ORIGINAL ARTICLE

Finger and foot tapping sensor system for objective motor assessment

Senzorski sistem za objektivnu motornu procenu na osnovu *tapping*-a prstima i stopalom

Milica Djurić-Jovičić*[†], Nenad Jovičić[†], Saša Radovanović[‡], Milica Ječmenica
Lukić[‡], Minja Belić[†], Mirjana Popović[†‡], Vladimir Kostić[§‖]

University of Belgrade, *Innovation Center School of Electrical Engineering, [†]School of
Electrical Engineering, [‡]Institute for Medical Research, [§]Faculty of Medicine, Belgrade,
Serbia; Clinical Center of Serbia, [‖]Clinic for Neurology, Belgrade, Serbia

Abstract

Background/Aim. Finger tapping test is commonly used in neurological examinations as a test of motor performance. The new system comprising inertial and force sensors and custom proprietary software was developed for quantitative estimation and assessment of finger and foot tapping tests. The aim of this system was to provide diagnosis support and objective assessment of motor function. **Methods.** Miniature inertial sensors were placed on fingertips and used for measuring finger movements. A force sensor was placed on the fingertip of one finger, in order to measure the force during tapping. For foot tapping assessment, an inertial sensor was mounted on the subject's foot, which was placed above a force platform. By using this system, various parameters such as a number of taps, tapping duration, rhythm, open and close speed, the applied force and tapping angle, can be extracted for detailed analysis of a patient's motor performance. The system was tested on 13 patients with Parkinson's disease and 14 healthy controls. **Results.** The system allowed easy measurement of listed parameters, and additional graphical representation showed quantitative differences in these parameters between neurological patient and healthy subjects. **Conclusion.** The novel system for finger and foot tapping test is compact, simple to use and efficiently collects patient data. Parameters measured in patients can be compared to those measured in healthy subjects, or among groups of patients, or used to monitor progress of the disease, or therapy effects. Created data and scores could be used together with the scores from clinical tests, providing the possibility for better insight into the diagnosis.

Key words:
parkinson disease; muscle tonus; neurophysiology; toe phalanges; hand; fingers; equpment and supplies; serbia.

Apstrakt

Uvod/Cilj. *Tapping* tj. tapkanje prstiju šake i stopala se uobičajeno koristi u neurološkim ispitivanjima kao test motorike. Prikazan je novi sistem koji sadrži inercijalne senzore i senzore sile, kao i odgovarajući softver za kvantitativnu procenu dijagnostičkog motornog testa na osnovu *tapping*-a prstima i stopalima. Uz pomoć ovog sistema moguća je objektivna evaluacija motornog obrasca bolesnika, a samim tim i lakše postavljanje određenih dijagnoza i praćenje progresa bolesti ili terapije. **Metode.** Minijaturni inercijalni senzori su bili postavljeni na vrhove prstiju u cilju kvantifikovanja pokreta prstiju. Senzor sile postavljen je na jagodicu jednog prsta i merio je silu primenjenu u toku *tapping*-a – tapkanja kažiprsta o palac. Za ocenu *tapping*-a stopalom, inercijalni senzor je postavljen na gornji deo stopala ispitanika koje je bilo postavljeno na platformu za merenje sile. Pomoću ovog sistema mogu se posmatrati brojni parametri poput broja i trajanja svakog pokreta, ritma i promena ritma, brzine otvaranja i brzine zatvaranja prstiju, primenjene sile, promene ugla između prstiju, i na osnovu ovih parametara može se vršiti detaljna analiza motornog stanja bolesnika. Sistem je testiran na 13 bolesnika sa Parkinsonovom bolešću i 14 zdravih ispitanika. **Rezultati.** Sistem je omogućio jednostavno merenje navedenih parametara i grafički prikaz kvantitativnih razlika u ovim parametrima između zdravih ispitanika i bolesnika sa neurološkim oboljenjem. **Zaključak.** Novi sistem za *tapping* prstima i stopalima je kompaktan, jednostavan za upotrebu i efikasan za prikupljanje podataka o bolesniku. Izmereni parametri mogu se koristi za poređenje bolesnika sa zdravim ispitanicima, ili sa drugim grupama bolesnika, ali i za praćenje progresa bolesti ili efekata terapije. Dobijeni podaci mogu se koristiti zajedno sa rezultatima drugih kliničkih testova, dajući tako mogućnost za bolji uvid u dijagnozu.

Ključne reči:
parkinsonova bolest; mišići, tonus; neurofiziologija; prsti noge; šaka; prsti; oprema i pribor; srbija.

Correspondence to: Milica Djurić-Jovičić, Bulevar kralja Aleksandra 73, 11 000 Belgrade, Serbia. Phone: +381 11 3370 123.
E-mail: milica.djuric@etf.rs

Introduction

Finger tapping test is commonly used in neurological examinations as the test of motor performance [1]. Patients tap their thumb and index fingers as quickly as possible for a required period of time, usually 10 to 15 s. The rhythm, amplitude, and velocity of tap movements depend on patient's motor capabilities and symptoms, providing an estimation of the integrity of central nervous system components [2]. Foot tapping is proven to be a reliable and valid measure of Parkinson's disease (PD) motor function [3] and estimation of rigidity or tremor in PD [4].

