RESEARCH ARTICLE

The role of sex and handedness in the performance of the smartphone-based Finger-Tapping Test

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Abstract

The Finger Tapping Test (FTT) is a classical neuropsychological test that assesses motor functioning, and recently it has been employed using smartphones. For classical protocols, it has been observed that sex and handedness influence the performance during the test. By assessing the influence of sex and handedness on the test, it is possible to adjust the performance measurements to ensure the validity of test results and avoid sex- and handedness-related bias. The present study aimed to evaluate the influence of sex and handedness on smartphone-based FTT performance. We developed an Android application for the FTT and recruited 40 males and 40 females to carry out three spatial designs on it (protocols I, II, and III). Participants' performance was measured using the global, temporal, and spatial parameters of the FTT. We observed that for the performance in protocol I, handedness had a significant influence on global and temporal variables, while the interaction between handedness and sex had a greater influence on spatial variables. For protocols II and III, we observed that handedness had a significant influence on global, temporal, and spatial variables compared to the other factors. We concluded that the smartphone-based test is partly influenced by handedness and sex, and in clinical implications, these factors should be considered during the evaluation of the smartphone-based FTT.

Author summary

The finger tapping test is a test that measures how well someone can tap a surface quickly. It has been used for many years to evaluate motor function in people with neurological diseases. In the past, telegraph keys, computer mice, and keyboards were used to do the test. However, nowadays smartphones with touchscreens are often used. Before this

technology can be widely used in clinics, it's important to investigate factors that could affect the test results. Two factors that might impact the results are a person's sex and handedness, which is their preference for using one hand over the other. In this study, we investigated whether sex and handedness influence how well someone performs in the finger tapping test using a smartphone. We found that both sex and handedness play a role in how well someone performs, and in general, we observed that males using their dominant hand tend to perform the best on the test. These results suggest that it's important to consider a person's sex and handedness when interpreting the results of the smartphone-based finger tapping test.

Introduction

The Finger-Tapping Test (FTT) is a widely used neuropsychological test that assesses motor functioning, lateralized coordination, and motor speed [1]. This test involves the subject tapping their index finger on a surface as quickly as possible for a set period while keeping their hand resting on a board [2]. The original version of the test required participants to complete 10 trials with each hand, which made the test time-consuming. The original version measured the number of taps made in a set amount of time, but modifications to the test protocol, instruments, and analysis have been suggested over the years to shorten the test duration [3], adapt it to new technologies [2], and extract more features [4] from motor performance during the test.

The FTT is a widely used tool in both clinical and research settings for assessing various conditions that affect motor function and neurological health. It has been utilized to evaluate the effects of traumatic brain injury, stroke, Parkinson's disease, multiple sclerosis, and other neurological disorders [2,5–7]. This simple, non-invasive, and cost-effective test can be administered in various settings and provides valuable insights into the underlying neurological mechanisms that contribute to motor performance.

Initially, the telegraph key was commonly used to record finger taps during the FTT, however, alternative technologies have been proposed, such as the computer mouse [2], keyboard [8], and image-based motion [6]. In recent years, touchscreens from smartphones have emerged as a novel surface for performing the FTT. This approach offers several advantages and potential benefits over traditional methods. The widespread availability and portability of smartphones make it easier to administer the test remotely or in non-clinical settings. The use of smartphones allows for standardization of test administration, as the device can be programmed to deliver the test in a consistent and reproducible manner. Furthermore, smartphones enable precise measurement of tapping speed and duration, as well as facilitating data collection and analysis through digital recording and storage of test results. In summary, the use of touchscreens from smartphones provides a promising and convenient approach to administering the FTT, with potential implications for improving assessment and monitoring of neurological conditions.

Typically, the FTT quantifies performance by measuring the total number of taps and temporal variables such as frequency of taps, interval between taps, and duration of taps [2]. However, the emergence of smartphone touchscreen technology has opened up the possibility of recording the position of the screen where finger taps were performed and extracting spatial features of the task, such as the distance between tap coordinates and total distance of finger movements. Lee et al. [4] pioneered the evaluation of spatial parameters obtained from a smartphone-based FTT to assess bradykinesia in patients with Parkinson's disease compared

to healthy individuals. Subsequent studies using smartphone-based FTT have also applied the test in clinical conditions, mostly in patients with Parkinson's disease, comparing global, temporal, and spatial variables between controls and patients [9–16]. By incorporating spatial parameters into FTT assessment, smartphone technology provides a promising avenue for more comprehensive and accurate evaluation of motor function in clinical settings.

Given the advantages that smartphones offer as a tool for performing FTT, it is crucial to examine potential factors that may interfere with motor performance during the test. Sex and handedness, i.e., preference or ability to use one hand rather than the other across a range of common activities, are two such factors that have been shown to affect performance [17,18]. By assessing the influence of sex and handedness on finger tapping, researchers can determine whether adjustments are necessary to ensure the accuracy and validity of test results. This approach can help to mitigate bias and ensure that the FTT is applicable to individuals of all sexes and handedness. Ultimately, such evaluations can enhance the reliability and clinical utility of FTT for assessing motor function.

To date, no study has examined how participant characteristics such as sex and handedness may influence performance on smartphone-based FTT. In the current study, we sought to investigate the influence of sex and handedness on global, temporal, and spatial parameters obtained from smartphone-based FTT. By shedding light on these issues, our findings could inform the development of more accurate and reliable assessments of motor function in clinical and research settings.

Methods

Ethical considerations

The present study was approved by the Research and Ethics Committee of the Federal University of Pará (report # 6.036.494). All participants were informed about the experimental procedures and signed an informed consent form to participate in the study. All procedures are in accordance with the Declaration of Helsinki complying with all relevant ethical regulations.

Participants

Eighty right-handed participants (40 males and 40 females) comprised the sample of the present study, ranging between 18 and 50 years (males: 31.7 ± 8.04 years; females: 34.63 ± 9.37 years). The participants in this study were recruited through convenience sampling from a university population. The handedness of the participants was evaluated using the short version of the self-report Edinburgh handedness inventory [19]. Only right-handed participants were included, because there are differences in the cortical organization and motor performance between right-handed and left-handed people [20,21]. All participants had no history of degenerative diseases or use of drugs that could compromise movements.

