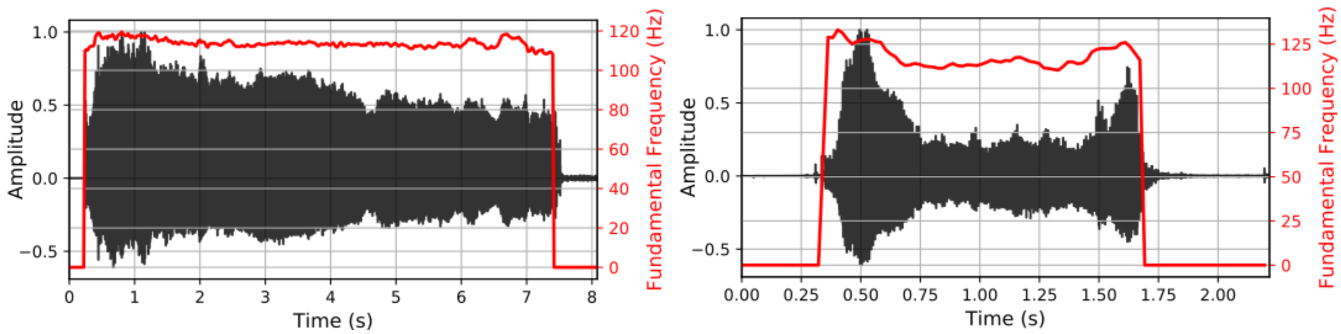


Figure 4. (left) Pitch contour of the sustained phonation of vowel /a/ from a HC speaker, (right) pitch contour of the sustained phonation of vowel /a/ from a PD patient.

Figure 5 shows the box-plot of jitter values computed from the recordings of the sustained phonation of the vowel /a/ obtained from the participants of this study. It can be observed that jitter values are lower for the HC group compared to PD patients. A Kruskal-Wallis test was performed and significant differences have been found between the two groups (H=4.83, p=0.02).

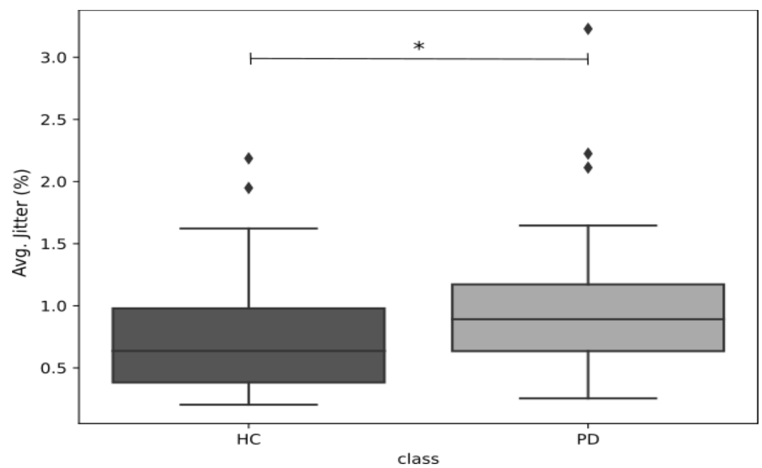


Figure 5. Box plot of jitter values computed from speech recordings of healthy speakers (HC) and Parkinson's disease patients (PD). Kruskal-Wallis p*<0.05.

Speech rate

The speech rate is measured to evaluate the speed of the articulation movements necessary to produce DDK exercises. The speech rate is computed considering the number of voiced sounds per second produced by one speaker during the rapid repetition of /pa-ta-ka/, using Equation 2, where N_v is the number of voiced sounds extracted from the speech signal, f_s is the sampling frequency, and $L$is the number of samples in the speech signal.The method used in *Apkinson* to identify the voiced frames is based on the presence of pitch in short-time speech frames of 40 ms extracted with a time-shift of 10 ms.

$$SR = \frac{N_v * f_s}{L} \quad \text{Equation 2.}$$

The box-plots in Figure 6 show the difference in the speech rate computed between the group of PD patients and HC subjects. Note that the PD patients exhibit a lower speech rate than the HC speakers. The Kruskal Wallis test also indicates that the observed difference is significant (H=6.02, p=0.014).

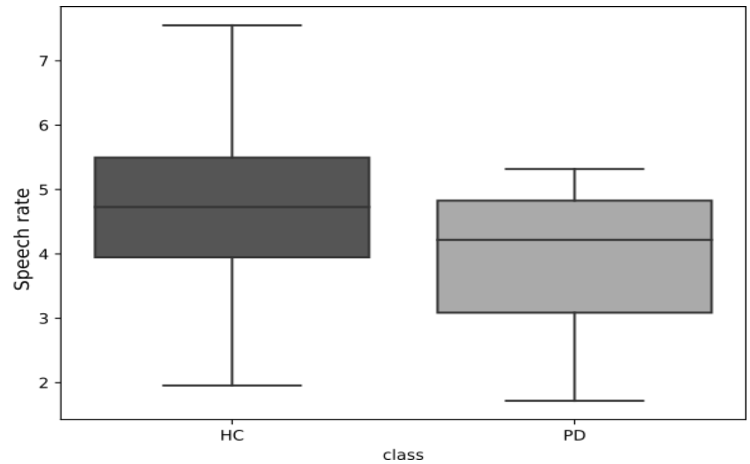


Figure 6. Difference in the speech rate computed between PD patients and HC subjects for the rapid repetition of /pa-ta-ka/. Kruskal-Wallis p*<0.05.