Large differences between the performance of the fingers on the left and right hand or differences in left and right foot speed may reflect a lateralized hemispheric dysfunction. Holmes [5] already proved that the rhythm of finger tapping movements acts as an efficient index for cerebellar function testing. Tapping tests have been widely used for quantification of ataxia [6], assessment of stroke recovery [7] or quantification of Alzheimer's disease [8].

Repetitive finger tapping is commonly used to assess bradykinesia in Parkinson's disease. It is included in the Unified Parkinson's Disease Rating Scale (UPDRS test, e.g. Fahn et al. [9] 1987), providing descriptive characteristics of the patient motor ability. UPDRS levels are categorized as: mild slowing and/or reduction in amplitude; moderately impaired; severely impaired, with frequent hesitation in initiating movement or arrests in ongoing movement, and, can barely perform the task. In patients with PD, finger tapping was selected as it is more severely affected than hand opening and closing, and hand pronation and supination elements of the motor section of Part III of the UPDRS [10, 11]. The rhythm, amplitude and velocity of the index tap movements vary with patient's motor capabilities and symptoms. Tapping is simple and commonly used in assessment, and any distinctive features identified for the condition would provide helpful diagnostic clinical clues. Furthermore, the foot tapping technique was used to compare reliability to measure improvement in parkinsonism during different applied medication [3]. It has been shown that foot tapping provides more information than finger tapping, i.e., the alternate foot tapping correlates better with PD outcome measures than finger tapping [3]. Foot tapping may be a useful outcome measure for determination of dopaminergic medication effect in PD clinical trials [4].

In clinical practice tapping is often evaluated visually, estimating speed and regularity of the movements. However, very small finger tapping differences in amplitudes cannot be easily and correctly identified during neurological examination. It has already been reported that tapping score is one of the most difficult items to assess [12]. Several tapping-measuring mobile devices were described in literature, [13] with different measurement protocols – finger tapping, alternate and repetitive foot-tapping (between two, or on one pedal) [3]. Their aim was to create an efficient system for use in general clinical environment and to validate the measurement and evaluation method for finger and foot tapping movements.

Several research groups have worked on making quantitative evaluation more accurate through the use of various finger-tapping systems. Some relied on 3D recordings from an optoelectronic motion capture system with markers placed on a hand of a subject for reconstructing the tapping motions [14–16]. In other studies, different kind of sensors were mounted on a subjects' fingers, or were constructed in form of touch pads [17–20].

Okuno et al. [17] presented a finger tapping acceleration measurement system for the quantitative diagnosis of PD, which uses 3-axis piezoelectric accelerometers, a pair of touch sensors made of thin stainless steel sheets, an analog to digital converter and a personal computer. Finger stalls, with these sensors, were attached to the index finger and thumb, and the subjects were prompted to perform finger tapping motion, so that their index finger and thumb should touch, continuously for 60 s at a time. They showed that relevant features could be extracted from accelerometer and touch sensor output. The features included standard deviation of single finger-tapping intervals, average of maximum single finger-tapping velocities and average of maximum single finger-tapping amplitudes.

Ling et al. [14] observed the same type of movement with a measurement system that consisted of infrared emitting diodes placed across the subject's hands and a 3D motion analyzer. Amplitude, cycle duration and mean speed were measured for each cycle of finger tapping from one finger-thumb separation to the next. This study showed a difference in tapping patterns between patients with PD and those with progressive supranuclear palsy.

A study using an image based motion analyzer was introduced by Jobbágya et al. [15] who analyzed motion of fingers while simulating playing the piano. They assessed the speed and regularity of these movements in patients with PD and a control group of healthy subjects, with the help of an image based motion analyzer and passive markers attached to anatomical landmark points. Another group [18] developed a system for estimating piano-playing-like motions, designed in form of four electronic touch plates in fan shape and a hand rest as the fifth plate. An oscillator was attached to the fifth plate, which resistively induced a small sinusoidal current in the hand. When a finger should touch one of the touch plates, the induced signal on the finger would be of sufficient amplitude to toggle the output of a digital logic gate. Subjects had their free tapping motion tested, as well as tapping with weights attached.

An interesting system was presented by Shima et al. [21], working with a magnetic sensor with two coils mounted on the hand of a subject. The coil voltage created by electromagnetic induction changed depending on the distance between the two coils. The system had a graphical output, displaying the measured fingertip distance, velocity, acceleration, computed indices and radar charts, phase-plane trajectories of the fingertip distance and velocity, as well as velocity and acceleration in real-time.

Despite various mentioned and other related systems, currently there is no commercially available system for finger and foot tapping assessment in patients with PD or rela-

ted movement disorders. In this paper, we propose a novel sensor system for quantitative and qualitative finger and foot tapping assessment. The system comprises miniature inertial sensors placed on the index and thumb finger ends (top side), or on the upper side of the foot. Along with inertial sensors, the system includes a force sensor placed on a fingertip and a force platform for foot tapping force assessment. The system outputs are quantitative measures, such as tapping durations, number of taps, tapping velocity, tapping force, and tapping angle (angle between the fingers or between the foot and the ground). The system was used to record tapping in neurologic patients as well as in healthy controls.

Methods

Instrumentation

The system comprises of three sensor control units (SCU) which acquire signal data from the sensors and wirelessly transmit them to a remote computer though the interface unit (Figure 1). Data acquisition is controlled through a user-friendly graphical interface. Wireless communication enables convenient usage of the system in clinical environment, covering the radius of 20 m indoors [22].