Protocols of a smartphone-based finger-tapping test

An Android OS application, *Momentum Touch app*, was programmed using Android Studio and installed on a Samsung Galaxy S10 Plus smartphone. The smartphone had a 6.4-inches Dynamic AMOLED, QHD+ Display (3040 x 1440 Pixels), HDR10 19:9 Aspect Ratio, Gorilla Glass 6, 536 pixels per inch, 120 Hz resolution to touch capture.

For the test, the smartphone was placed on a table in landscape orientation related to the participant, with the top of the smartphone facing left. Participants performed the test while sitting in a chair with the foot touching the ground, and a chair height that allowed the hand to rest on the table with the elbow in 90˚ flexion, pronated forearm and the wrist at 0˚ flexion.

Prior to the experiments, all participants underwent a training test and received instructions by the same experimenter to ensure they were familiar with the procedures and tasks. This step was taken to minimize any potential confusion or misunderstandings during the actual experiment and to ensure that all participants had a consistent level of understanding and preparation. All participants carried out three modified protocols of FTT based on smartphones:

Protocol I: it was designed to evaluate the performance of the participant targeting a single-centered area of the smartphone. Protocol I is the closer condition to the classical FTT, in which the participant was asked to tap repeatedly on the same target during the test. For Protocol I, the participant's task was to tap the index finger in the center area as fast as possible. Taps outside the central target were considered errors in the task.

Protocol II: it was designed to evaluate the performance of the participant in a task of alternating taps on both sides of the smartphone without a target on the screen. For Protocol II, the participant's task was to tap alternately as fast as possible on both sides of the central division (region 1 on the left and region 2 on the right). One consecutive tap on the same side of a previous tap was considered an error in the task.

Protocol III: it was designed to evaluate the performance of the participant in a task of alternating taps in targets centered on both sides of the smartphone. For protocol III, the participant's task was to tap alternatively as fast as possible in two central areas on both sides of the central division (region 1 on the left and region 2 on the right). One consecutive tap on the same side of a previous tap or a tap out of the central areas was considered an error in the task.

Fig 1 shows the spatial properties of the visual representation of the smartphone screen for each FTT protocol.
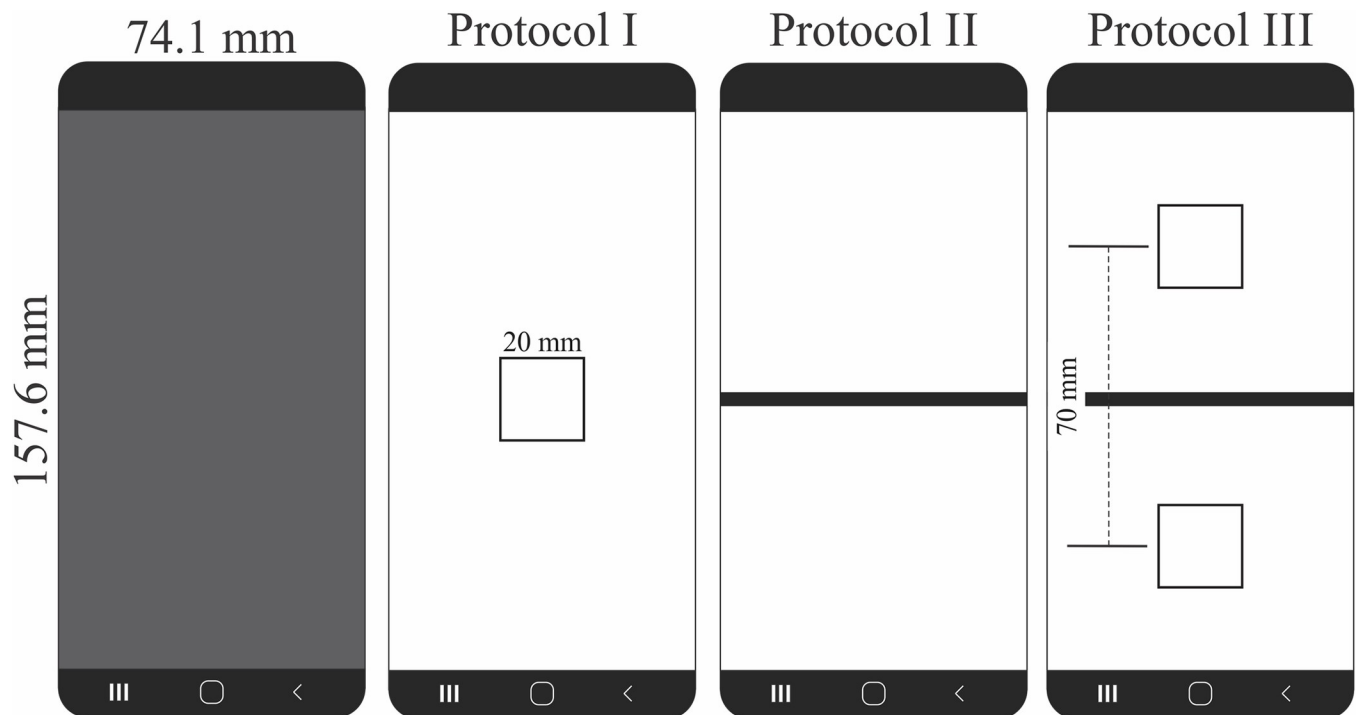

Fig 1. Smartphone dimensions of the model used in the present study and design of the three protocols proposed. Protocol I had a centered target (20 mm), Protocol II had a midline separating two equal areas without a restricted target, and Protocol III had a midline separating two equal sides with centered targets on each side 70 mm apart.