Intonation

One of the most frequent symptoms in the speech of PD patients is the monotone speech, which can be described as lacking of emotional expressiveness during speech communication, resulting in flatness of the pitch contour [10]. In *Apkinson*, the intonation is measured as the standard deviation of the pitch contour extracted from the longest sentence included in the speech protocol.

Box-plots in Figure 7 show also differences in the variability of the pitch contour between the group of PD patients and HC subjects. Although the differences are not significant according to the statistical test (H=1.39, p=0.237), many PD patients have a lower variability than the observed in the HC speakers, which confirms monotonicity exhibited by those patients in continuous speech.

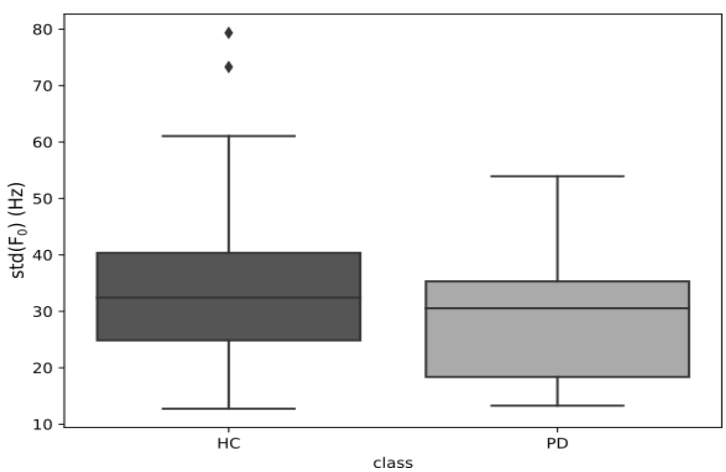


Figure 7. Difference in the variability of the pitch contour between PD patients and HC subjects measured in the longest sentence of the speech exercises. Kruskal-Wallis p=0.237.

Pronunciation

This feature is based on the phonological analysis tool called "Phonet" recently released by our team [11]. The phonological features are represented with a vector with information about the pronunciation of different phonemes grouped into phonological classes according to their mode and manner of articulation. The phonological features will be the conditional posterior probability of a speech frame to belong to one or more phonological classes. The phonological posteriors are computed with a bank of parallel recurrent neural networks (RNNs), which estimate the probability of occurrence of a specific phonological class. In *Apkinson*, we evaluate the pronunciation of "stop" consonants (/p-t-k/) when the patients perform the DDK exercises. Figure 8 shows the difference between the phonological features extracted from an HC and a PD patient when they perform the rapid repetition of /pa-ta-ka/. Note that the estimated posteriors are more stable and accurate in the HC than in the PD patient, where even the phonological posteriors for the /k/ and /p/ phonemes are not detected, or detected with a lower probability.

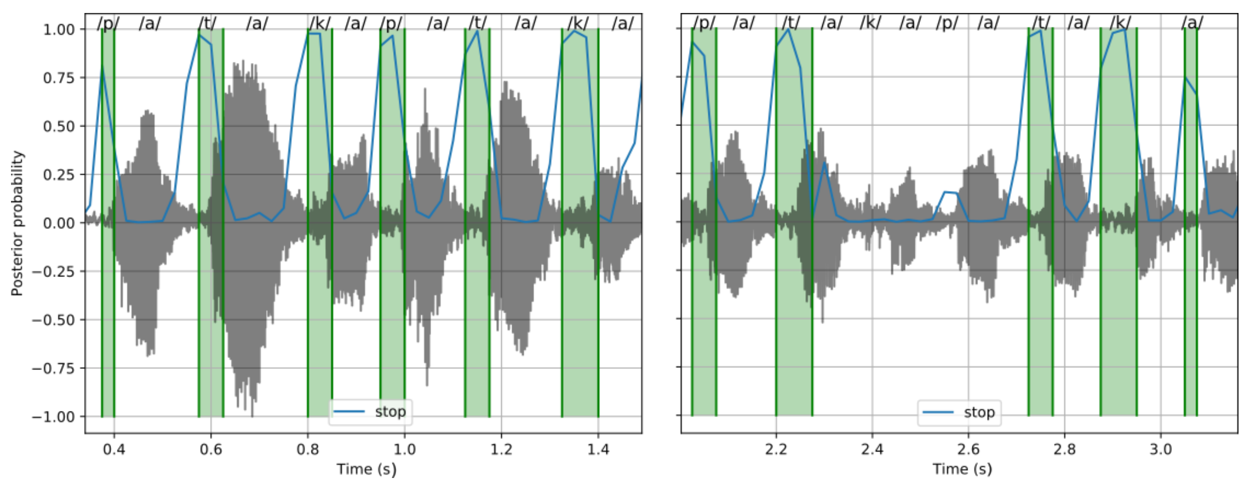


Figure 8. (a) "stop" phonological posterior estimated for a HC speaker when performing a DDK exercise. (b) "stop" phonological posterior estimated for a PD patient.