Both the index finger and the thumb are mounted with sensors and connected to their SCU (SCU1 and SCU2 in Figure 1). In order to measure the contact force between the fingers, SCU1 is additionally equipped with a force sensing resistor (FSR, Interlink, USA), connected to the control unit with a tiny cable. The third control unit (SCU3), used for foot tapping, is additionally connected to a force sensing platform. The force platform is a custom made combination of active (metatarsal) and passive (heel) areas. The mechanical construction of the platform enables free movement of the active plate in the nominal force range up to 50N, while the passive plate is connected to the fixed part of the platform. A load cell (AMI-5, GLIKI, Austria) is placed between active and passive metal plates, so it measures the force applied to the active area. The load cell interface contains an instrumentation amplifier and additional passive electronic components. The gravitational component is eliminated by software calibration (Figure 2).

Data is sampled with 200 samples per second. The effective resolution is 12 bits for the inertial sensors, while for the force sensing sensors the effective resolution is 8 bits. The acquired signals are monitored online and automatically stored for further processing. The acquisition software was designed in LabWindows CVI (National Instruments, USA),
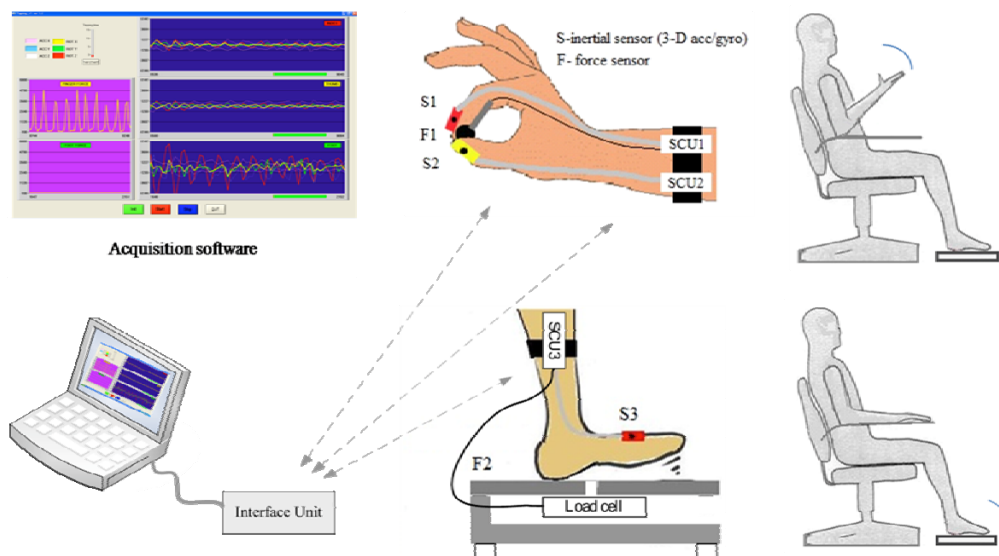

Fig. 1 – Left: Finger and foot tapping acquisition scheme. Middle panels: placements of the inertial sensors (Si) and force sensors (Fi) for finger (Top) and foot (Bottom) tapping. Right panels: initial subject's position during finger (Top) and foot (Bottom) tapping testing.

Each SCU is equipped with a miniature inertial measurement unit (IMU), which comprises of a 3D accelerometer LIS3DH, and a 3D gyroscope L3G4200 (STMicroelectronics, USA). IMUs and control units are connected with a tiny flat cable. IMUs are placed directly either on the finger or foot, while the control unit is attached to the stable part of the body in the vicinity (arm or leg, respectively). IMU's are light, with small dimensions, allowing the subject to perform the movements in a natural manner.

while signal analysis was performed in Matlab (MatWorksInc, USA).