The test duration for each protocol was 30 seconds, with 1 minute interval between trials. The hand and the protocol to be tested were randomly chosen. Total duration of all experiments was 9.5 minutes. Our choice for an abbreviated version of FTT is to reduce the total testing duration similarly other researchers have tried [3,22].

Data analysis

The smartphone recorded the spatial coordinates of the screen where there was a tap, the moment of the tap, and a Boolean variable indicating whether the tap was done in the target area and exported a text file to be analyzed in routines in the MATLAB/OCTAVE or R environment. The following parameters were used to quantify the performance of the participant in each FTT protocol previously described:

i. *Global parameters*:

- Total number of taps.

- Number of errors.

ii. *Temporal parameters*:

- Median frequency of taps.

- Maximum frequency of taps.

- Minimum frequency of taps.

iii. *Spatial parameters*:

- Total displacement: the sum of all distances between the taps. The distance between the taps was calculated following Eq 1.

$$Distance = \sqrt{(x_i - x_{i+1})^2 + (y_i - y_{i+1})^2} \tag{1}$$

Where x_i and y_i are the screen coordinates of the *ith* tap.
- Area of a confidence ellipse covering 95% of the balance sway (Eq 2) that was fitted using the MATLAB/OCTAVE code.

$$area = \pi \times D \times d \tag{2}$$

Where D is the major axes of the ellipse, and d is the minor axis of the ellipse.
- Major axes of the ellipse obtained from the ellipse model that best fit the body sway data.
- Minor axes of the ellipse obtained from the ellipse model that best fitted to the body sway data.
- Kernel density estimation to calculate the peak density and bandwidths for the X- and Y-axis performed using kde2d() in the R package MASS.

For the protocols II and III, the ellipse area, major and minor axis were estimated for the tap coordinates from both screen sides.

Statistics

To test the influence of sex and handedness on the FTT performance, we applied Linear Mixed Models to the parameters extracted from the FTT dataset. Subject ID was included as a random effect. Type-III ANOVA was used to estimate the *F*-statistic and *p*-value for each variable in the models. To verify model assumptions, we applied visual inspection followed by a

Shapiro-Wilk normality test and a Bartlett test of homogeneity of variance on models' residuals. For these models, we calculated the partial η^2 to compute the effect size. In the cases the model did not fit well, we applied a Friedman repeated measures test followed by a Dunn multiple comparison test. All analyzes were performed using R and the following packages: lme4, lmerTest, and performance. A confidence level of 0.05 was considered for all statistical tests.

Results

Results of protocol I

Fig 2A–2D shows the mean temporal series (± confidence interval) of the tapping frequency during the test execution for male and female participants using dominant and nondominant hands. The mean frequency was maximal at the beginning of the test and decreased along the test duration. Additionally, Fig 2E shows an example of the spatial distribution of the taps for a representative participant.

Table 1 shows the results of protocol I we proposed for FTT. Number of errors was not significantly influenced by sex and handedness and no significant interaction between the factors was observed (Friedman $Q_{(3,40)} = 1.2$, $p = 0.75$). Sex significantly influenced the total number of taps (ANOVA $F_{(1,78)} = 17.97$, $p < 0.001$), median frequency (ANOVA $F_{(1,78)} = 17.29$,

Fig 2. Performance in Protocol I of the Finger-Tapping Test proposed in the present study. (A) is the FTT frequency as a function of time for dominant hand from males; (B) Spatial kernel density estimation plot generated by the FTT executed from dominant hand from males; (C) is the FTT frequency as a function of time for non-dominant hand from males; (D) Spatial kernel density estimation plot generated by the FTT executed from non-dominant hand from males. (E) is the FTT frequency as a function of time for dominant hand from females; (F) Spatial kernel density estimation plot generated by the FTT executed from dominant hand from females; (G) is the FTT frequency as a function of time for non-dominant hand from females; (H) Spatial kernel density estimation plot generated by the FTT executed from non-dominant hand from females. Black crosses represent valid taps, red crosses represent non-valid taps and red ellipsis are the 95% confidence ellipsis fitted to the data.

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Table 1. Descriptive statistics [median (interquartile range)] of the global, temporal, and spatial parameters for Protocol I.

	Female		Male		
	DH	**NDH**	**DH**	**NDH**	**Significant effect size**
Global parameters					
Total number of taps	169 (22.5)	148.5 (21.5)	184 (17.5)	162.5 (23)	Sex*, handedness*
Number of errors	0 (0)	0 (0)	0 (0)	0 (0)	None
Temporal Parameters					
Median frequency	5.75 (0.73)	5.06 (0.60)	6.23 (0.49)	5.46 (0.77)	Sex*, handedness*, Interaction***
Maximum frequency	7.72 (1.83)	7.12 (4.18)	8.55 (2.43)	8.00 (1.64)	None
Minimum frequency	3.62 (1.05)	4.57 (0.79)	4.48 (1.33)	4.10 (0.86)	Handedness**, Interaction**
Spatial parameters					
Total displacement	7529.70 (1081.28)	6682.23 (846.56)	8171.38 (828.49)	7243.70 (1057.14)	Sex*, handedness*
Major axis	2.70 (1.28)	3.09 (1.07)	2.98 (1.08)	2.84 (0.90)	Interaction*
Minor axis	1.74 (0.65)	2.16 (0.70)	1.99 (0.61)	1.97 (0.79)	Interaction*
Area	14.03 (9.74)	22.25 (13.21)	19.24 (13.24)	18.55 (9.46)	Interaction*
Peak density	3.03 (2.17)	2.09 (1.78)	2.52 (2.3)	1.99 (1.46)	None
Bandwidth X	38.52 (15.90)	45.42 (20.60)	39.18 (19.65)	42.56 (18.16)	Handedness*
Bandwidth Y	33.38 (14.00)	40.26 (16.08)	35.82 (18.91)	41.96 (22.94)	Handedness*

DH: dominant hand; NDH: nondominant hand.