The box-plots in Figure 9 show the difference between the average posterior probability of "stops" between HC subjects and PD patients. Despite the difference between both groups is not significant according to the Kruskal-Wallis test (H=0.49, p=0.483), note that several PD patients exhibit a lower probability than the observed in the HC group.

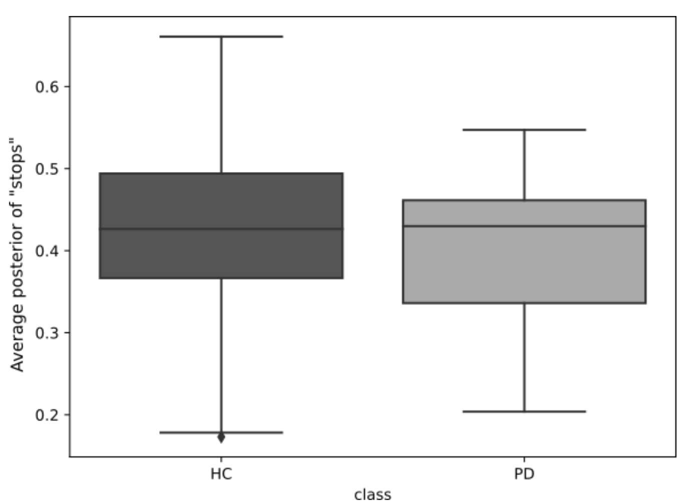


Figure 9. Box plot of the average probability of “stops” computed from speech recordings of healthy speakers (HC) and Parkinson’s disease patients (PD). Kruskal-Wallis p=0.483.

Intelligibility

Intelligibility is related to the capability of a person to be understood by another person or by a speech recognizer. This speech dimension shows loss of the communication abilities of the patients, producing social isolation especially at advanced stages of the disease [12, 13]. Although extensively reported, impairments in speech intelligibility of PD patients have been analyzed through perceived intelligibility. However, it can be automatically measured using automatic speech recognizers (ASRs). To evaluate that, typically the word error rate (WER) between a read sentence and the recognized words is measured. Previous studies showed that PD patients are make more pronunciation errors, then they exhibit a higher WER compared to HC subjects [14, 15]. Intelligibility analysis in *Apkinson* was performed with a trained ASR and the WER was measured between the target sentence the patients had to read and the recognized by the ASR. The WER is computed according to Equation 3, where S is the number of substitutions, I is the number of insertions, D is the number of deletions and N is the number of total words in the original transcription.

$$WER = \frac{S+I+D}{N} \text{ Equation 3.}$$

The ASR was trained using the Kaldi framework [16], and it is installed in the web server. The model was trained with the 10 sentences from the PC-GITA corpus [17] read by 103 participants. Each sentence was repeated 10 times, which gives us 10300 recordings, for an approximate of 10 hours duration of recordings to train the ASR.

2.5. Movement modeling

These analyses are mainly focused on studying how the patients move the lower limbs while walking. The features that are being extracted in this case include measures of regularity, freezing of gait, hand tremor, postural stability, and gait dynamics. All of they are computed on the phone.

Regularity

Apkinson includes several movement exercises where the patients have to perform repetitive patterns that form quasi-periodic signals. These exercises are inspired in the MDS-UPDRS-III scale [6] and include: (1) the *finger-to-nose test*, where the patient with the elbow extended, is asked to bring tip of the index finger to the tip of nose, several times; (2) the *pronation-supination test*, where the patient has to rotate an extended arm in a clockwise and counterclockwise directions; and (3) the *arm-circles exercise*, where the patient has to make forward and backward circles with the extended arm. *Apkinson* evaluates the regularity in the repetition of these exercises according to the temporal variability of the fundamental period of the acceleration signals. Such a variability (TV) is measured according to the standard deviation of the fundamental period of the signal computed for a window frame of 400 ms with a time-shift of 20 ms. The value of TV is normalized according to a sigmoid factor to get a regularity index (RI) score between 0 and 100%, following Equation 4. With the normalized score, a person with very regular movements will get a regularity measure near to 100%, while a patient with irregular movements will get lower scores.

$$RI = \frac{200}{1+e^{2TV}}$$ Equation 4.

Freezing of gait

Freezing of Gait (FoG) is one of the most debilitating motor symptoms in advanced stages of PD [18]. It is characterized by sudden impairments to initiate or continue walking. FoG is also associated with falls [19], interfering with the daily activities of the patients. FoG can be defined as an absence or marked reduction of forward progression of the feet despite the intention to walk [20]. Although medication reduces FoG occurring frequency, usually it is resistant to the pharmacology treatment [21]. Based on this evidence, and in order to measure how the patient is affected by FoG, the freeze index (FI) [22] was included in *Apkinson* in a similar implementation of the one introduced in [23], where the authors used FI in gait signals captured with smartphones.

FI is defined as the ratio between the power spectrum of the "Freeze band" (3-8 Hz) and the power spectrum of "Locomotor band" (0.5-3 Hz). Before computing FI, it was performed a pre-processing step that consists of the segmentation of the initial part of the gait to avoid the moment when the patient place his/her smartphone into the pocket. In addition, we removed the effects of gravity in the gait signals. Finally, we computed the energy in the freeze and locomotor bands, and computed their ratio to have the FI. Box-plots in Figure 10 show the difference in the FI computed for HC and PD patients, when they perform the 4x10 walking test, i.e., to walk 40 meters with a pause every 10 meters. The difference is not statistically significant (H=1.28, p=0.26) because not all of the PD patients exhibit FoG episodes in their gait, however note that several patients have a higher FI with respect to the HC subjects.