Participants

This study included two groups of right-handed participants: 13 patients with PD diagnosed according to the UK Queen Square Brain Bank Criteria [23]; 14 healthy controls (CTRL) with no history of neurological or psychiatric disea-
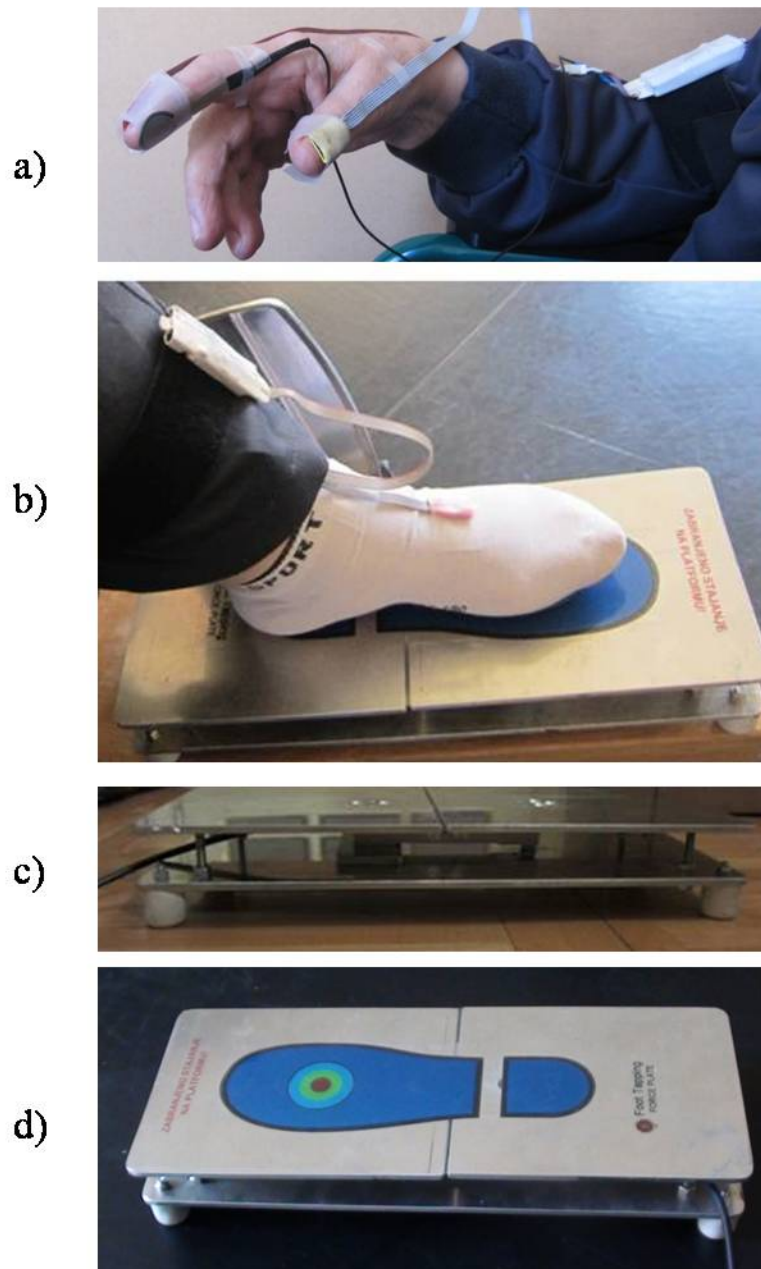
Fig. 2 – Sensor system for finger and foot tapping: a) finger tapping system mounted on a patient; b) foot tapping system mounted on a patient; c) force platform (cross section); d) force platform (view from above).

se. CTRLs were age- and sex-matched with the patient group (Table 1). Participants were recruited from the Movement Disorders Unit at the Clinic for Neurology, Clinical Centre of Serbia, Belgrade.

Patients with tremor/dyskinesia and hand dystonia, as well as any disability of the extremities that might interfere with motor tasks, were excluded from the study. Other exclusion criteria were: scores < 26 on the Mini Mental Status Examination [24] and < 15 on the Frontal Assessment Battery [25], respectively; score > 14 for the Hamilton Depression Rating Scale [26]; and history of psychosis or major medical disease.

Disease staging was assessed according to the Hoehn and Yahr [27] system and motor disability using the UPDRS III [9]. Levodopa equivalent dose was also calculated [28]. All

the tests, including FT performed in accordance with the recommendations for FT assessment, were conducted in the morning after an overnight treatment withdrawal of at least 12 hours where applicable (patients with PD were tested during "off" time) [19].

Experiments: system setup and recording protocol

Subjects were asked to sit comfortably in a chair. The sensors were carefully mounted on patients' fingers so as to minimize obstruction of natural movements. The inertial sensors (S_i) were placed on top of index and thumb nails, along the finger's length, while the force sensor (F_i) was placed on finger tip (Figure 1, upper middle panel). The sensors were fixed with Leucopor® or similar adhesive tape. Complete

Table 1
Demographic and clinical features of patients with Parkinson's disease (PD)
and healthy controls (CTRL)

Parameters	CTRL (n=14)	PD (n=13)	p value
Age (years)	56.8 ± 9.0	60.9 ± 9.9	/
Female/Male	8/6	6/7	/
Disease duration, years	/	4.6 ± 4.5	/
LED (mg/day)	/	664 ± 531	/
Hoehn&Yahr Stage	/	2.1 ± 0.9	/
UPDRS total	/	47.1 ± 18.9	/
UPDRS motor part	/	27.2 ± 10.3	/
MMSE	29.4 ± 0.9	28.8 ± 1.1	0.001
HDRS	4.0 ± 2.1	8.2 ± 4.7	0.023
FAB	17.9 ± 0.3	15.5 ± 1.3	0.001

Note: Values present mean ± standard deviation.
HDRS – Hamilton Depression Rating Scale; LED – levodopa
equivalent dose; UPDRS – Unified Parkinson's Disease Rating
Scale; MMSE – Mini Mental Status Examination; FAB – Frontal
Assessment Battery.

mounting of the sensors and system setup requires less than five minutes.

For the finger tapping test, the subjects were asked to place their hand in front of them in the way they found most convenient (Figure 1, top right). In order to allow unobstructed foot tapping, the chair height was carefully adjusted so that the subject's thighs were parallel to the ground, knee's flexion less than 90 deg, and there was enough distance between the seat borderand the knee (Figure 1, bottom right).

Before the tapping, the participant's maximal voluntary contraction (MVC) was recorded. The participants were asked to press the sensor between their index and thumb fingers as hard as they can for 5 s, or in the same manner, to press the force platform with their metatarsal and toe areas. After that, the participants were instructed to repeatedly tap their index finger and thumb as rapidly and as widely as possible for 15 s [14]. The same time period was recorded for repetitive foot tapping, using a single pedal. Because fatigue may affect performance, a rest period of one minute is given between trials. Each trial began and ended with fingers closed, or foot placed on the force platform (zero angle). Both hands and both feet were tested.

The recordings of subjects and different patient groups were performed at the Clinic for Neurology, Clinical Centre of Serbia, Belgrade. The study was performed in accordance with the ethical standards of the Declaration of Helsinki. All participants gave written informed consent prior to participation in the study.