*p < 0.001

**0.001 ≤ p < 0.01

***0.01 ≤ p < 0.05

$p < 0.001$), total displacement (ANOVA $F_{(1,78)} = 16.42$, $p < 0.001$). Handedness significantly influenced the total number of taps (ANOVA $F_{(1,78)} = 119.63$, $p < 0.001$), median frequency (ANOVA $F_{(1,78)} = 149.55$, $p < 0.001$), minimum frequency (ANOVA $F_{(1,78)} = 7.47$, $p = 0.007$), total displacement (ANOVA $F_{(1,78)} = 116.31$, $p < 0.001$), bandwidth X (ANOVA $F_{(1,78)} = 18.22$, $p < 0.001$) and bandwidth Y (ANOVA $F_{(1,78)} = 30.16$, $p < 0.001$). The interaction between both factors was significant in the median frequency (ANOVA $F_{(1,78)} = 4.20$, $p = 0.04$), minimum frequency (ANOVA $F_{(1,78)} = 9.28$, $p = 0.003$), major axis (ANOVA $F_{(1,78)} = 88.28$, $p < 0.001$), minor axis (ANOVA $F_{(1,78)} = 96.67$, $p < 0.001$), and area of the ellipse (ANOVA $F_{(1,78)} = 141.09$, $p < 0.001$). In peak density variable was found significant differences (Friedman $Q_{(3,40)} = 18.8$, $p < 0.001$), in which for both sexes there was significant differences between dominant and non-dominant hands.

Global and temporal variables had more frequent significant effects and larger effect size on handedness, while spatial variables had larger and more frequent significant effect sizes of the interaction between the factors.

Results of the protocol II

Fig 3A–3D shows the mean temporal series (± confidence interval) of the tapping frequency during the test execution for male and female participants using dominant and nondominant hands. Here, the mean frequency also reached higher values in the first 5 seconds of the test and decayed throughout the duration of the test. Fig 3E shows an example of the spatial distribution of the taps on both sides of the screen for a representative participant.

Table 2 shows the results of protocol II we proposed for FTT. Number of errors was not significantly influenced by sex and handedness and no significant interaction between the factors was observed (Friedman $Q_{(3,40)} = 3.06$, $p = 0.38$). Sex significantly influenced the total
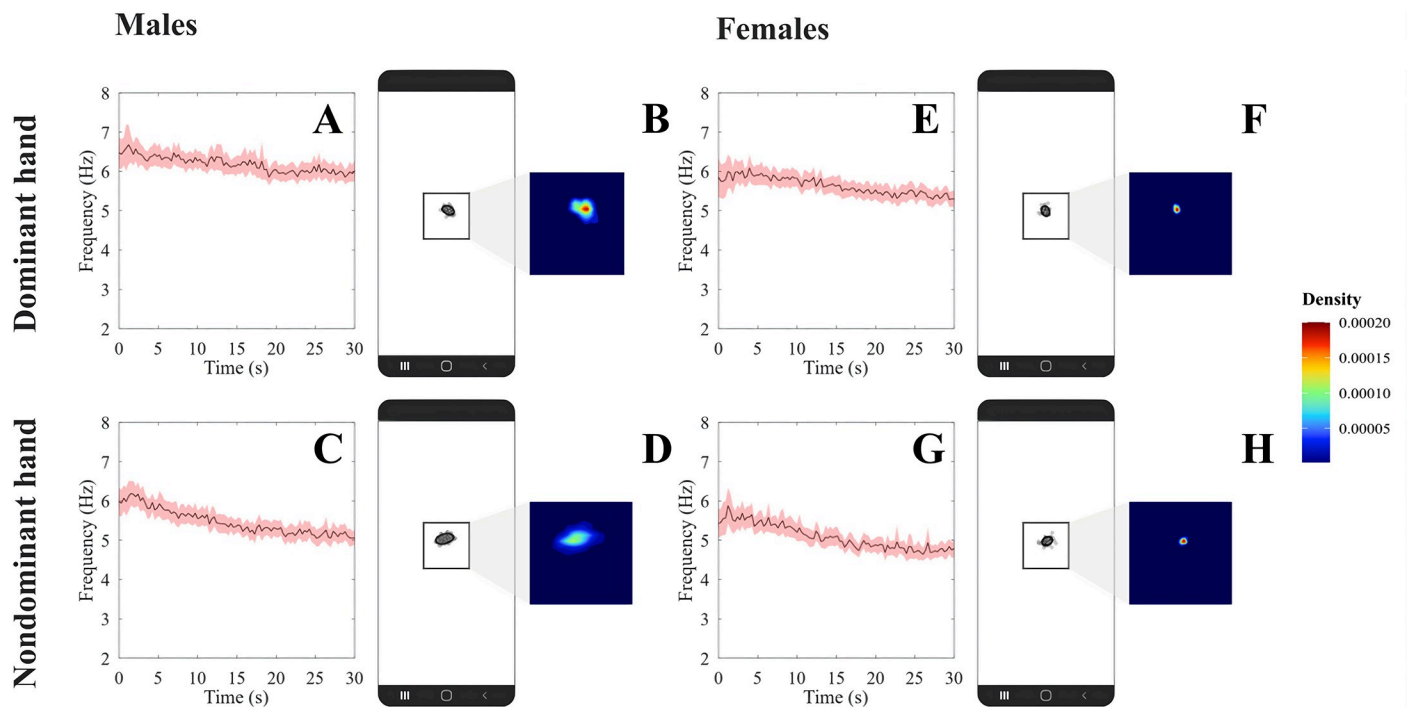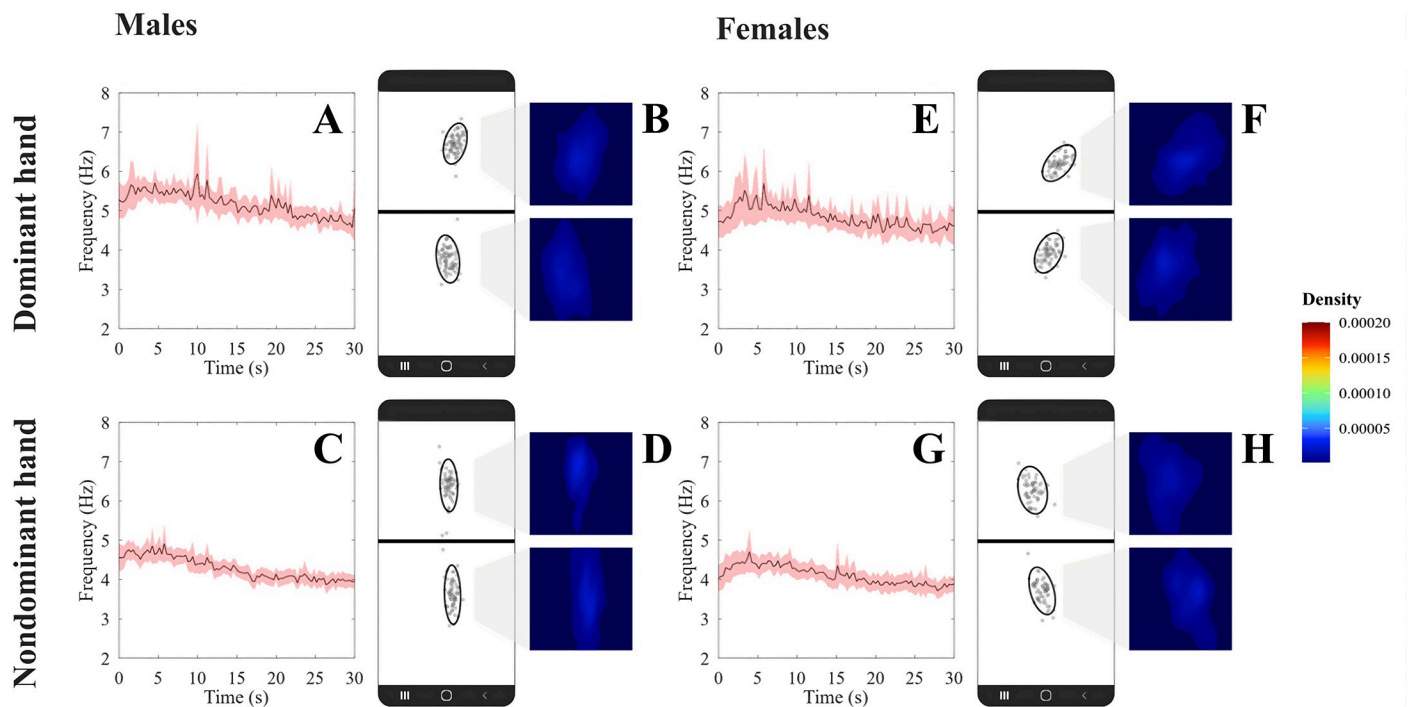
Fig 3. Performance in Protocol II of the Finger-Tapping Test proposed in the present study. (A) is the FTT frequency as a function of time for dominant hand from males; (B) Spatial kernel density estimation plot generated by the FTT executed from dominant hand from males; (C) is the FTT frequency as a function of time for non-dominant hand from males; (D) Spatial kernel density estimation plot generated by the FTT executed from non-dominant hand from males. (E) is the FTT frequency as a function of time for dominant hand from females; (F) Spatial kernel density estimation plot generated by the FTT executed from dominant hand from females; (G) is the FTT frequency as a function of time for non-dominant hand from females; (H) Spatial kernel density estimation plot generated by the FTT executed from non-dominant hand from females. Black crosses represent valid taps, red crosses represent non-valid taps and red ellipsis are the 95% confidence ellipsis fitted to the data.