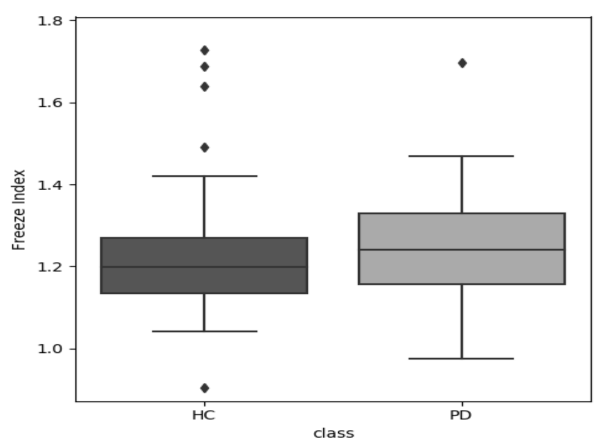


Figure 10. Difference in the Freeze index between PD patients and HC subjects who performed the 4X10 walking task. Kruskal-Wallis p=0.26.

Posture

Posture stability (PS) is a common problem in PD patients and one of the main causes of falls. Several studies show that PD patients suffer 62% more falls that patients with other neurological disorders like Alzheimer's or Huntington's [24]. In order to evaluate posture using *Apkinson*, we consider the standing task, where the patient should be standing straight for 30 seconds with the smartphone in his/her pocket. PS is evaluated in *Apkinson* based on the energy of the acceleration signals in the three axes, according to Equation 5, where a_x, a_y and a_z correspond to the acceleration measured in frontal, sagittal, and transversal planes, and N is the length of the gait signal. The value of the energy is normalized according to a sigmoid factor to get values between 0 and 100%, following Equation 6. With the normalized score, a person with small movements will get a PS near to 100%, while a patient with strong movements will get a lower score.

$$E = \frac{1}{N}\sum\left(a_x^2 + a_y^2 + a_z^2\right) \quad \text{Equation 5}$$

$$PS = \frac{200}{1+e^{2E}} \quad \text{Equation 6.}$$

The box-plots shown in Figure 11 confirm that most of PD patients have stability problems compared to HC subjects, which have a higher PS score. The difference in the postural stability is also significant, according to the Kruskal-Wallis test (H=5.01, p=0.025).

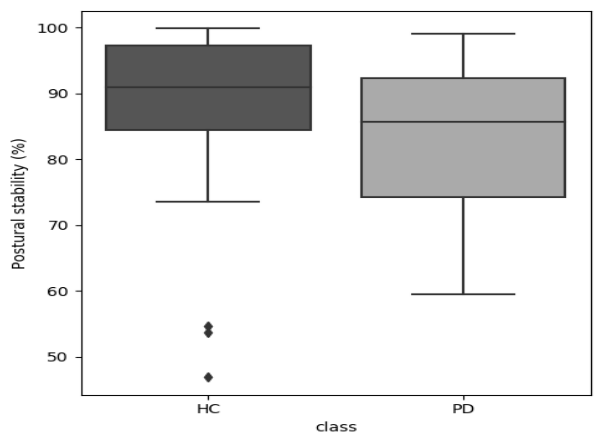


Figure 11. Difference in the postural stability between PD patients and HC subjects. Kruskal-Wallis p*=0.025.

Hand tremor

Hand tremor is a well-known symptom of PD patients. It is defined as a rapid back-and-forth movement of a body segment [25]. Tremor in PD patients appears mainly at rest, and tends to disappear during posture or movement [26]. However, in severe stages of the disease, the tremor may remain present during hand posture or movement. Hand tremor in *Apkinson* is evaluated in the "postural tremor exercise", where the patient extends the arm holding the phone, and keeping such a position for at least 10 seconds. *Apkinson* computes the energy of the acceleration signals when the patient is holding the phone, using the same strategy considered for the postural stability (see Equations 5 and 6) in order to get a performance measure of the exercise (patients with low tremor will have a higher performance). The evaluation is performed both with the right and left hands, in order to consider the contra-laterality effect, observed in the addressed population [27].

The difference observed in the performance of the postural tremor exercise between PD patients and HC subjects is significant for the left arm (H=7.65 p=0.005) but not for the right arm (H=0.38 p=0.53), which is the dominant hand for most of the participants. This confirms the presence of the contra-laterality effect in the studied group. These results are observed with more detail in Figure 12.