Signal processing

In order to provide 3-D movement analysis, we estimated the angles between the index finger and the thumb (finger tapping angle). The developed software employs transformation matrices and introduces biomechanical constraints of tapping movements [22]. Hand orientation or possible changes in position and orientation are irrelevant for the system performance. Tapping segmentation is performed based on estimated angles through identification of local

maxima/minima. This segmentation is additionally confirmed from force sensors by applying threshold clipping to 5% of their values normalized to its maxima. This kind of normalization is applied only for tapping segmentation. Forces which are displayed as system output are normalized to MVC, i.e., normalized to the maximal force between the fingers applied on the force sensor (Fi) and maximal force applied by metatarsal and toe area on the force platform. Tapping speed is estimated as a derivative of the tapping angle.

Results

The recorded data were extracted from the storage medium and analyzed.

First, we presented examples from one healthy subject and one patient with a neurodegenerative disease manifested with movement disorders (Figures 3–6). Extracted and analyzed data were displayed on the computer screen or printed and added to a patient's chart. Obtained results allowed clinicians to monitor movements of the fingers and foot during tapping.Tapping performance may be followed through the series of quantitative parameters (Figures 4 and 6) such as duration of each tap, tapping frequency, "open" and "close" speed for finger tapping (i.e., "upward" and "downward" speed for foot tapping), and by monitoring the force and tapping angles achieved during tapping (Figures 3 and 5). Visual inspection of presented results clearly pointed out the difference between the patient and the healthy control subject.

Here we present the results for the tested groups of PD patients and healthy controls. Group results for patients with PD and healthy controls are presented in Figures 7 and 8, for finger and foot tapping, respectively.

The upper panels show calculated mean values for the tapping amplitude (angle), tapping duration and tapping speed. The results are presented with bar charts presenting average values with standard deviations within the observed group.

Progressive changes in amplitude, duration and speed across a 15 s tapping trial can be represented by the slope of
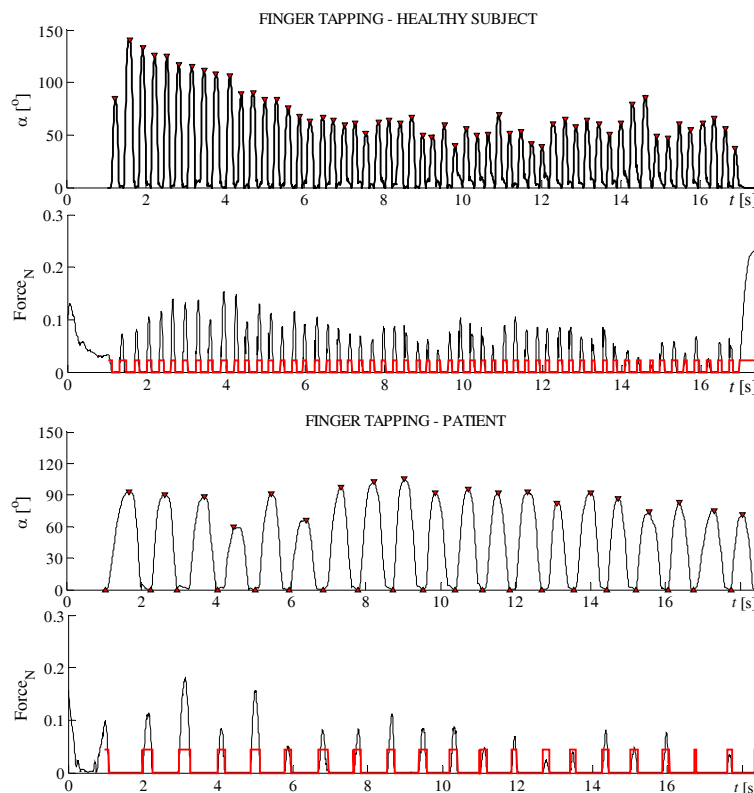
Fig. 3 – Estimated finger tapping angle and measured force normalized to maximal voluntary contraction (MVC), example for one healthy subject and one patient. The duration of finger tapping contacts are marked with red rectangular pulses over force traces. Maximal tapping angles (fingers "open") are marked with red triangular markers pointing downwards. Minimal tapping angles (fingers "closed") are marked with triangular markers pointing upwards, and they are used as separator of consecutive taps.
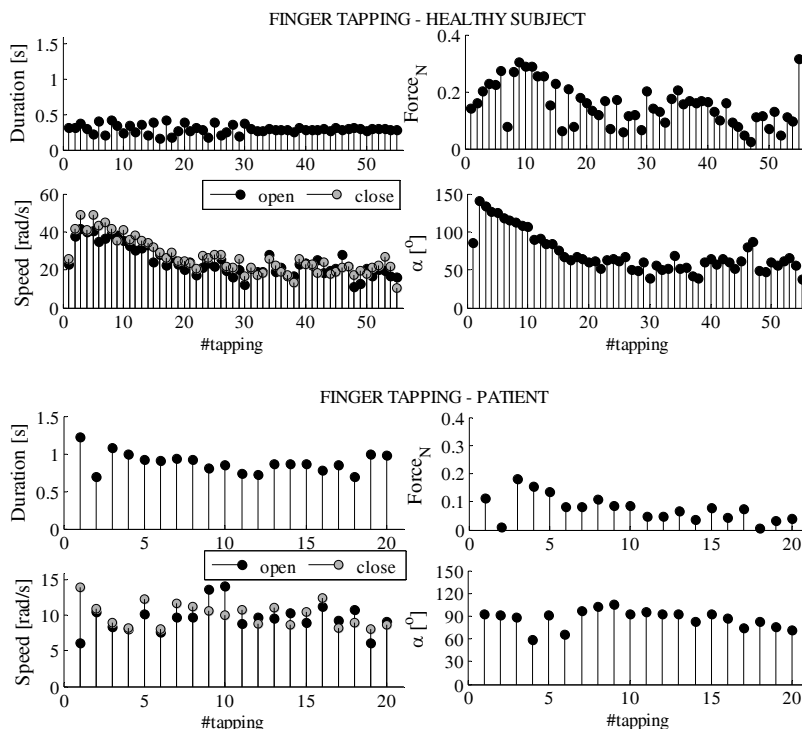