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displacement (ANOVA $F_{(1,78)} = 4.05$, $p = 0.04$), major axis 1 (ANOVA $F_{(1,78)} = 14.37$, $p < 0.001$) and major axis 2 (ANOVA $F_{(1,78)} = 7.12$, $p = 0.008$). Handedness significantly influenced the total number of taps (ANOVA $F_{(1,78)} = 202.30$, $p < 0.001$), median frequency (ANOVA $F_{(1,78)} = 393.71$, $p < 0.001$), maximum frequency (Friedman $Q_{(3,40)} = 37.97$, $p < 0.001$), minimum frequency (ANOVA $F_{(1,78)} = 6.85$, $p = 0.01$), total displacement (ANOVA $F_{(1,78)} = 214.67$, $p < 0.001$), minor axis 1 (ANOVA $F_{(1,78)} = 6.57$, $p = 0.01$), area of the ellipse 1 (ANOVA $F_{(1,78)} = 5.39$, $p = 0.02$), bandwidth Y 1, major axis 2 (ANOVA $F_{(1,78)} = 12.64$, $p < 0.001$), bandwidth Y 1 (ANOVA $F_{(1,78)} = 20.92$, $p < 0.001$) and Y 2 (ANOVA $F_{(1,78)} = 21.80$, $p < 0.001$). The interaction between both factors was significant in the median frequency (ANOVA $F_{(1,78)} = 5.52$, $p = 0.02$), minor axis 1 (ANOVA $F_{(1,78)} = 10.59$, $p = 0.002$) and minor axis 2 (ANOVA $F_{(1,78)} = 34.02$, $p < 0.001$), area of the ellipse 1 (ANOVA $F_{(1,78)} = 11.66$, $p = 0.001$), and bandwidth Y 2 (ANOVA $F_{(1,78)} = 4.47$, $p = 0.04$).

Handedness showed more significant and larger effect sizes on global, temporal, and spatial variables than the other factors.

Results of the protocol III

Fig 4A–4D shows the mean temporal series (± confidence interval) of the tapping frequency during the test execution for male and female participants using dominant and nondominant

Table 2. Descriptive statistics [median (interquartile range)] of the global, temporal, and spatial parameters for Protocol II.