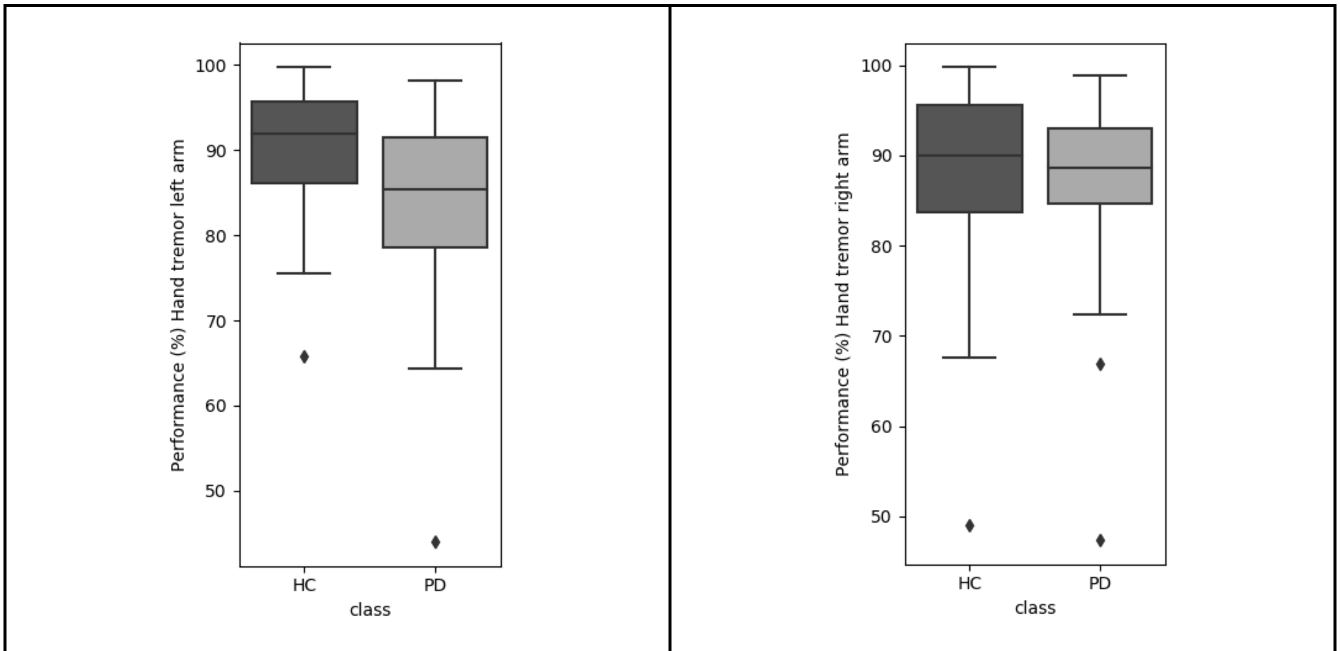


Figure 12(a)	Figure 12(b)

Figure 12. (a) Difference in the hand tremor between PD patients and HC subjects when performing the exercise with the left hand. Kruskal-Wallis p*=0.005., (b) Difference in the hand tremor between PD patients and HC subjects when performing the exercise with the right hand. Kruskal-Wallis p=0.53.

Gait dynamics

One of the most important feature sets considered in modeling motor impairments of PD patients are those based on the kinematic analysis of the gait process [28]. Conventional kinematic features are based on the duration, length, and velocity of the strides.

Apkinson has incorporated a step detection algorithm based on a peak detection method of the acceleration signals. With the number of detected steps and their location in the acceleration signal, we computed the duration of each step. The number of steps and the average duration are also included in the dashboard section of *Apkinson* to show the patient their current performance when they perform the 2 minutes walking test.

2.6. Fine movement modeling

Fine movement tasks aim to evaluate different dimensions of PD. Symptoms reported in the scientific literature are akinesia (inability to initiate movement), bradykinesia (slow movements), freezing (momentary loss of movement), deficit in space-visual ability and loss of cognitive ability. In order to evaluate the patient's performance in fine movements, three finger tapping tasks have been included in *Apkinson* based on those proposed in [29]. The first one consists on tapping with the thumb of the dominant hand ladybugs that randomly appear on the screen for 10 seconds. In the second task the previous procedure is repeated but now both thumbs are used to hit two ladybugs that appear randomly on the screen (each ladybug is located in the right and left half of the screen so that each finger is close to a ladybug and a natural movement is guaranteed). The third task is to slide horizontally a bar until reaching a target point, which moves randomly every time once it is reached. This third task is inspired in the Fitt’s test to evaluate human computer interaction systems [30]. Each task presented requires rapid reaction, concentration, ability to associate, spatial location and repeated movements of extension and contraction of the fingers. The evaluation of the fine movement skills of the patients is performed with the four features described below:

Tapping accuracy
This feature indicates the number of insects that the patient manages to capture during the time of the exercise, relative to the number times the patient touches the screen, according to Equation 7. The value is limited to a maximum of 100%. With this indicator, vertical extension and contraction movements of the fingers are evaluated. The tapping accuracy is computed both for the one finger and two fingers tapping exercises, and the value displayed in the result screen corresponds to the average accuracy for both exercises.

$$Tapping\ accuracy = \frac{100 * Number\ of\ correct\ hits}{Total\ Number\ of\ hits} \quad \text{Equation 7.}$$

Tapping velocity
This feature is computed as the number of taps performed, relative to the duration of the tapping exercise. The velocity is computed for both tapping exercises, and the displayed value corresponds to the average velocity.