Fig. 4 – Finger tapping parameters: tapping duration, speed, normalized force and tapping angle, example for one healthy subject (upper four panels) and one patient (lower four panels). Horizontal axes show the order of taps.
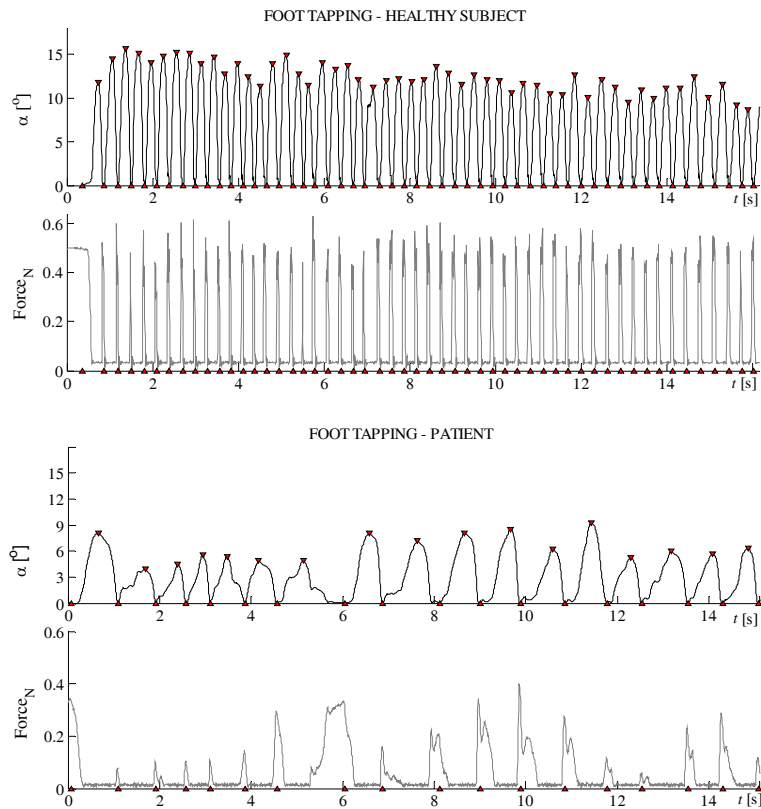
FOOT TAPPING - HEALTHY SUBJECT

FOOT TAPPING - PATIENT

Fig. 5 – Evaluated foot tapping angle and normalized force (upper and lower panel, respectively).
Triangular markers oriented upwards separate taps. Triangular markers oriented downwards (upper panel) show the
maximal angle achieved within the particular tap (upper two panels – healthy subject: lower two panels – patient).
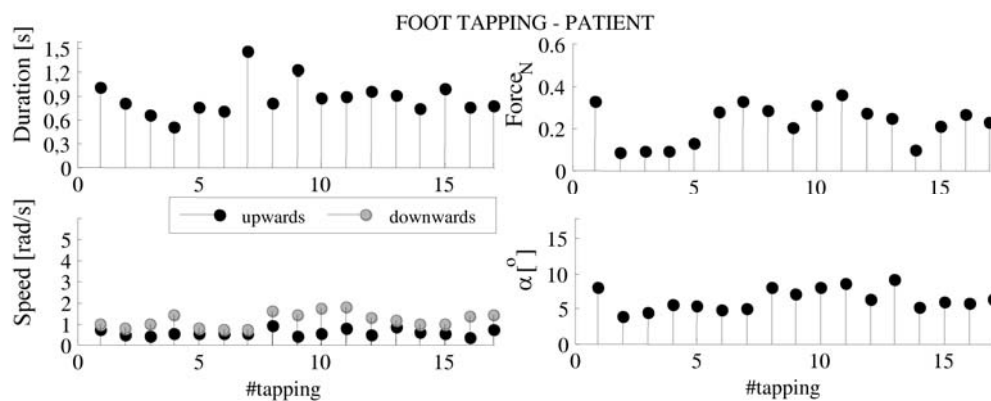
FOOT TAPPING - PATIENT

Fig. 6 – Foot tapping parameters: tapping duration, speed (separately for upward/downward foot movements),
normalized force, tapping angle.
Upper four panels: example for one healthy subject; lower four panels: example for one patient.

the fitted linear regression line. The slope of change in amplitude can be used to assess progressive hypokinesia or "decrement". The slope of change in speed that encompasses both amplitude and duration can be used to assess progressive slowing of movement[14]. The slopes of finger and foot tapping movements for the observed kinematic parameters are also presented in Figures 7 and 8, in lower rows.