	Female		Male		
	DH	**NDH**	**DH**	**NDH**	**Significant effect size**
Global parameters					
Total number of taps	138 (23.25)	118 (21.5)	153 (26)	128.5 (17.5)	Handedness*
Number of errors	0 (1.25)	0 (1)	1 (3.25)	0 (2)	None
Temporal Parameters					
Median frequency	4.80 (0.63)	4.1 (0.85)	5.22 (0.87)	4.42 (0.57)	Handedness*, Interaction***
Maximum frequency	6.16 (0.84)	5.80 (1.76)	7.31 (8.82)	5.71 (1.25)	None
Minimum frequency	2.42 (2.12)	2.32 (1.19)	2.76 (1.95)	2.37 (1.04)	Handedness***
Spatial parameters					
Total displacement	6289.24 (1271.43)	5350.08 (964.54)	6856.21 (794.73)	5806.12 (807.19)	Sex***, Handedness*
Major axis 1	9.13 (4.79)	9.62 (4.55)	9.82 (5.03)	10.88 (3.94)	Sex*
Minor axis 1	4.23 (1.88)	4.36 (1.84)	4.84 (3.46)	4.68 (1.7)	Handedness***, Interaction**
Area 1	118.48 (71.68)	118.48 (98.85)	159.92 (162.77)	174.25 (106.93)	Handedness***, Interaction**
Major axis 2	8.93 (3.78)	7.86 (5.04)	10.07 (4.46)	10.96 (5.23)	Sex**, Handedness*
Minor axis 2	4.06 (1.83)	4.35 (2.33)	4.69 (1.98)	4.41 (1.84)	Interaction*
Area 2	102.96 (102.83)	125.17 (83.21)	131.22 (89.97)	169.00 (109.95)	None
Peak density area 1	2.95 (1.51)	2.22 (0.90)	2.41 (1.69)	2.10 (1.3)	None
Bandwidth X Area 1	97.94 (38.35)	106.06 (38.89)	103.73 (41.87)	109.23 (48.45)	None
Bandwidth Y area 1	162.27 (53.23)	192.02 (44.45)	184.88 (61.71)	207.70 (82.41)	Handedness*, Interaction***
Peak density area 2	2.7 (2.1)	2.4 (1.7)	2.6 (2.2)	2.2 (1.5)	None
Bandwidth X area 2	96.59 (44.01)	109.45 (44.87)	106.14 (42.83)	107.31 (37.55)	None
Bandwidth Y area 2	163.03 (74.23)	184.21 (61.30)	161.28 (54.73)	206.13 (110.91)	None

DH: dominant hand; NDH: nondominant hand.

*p < 0.001

**0.001 ≤ p < 0.01

***0.01 ≤ p < 0.05

hands. The tapping frequency was kept constant during the entire test in this protocol. Fig 4E shows an example of the spatial distribution of the taps in both targets for a representative participant.

Table 3 shows the results of protocol III we proposed for FTT. Number of errors was not significantly influenced by sex and handedness and no significant interaction between the factors was observed (Friedman $Q_{(3,40)}$ = 6.81, p = 0.08). Sex significantly influenced the minor axis 1 (ANOVA $F_{(1,78)}$ = 11.87, $p < 0.001$) and minor axis 2 (ANOVA $F_{(1,78)}$ = 7.63, p = 0.007), area of the ellipse 1 (ANOVA $F_{(1,78)}$ = 5.16, $p < 0.001$) and 2 (ANOVA $F_{(1,78)}$ = 9.70, p = 0.002). Handedness significantly influenced the total number of taps (ANOVA $F_{(1,78)}$ = 118.71, $p < 0.001$), median frequency (ANOVA $F_{(1,78)}$ = 290.15, p = 0.03), minimum frequency (ANOVA $F_{(1,78)}$ = 26.80, $p < 0.001$), total displacement (ANOVA $F_{(1,78)}$ = 112.87, $p < 0.001$), major axis 1 (ANOVA $F_{(1,78)}$ = 4.66, p = 0.03), bandwidth X 1 (ANOVA $F_{(1,78)}$ = 25.73, $p < 0.001$), bandwidth Y 1 (ANOVA $F_{(1,78)}$ = 17.56, $p < 0.001$), minor axis 2 (ANOVA $F_{(1,78)}$ = 18.35, $p < 0.001$), area of the ellipse 2 (ANOVA $F_{(1,78)}$ = 4.84, p = 0.03), bandwidth X 2 (ANOVA $F_{(1,78)}$ = 17.27, $p < 0.001$), and bandwidth Y 2 (ANOVA $F_{(1,78)}$ = 15.77, $p < 0.001$). The interaction between both factors was significant in the median frequency (ANOVA $F_{(1,78)}$ = 7.61, p = 0.007) and major axis 1 (ANOVA $F_{(1,78)}$ = 6.02, p = 0.02).