Precision
The tapping precision measures the distance between the point in the screen pressed by the patient and the real place of the lady bugs in the tapping exercises. The precision is computed based on Equation 8, where $R$is a reference factor computed as the average distance to the lady bugs for HC subjects normalized by the size of the screen (in pixels). d_i is the i-th distance to the lady bug for the total of tappings Tin the exercise.

$$Tapping\ precision = 1 - \frac{100}{R}\sum_{i=1}^{T} d_i \quad \text{Equation 8.}$$

Sliding velocity
Similar to the tapping velocity, this feature measures the number of times the patient is able to reach the target bar during the time of the exercises.
The box-plots in Figure 13 show the difference between the tapping features computed for the group of PD patients and HC subjects. Note that PD patients exhibit a lower tapping accuracy, a lower tapping velocity, and a lower tapping precision, compared to the HC group. The results from the Kruskal-Wallis test indicate that there is a significant difference between the features extracted from the PD patients and HC subjects ($p<0.05$).

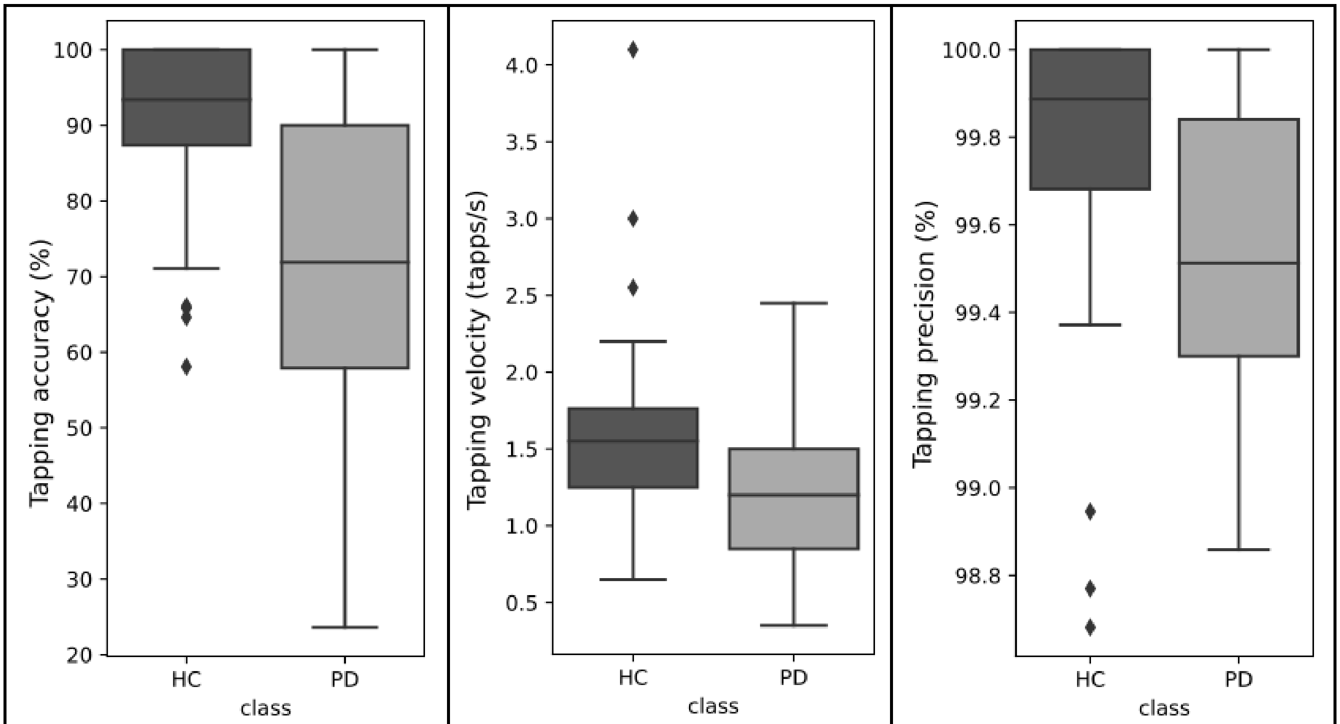
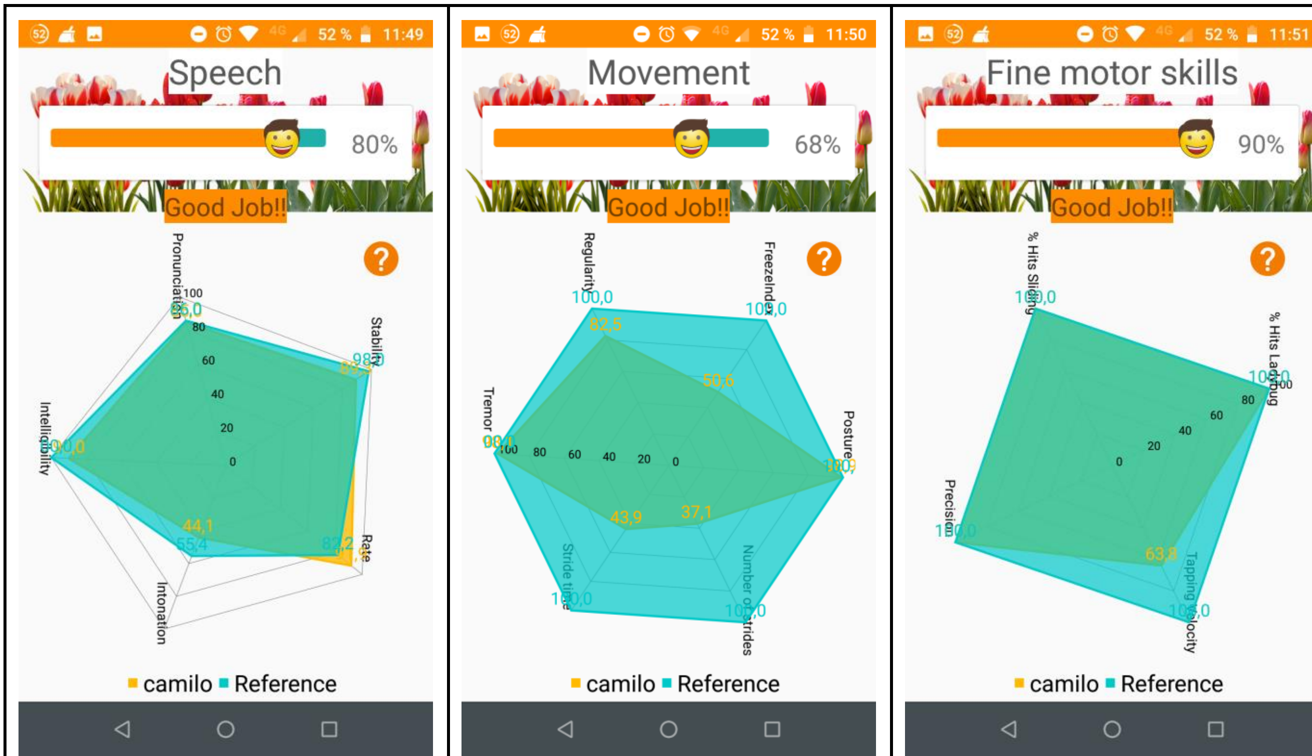