The numerical results for the performed tapping testing are shown in Table 2. The Table also presents the coefficients of variation (CV) of amplitude and speed across the tap trials [29].

Discussion

We emphasize several important aspects of the system presented here.

The system is easy to mount and allows recording of finger and foot tapping even in patients with very limited
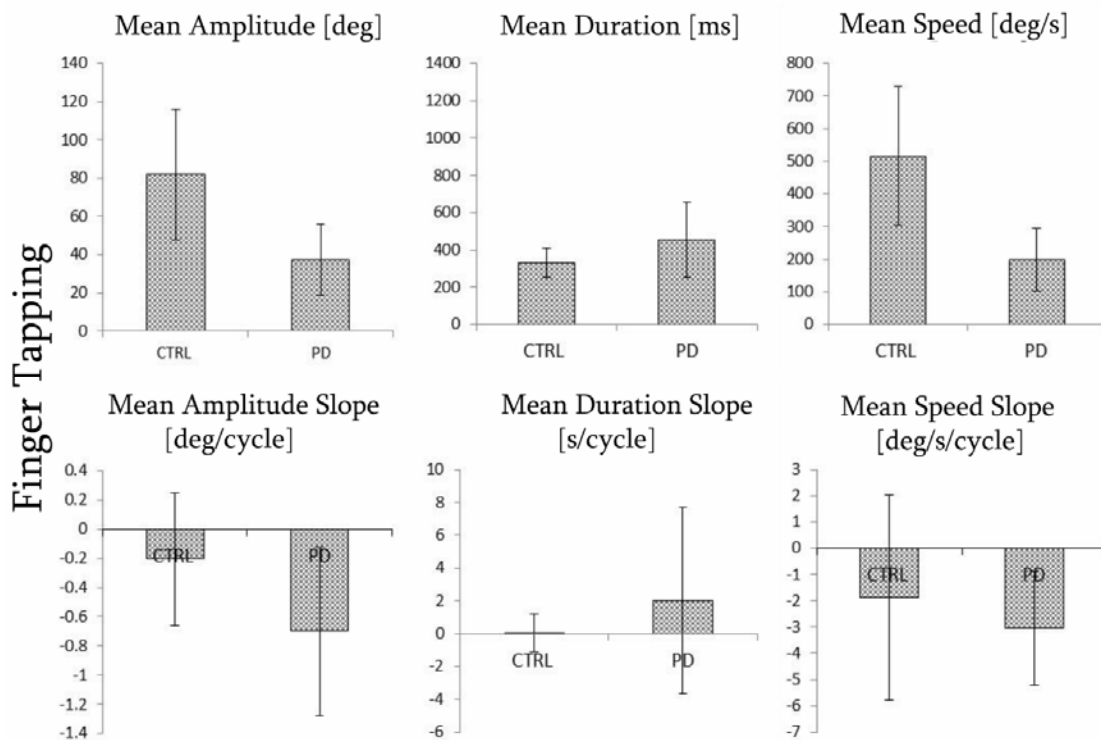
Fig. 7 – Kinematic finger tapping parameters (amplitude-left panel, duration – middle panel, and speed – right panel) of patients with Parkinson's disease (PD) and healthy controls (CTRL).
Parameters are presented according to their mean (upper row) and slope (lower row) values.
Each bar shows average values with standard deviations.
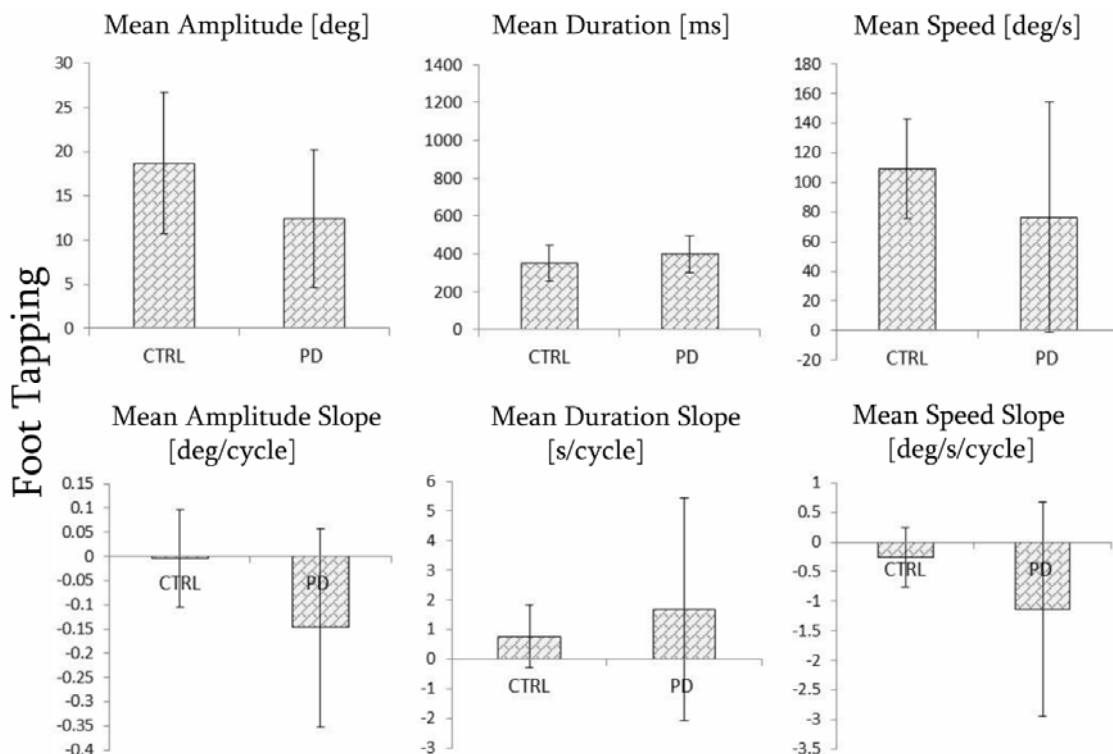