Handedness showed more significant and larger effect sizes on global, temporal, and spatial variables than the other factors.
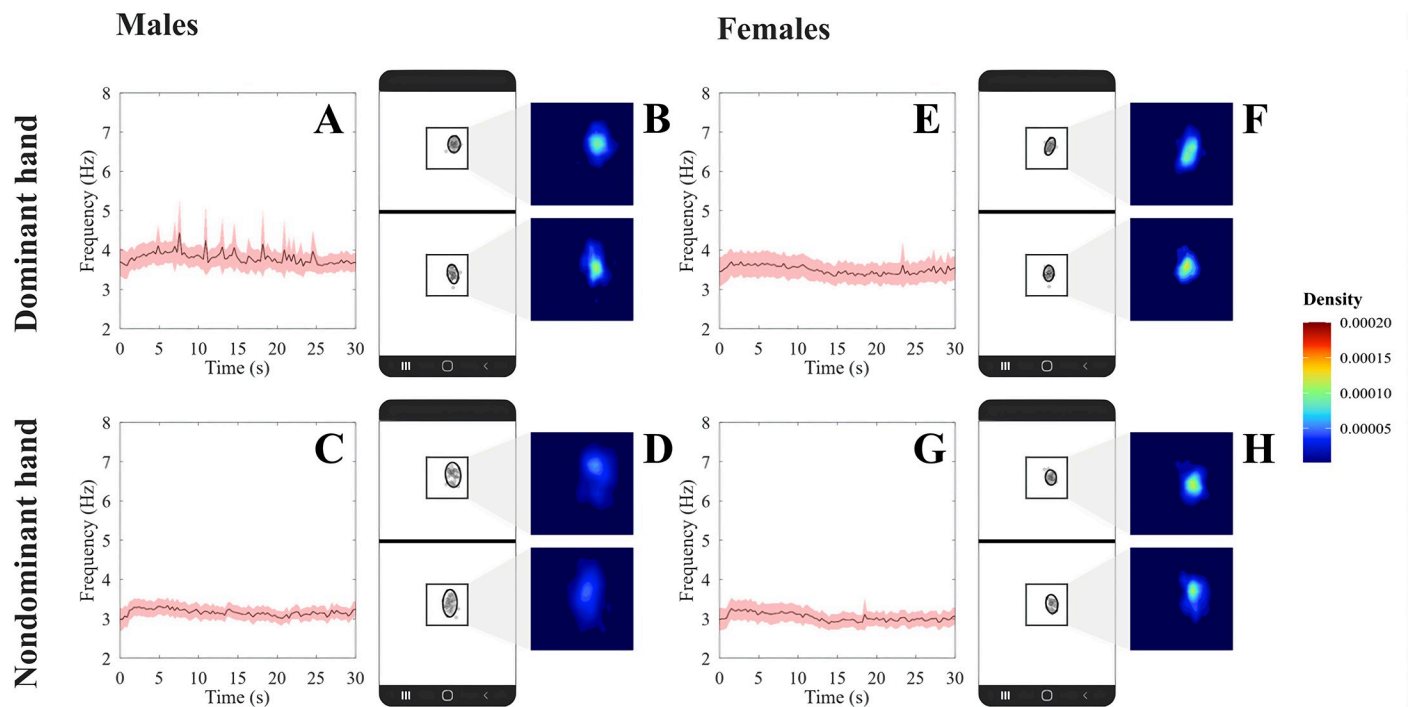
Fig 4. Performance in Protocol III of the Finger-Tapping Test proposed in the present study. (A) is the FTT frequency as a function of time for dominant hand from males; (B) Spatial kernel density estimation plot generated by the FTT executed from dominant hand from males; (C) is the FTT frequency as a function of time for non-dominant hand from males; (D) Spatial kernel density estimation plot generated by the FTT executed from non-dominant hand from males. (E) is the FTT frequency as a function of time for dominant hand from females; (F) Spatial kernel density estimation plot generated by the FTT executed from dominant hand from females; (G) is the FTT frequency as a function of time for non-dominant hand from females; (H) Spatial kernel density estimation plot generated by the FTT executed from non-dominant hand from females. Black crosses represent valid taps, red crosses represent non-valid taps and red ellipsis are the 95% confidence ellipsis fitted to the data.

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Discussion

Handedness and sex are recognized factors that influence the performance in the FTT using different instruments [2]. The novelty of the present investigation is a detailed description of the influence of handedness and sex on global, temporal, and spatial parameters obtained from three spatial designs of smartphone-based FTT in adults.

The common findings in the three protocols were: (i) total number of taps, minimum frequency, total displacement, and bandwidth Y were improved by handedness; and (ii) median frequency was significantly influenced by an interaction between sex and handedness in which males using dominant hand had better performance in the FTT. For Protocol I, the more common result was the presence of a significant main effect of sex and handedness on the variables.

The use of smartphones as instruments to perform FTT is a revolutionary advance in the method because it enables the development of different designs of finger-tapping tests and enables the addition of new parameters to the classical analysis. In the present investigation, we designed three protocols for smartphone-based FTT. Protocol I is the most similar protocol compared to classical approaches because the participant had to tap in a specific place to be as fast and accurate as possible. The results we observed for temporal parameters are qualitatively like those previously observed using different technologies: males had better performance than females and dominant hands had better performance than nondominant hands.

Table 3. Descriptive statistics [median (interquartile range)] of the global, temporal and spatial parameters for Protocol III.

	Female		Male		
	DH	NDH	DH	NDH	Significant effect size
Global parameters					
Total number of taps	99 (43.50)	86 (31.25)	111 (29.25)	91.5 (19.75)	Handedness*
Number of errors	1 (3.25)	1.5 (8.75)	2 (8.25)	3 (9)	None
Temporal parameters					
Median frequency	3.60 (1.04)	3.10 (0.89)	3.79 (1.08)	3.25 (0.62)	Handedness*, Interaction**
Maximum frequency	6.25 (1.12)	4.98 (0.6)	4.99 (1.13)	4.83 (0.24)	None
Minimum frequency	2.20 (0.83)	2.06 (0.56)	2.30 (1.01)[9]	1.79 (0.42)	Handedness*
Spatial parameters					
Total displacement	4489.62 (1884.95)	4061.68 (1253.50)	4999.15 (1508.71)	4138.80 (876.3)	Handedness*
Major axis 1	4.92 (1.04)	4.96 (0.87)	4.74 (1.10)	4.91 (1.01)	Handedness***, Interaction***
Minor axis 1	3.64 (1.53)	3.29 (1.25)	2.63 (1.05)	2.96 (0.84)	Sex*
Area 1	57.65 (32.00)	50.33 (30.28)	40.40 (20.50)	46.08 (16.98)	Sex***
Major axis 2	5.1 (0.86)	4.92 (1.89)	4.76 (1.38)	5.8 (0.62)	None
Minor axis 2	3.51 (1.66)	2.78 (1.34)	2.57 (1.04)	3.34 (0.91)	Sex**, Handedness*
Area 2	56.41 (33.32)	41.58 (34.92)	36.98 (22.72)	59.58 (23.24)	Sex**, Handedness***
Peak density area 1	6.01 (4.00)	6.64 (4.90)	6.09 (6.18)	4.89 (2.98)	None
Bandwidth X area 1	61.92 (17.93)	69.90 (28.62)	62.80 (27.19)	71.18 (19.18)	Handedness*
Bandwidth Y area 1	114.28 (45.38)	123.76 (36.83)	123.42 (39.37)	141.46 (47.54)	Handedness*
Peak density area 2	6.55 (3.86)	7.81 (5.27)	6.64 (4.86)	5.38 (3.61)	None
Bandwidth X area 2	61.96 (24.54)	68.31 (28.23)	63.90 (20.25)	71.37 (23.30)	Handedness*
Bandwidth Y area 2	116.20 (40.70)	127.67 (43.34)	130.60 (46.71)	139.32 (43.97)	Handedness*

DH: dominant hand; NDH: nondominant hand.