Figure 13(a)	Figure 13(b)	Figure 13(c)

Figure 13. (a) Difference in the tapping accuracy between PD patients and HC subjects (H=15.36, p<<0.005), (b) Difference in the tapping velocity between PD and HC subjects (H=7.36, p=0.007). (c) Difference in the Tapping precision between PD and C subjects (H=8.05, p=0.005).

2.7. Feedback to the patient and global motor evaluation

Patients can see their performance after doing the exercises, and also compare results with respect to previous sessions, i.e., follow-up evaluation. Figure 14 shows the different screens of results that the patient can visualize to get feedback about the current state. Figure 14(a) shows the results obtained from the speech exercises. The five vertices of the radar-type plot correspond to the evaluation of stability, speech rate, intonation, intelligibility, and pronunciation. A general performance in speech is obtained from the area of the resulting pentagon. Figure 14(b) indicates results obtained from movement exercises and the six vertices of the plot correspond to regularity of movements performed with the upper limbs, postural tremor, average duration of the strides in the walking exercises, number of steps in the 4x10 exercise, postural stability, and the freeze index. As in the previous case, the area of the resulting hexagon is computed as a general performance for movement analysis. Finally, Figure 14(c) shows results of the evaluation of fine motor skills including the taping accuracy, velocity of tapping, the tapping precision, and number of times the bar reaches the target in the sliding exercise. The general fine motor skill of the patient is computed as the area of the resulting quadrangular. In all of the cases, the reference plot in cyan color is computed as the result of evaluating 60 healthy control subjects. The plot computed for the patient is in orange and when there is overlap between the reference subjects and the patient, the resulting plot is in light green.



(a) Speech results | (b) Movement results | (c) Fine motor results

Figure 14. Results with feedback to the patient.

The global motor evaluation is performed considering the areas of the geometrical figures obtained from each evaluation separately (speech, movement, and fine motor). The result is composed by three area values which are used as the vertices for a triangle. As in the case of the individual evaluations, there is a reference plot computed with the results of 60 healthy subjects. Figure 15(a) shows an example of how *Apkinson* displays the overall results to the patient in terms of the area of the resulting triangle. Additionally, Figure 15(b) indicates how the historic results are displayed. Note that these two figures provide immediate feedback to the patient, one is specific for the last recorded session and the other one is general with the overall results obtained in the current and previous sessions.

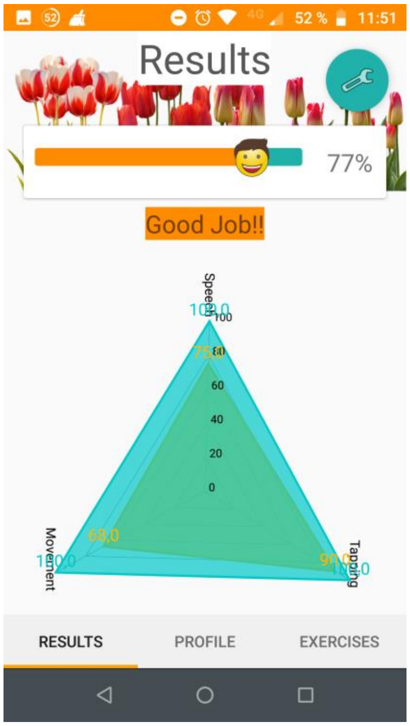


Figure 15(a)