Fig. 8 – Kinematic foot tapping parameters (amplitude –left panel, duration - middle panel, and speed - right panel) of patients with Parkinson's disease (PD) and healthy controls (CTRL).
Parameters are presented according to their mean (upper row) and slope (lower row) values.
Each bar shows average values with standard deviations.

Analysis of kinematic parameters during finger tapping task

Parameters	Finger tapping		Foot tapping	
	CTRL (n = 14)	PD (n = 13)	CTRL (n = 14)	PD (n = 13)
Cadence [n/15s]	47,81 ± 12.65	40,11 ± 18,37	46.61 ± 12.78	41.18 ± 12.45
Amplitude [deg]	81.82 ± 33,94	37,18 ± 18,50	18.76 ± 8.11	12.53 ± 7.86
Duration [ms]	331.74 ± 76.79	454.33 ± 201.86	344.4 ± 92.31	388.85 ± 91.52
Close velocity [deg/s]	-1602,7 ± 503,1	-676,4 ± 370,5	-306.35 ± 167.7	-241.46 ± 175.37
Open velocity [deg/s]	1148,08 ± 499,05	483,52 ± 236,65	211.05 ± 82.93	157.933 ± 57.73
Speed [deg/s]	516,58 ± 213,88	198,25 ± 96,34	109.57 ± 33.38	76.7 ± 37.76
Amplitude CV [%]	12,31 ± 5,44	35,52 ± 14,15	12.09 ± 4.22	22.99 ± 12.39
Duration CV [%]	14,48 ± 6,93	22,79 ± 6,34	9.41 ± 6.14	15.03 ± 8.02
Speed CV [%]	16,14 ± 6,66	33,67 ± 12,31	12.45 ± 4.25	26.18 ± 12.19
Amplitude slope [deg/cycle]	-0,21 ± 0,46	-0,70 ± 0,58	0.0025 ± 0.11	-0.12 ± 0.21
Duration slope [ms/cycle]	0,04 ± 0.001	2,021 ± 5,67	0.51 ± 0.68	1.44 ± 0.81
Speed slope [deg/s/cycle]	-1,88 ± 3,89	-3,04 ± 2,18	-0.22 ± 0.52	-1.06 ± 1.8

Values present mean ± standard deviation; PD – Parkinson's disease; CTRL – healthy controls; CV – coefficient of variation.

movements. The sensors are lightweight and miniature, and do not hinder patient's movements. Also, the sensor do not require careful positioning, they just need to be placed on top of fingers (or foot), and the auto-calibration procedure will set the axes for further calculations. This is particularly important since it means that the system does not need specially trained medical or technical staff. The benefits of the proposed systems also include the economical aspect. The proposed system is low cost compared to any other commercially available system for motion capture. Using inertial sensors and force platform, any clinic could afford to introduce such system and methodology in their assessments.

The system is used for objective evaluation of the patients, as an addition to standard clinical tests and scoring system. It provides quantitative assessment, which is stored in database, and can be compared to the patient's previous recordings, thereby monitoring progress of the disease, or response to therapy. After recording, the software enables analysis of tapping sequence, and it displays the recorded sequence. It also enables observing the numerical results, offering list of parameters. The recorded data can be studied in two ways: by analyzing the numerical values of kinematic parameters – the average performance for the specified parameters, coefficients of variations, trends of changes, minima and maxima etc.; by observing the shapes of kinematic parameters – identifying problems with tapping rhythmicity, regularity, smoothness, freezing, tremor, and other irregular events that could be present in their motor pattern.

The proposed system also supports comparison among patients, or patients with healthy subjects, therefore providing a significant tool for studying characteristics of different epidemiologies [30].

The obtained data and numerical results could be used together with scores from clinical tests, providing better in-

sight into the diagnosis. Future research efforts will be directed at upgrading the system software to an expert system that would further assist clinicians in diagnostic procedures. A large number of particular patient groups would provide referent values for specific parameters, such as frequency, velocity, developed force and angles between fingers. This would enable automatic diagnostic indication in different groups of patients.

The obtained data and numerical results could be used together with scores from clinical tests to provide better insight into the diagnosis. Future research efforts will be directed at upgrading the system software to an expert system that would further assist clinicians in diagnostic procedures. A large number of particular patient groups would provide referent values for specific parameters, such as frequency, velocity, developed force and angles between fingers. This would enable automatic diagnostic indication in different groups of patients.

Conclusion

The novel system for finger and foot tapping test is compact, simple to use and efficiently collects patient data. Parameters measured in patients can be compared to those measured in healthy subjects, or among groups of patients, or used to monitor progress of the disease, or therapy effects. Created data and scores could be used together with the scores from clinical tests, providing the possibility for better insight into the diagnosis.

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