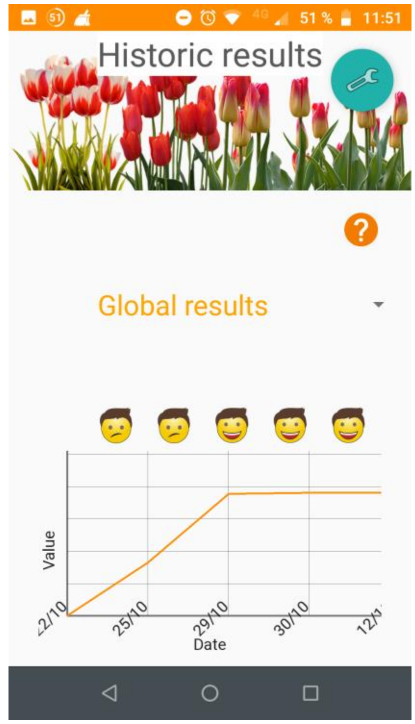


Figure 15(b)

Figure 15. (a) Overall results displayed to the patient with a reference computed from results of a set with healthy control people. (a) Historic results obtained by the patient.

2.8. Communication between *Apkinson* and the server

The system incorporates a database created in mysql version 15.1 Distribution 10.1.37-MariaDB. Several tables are created per patient. Each table stores metadata and information about the medication. There is also a table where all of the results of the exercises performed by each patient are stored, additionally, the server stores multimedia files with raw data of the speech and movement recordings. Potential users like patients, care givers, medical doctors, and the administrator, have permissions to access different levels of the data, which means not everybody can observe the same data because it will depend on the permissions granted by the admin (this option is still under development and will be configurable according to the Ethical regulations of each country or institution).

The access to the data is provided via a Web-based application developed on Django 1.11.

The communication between the server and the App is performed with the Volley 1.0.10 library, which is a high level interface that allows the exchange of HTTP requests from the App to the server. It is important to mention that the App senses the WiFi connection of the smartphone and files are only sent to the server when there is WiFi connection (unless the user changes this option). This is with the aim of avoiding consuming all of the mobile data of the user, which could potentially demotivate to use *Apkinson*. WiFi connection checking and the posterior files uploading are performed every hour in the background. Data on the smartphone are stored in a SQLITE database structure which allows the system to synchronize the smartphone and the server.

Discussion

This paper has introduced a new mobile Application called *Apkinson* that can be used for the evaluation and monitoring of motor impairments in PD patients. The App incorporates exercises and models for speech, walking, hands movement, and finger tapping. The patient receives immediate feedback with the results of the exercises. Since such a feedback is individual per patient, it motivates him/her to continue using the App and trying to perform better every day. Clinicians have access to the results and can configure the profile of each patient with the aim of updating the medication intake and dose. Preliminary results are reported here indicating that most of the features currently implemented in *Apkinson* allow a significant discrimination between PD patients and HC subjects. This mobile Application is a step forward in the development of technological tools for the accurate and unobtrusive monitoring of people suffering from Parkinson's disease. We are aware of the fact that preliminary results are based on a small sample of patients, however, our team is currently recruiting more people and we believe that more robust and conclusive results will be available in the near future.

Conclusions and future work

Preliminary results indicate that *Apkinson* can be potentially used for monitoring PD patients. Most of the evaluated features indicate that there is significant difference between patients and healthy controls; however, further recordings and experiments are required to find more stable and conclusive results.

According to what we have observed during the preliminary evaluation of the App, most patients are willing to use these kinds of technologies. We think that there are many aspects where the research community in Computer Science and Medicine can work on with the aim of contributing to slow down the impact of PD. Additionally, technologies like those developed in *Apkinson* can help in decreasing the economic burden of the treatment costs by providing the experts neurologists with remote access to quantitative evaluations that could help them to make timely and better informed decisions regarding the treatment without requesting the patient to come to the clinic.

Limitations of the system and future work

The current version of *Apkinson* is able to handle audio, video and files resulting from the recording of movement exercises. Additionally, the system is able to compute the WER of the speech tasks by using the Kaldi framework on the server side. Although all of the functionalities of the system are working properly, there is a need for a module that handles the requests by creating a queuing method. We are currently working on solving this limitation by implementing virtual services in the server side, such that they can manage all of the requests without intervening with other processes in the system.

Summary points

(1) *Apkinson* is open source, so all of the source code can be downloaded and used to improve the existing App or even to create a new one.

(2) The algorithms implemented in *Apkinson* allow the evaluation of different motor aspects like speech production, movement of arms, hands and legs, and also fine motor aspects including those related with finger tapping.

(3) The feature extraction module of *Apkinson* is based on measurements that have been developed and tested in previous scientific works.

(4) Direct feedback is provided to the patient and it allows the comparison of performance obtained in current and previous recording sessions. This aspect allows the patient to know about his specific progression.

(5) According to preliminary results, most of the extracted features are suitable to evaluate abnormal motor patterns in Parkinson's patients.

(6) Further recordings and experiments are required to report more conclusive and robust results.

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Ethical disclosure: this study was approved by the ethical committee at University of Antioquia and it follows the principles outlined in the Declaration of Helsinki for all human or animal experimental investigations. An informed consent was obtained from the participants involved in the study

Data sharing statement: All of the modules of *Apkinson* that run on the mobile side can be downloaded from the following link: https://github.com/jcvasquezc/SMA2 the modules that run on the server side can be downloaded from: https://github.com/jcvasquezc/apkinson_server
The results presented in this manuscript are original and the data is not publicly available due to privacy restrictions.