*$p < 0.001$

**$0.001 \leq p < 0.01$

***$0.01 \leq p < 0.05$

The other two protocols we designed (protocols II and III) cannot be compared to the classical settings of FTT, because they are composed of tests that request alternated taps in two neighbor regions, and few investigations using smartphone-based FTT are comparable to these designs. The smartphone-based FTT can be grouped in tests that use one target [9] and two targets [9–16]. The tests that used two targets also differed from the task for tapping using one or two fingers for alternating movements, and only Lee et al. [4] have a more detailed description of the spatial dimensions of the test design.

All these studies using smartphone-based FTT evaluated the performance of patients with some diseases, especially Parkinson's disease, and did not emphasize the influence of handedness and sex on performance. The present investigation is a first approach to describe the basic features of the smartphone-based FTT in the adult population.

Dominant hands consistently are reported as having better performance than non-dominant hands in FTT [2]. Cortical correlates seem to be associated with the different performance considering hand dominance. Some findings indicate that left-handers are less lateralized than right handers [23,24]. The difference in the FTT performance between sexes was usually reported [25], but it is not clear why males and females differ in FTT performance.

The lack of left handers and aged persons are limitations of the present study and future study focusing on them might be interesting. Considering that use of touchscreen technology

is relatively new, more information can be extracted in future besides different designs to improve specific motor skills during finger tapping test.

Overall, the FTT is a useful tool for evaluating motor and cognitive function in a variety of diseases and conditions. Smartphone-based FTT has potential applications in the same diseases that were previously evaluated using other technologies such as Parkinson's disease, Alzheimer's disease, multiple sclerosis, traumatic brain injury, attention deficit hyperactivity disorder, and depression. Previous investigations had shown significant reliability of smartphone-based FTT [22] that encourage for more clinical applications, additional studies of validation comparing its performance with the gold-standard technologies such as video capture, and studies comparing the performances using different smartphone models (and touchscreen technologies).

Smartphone-based FTTs represent an opportunity to apply an important neuropsychological test in a wider range of the population, including the poorest people with less access to more sensitive medical instruments. Even considering that sex and handedness have partial influence on the smartphone-based FTT variables, our results reinforce the needs to create norms for males and females with additional consideration about the hand dominance, or create models to compensate the differences associated to these factors. More basic and clinical studies for FTT based on smartphones can help in assessing the variables that could optimize its diagnostic power.

App availability

The a trial version of the app is available at the Play Store: https://play.google.com/store/apps/details?id=com.MomentumTouch

Supporting information

S1 Data. Raw files of all participants including the moment of the tap, x and y coordinates and the indication of the area where the tapping occurred.
(ZIP)

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References

1. Schmitt L. Finger-Tapping Test. In: Volkmar F.R. (eds) Encyclopedia of Autism Spectrum Disorders. Springer, New York, NY, 2013.

2. Hubel KA, Reed B, Yund EW, Herron TJ, Woods DL. Computerized measures of finger tapping: effects of hand dominance, age, and sex. Percept Mot Skills. 2013; 116, 929–952. https://doi.org/10.2466/25.29.PMS.116.3.929-952 PMID: 24175464

3. Ashendorf L, Horwitz JE, Gavett BE. Abbreviating the Finger Tapping Test. Arch Clin Neuropsychol. 2015; 30(2):99–104. https://doi.org/10.1093/arclin/acu091 PMID: 25564134

4. Lee CY, Kang SJ, Hong SK, Ma HI, Lee U, Kim YJ. A Validation Study of a Smartphone-Based Finger Tapping Application for Quantitative Assessment of Bradykinesia in Parkinson's Disease. PloS One. 2016; 11, e0158852. https://doi.org/10.1371/journal.pone.0158852 PMID: 27467066

5. Roalf DR, Rupert P, Mechanic-Hamilton D, Brennan L, Duda JE, Weintraub D, et al. Quantitative assessment of finger tapping characteristics in mild cognitive impairment, Alzheimer's disease, and Parkinson's disease. J Neurol. 2018 265(6):1365–1375. https://doi.org/10.1007/s00415-018-8841-8 PMID: 29619565

6. Guo Z, Zeng W, Yu T, Xu Y, Xiao Y, Cao X, et al. Vision-Based Finger Tapping Test in Patients With Parkinson's Disease via Spatial-Temporal 3D Hand Pose Estimation. IEEE J Biomed Health Inform. 2022; 26(8):3848–3859. https://doi.org/10.1109/JBHI.2022.3162386 PMID: 35349459

7. Térémetz M, Colle F, Hamdoun S, Maier MA, Lindberg PG. A novel method for the quantification of key components of manual dexterity after stroke. J Neuroeng Rehabil. 2015; 12:64. https://doi.org/10.1186/s12984-015-0054-0 PMID: 26233571

8. Akram N, Li H, Ben-Joseph A, Budu C, Gallagher DA, Bestwick JP, et al. Developing and assessing a new web-based tapping test for measuring distal movement in Parkinson's disease: a Distal Finger Tapping test. Sci Rep. 2022; 12, 386. https://doi.org/10.1038/s41598-021-03563-7 PMID: 35013372

9. Bermeo A, Bravo M, Huerta M, Bermeo J, Punin B, Barzallo B. Statistical characterization of the finger tapping test using an android mobile app, 2017 IEEE Second Ecuador Technical Chapters Meeting (ETCM), 2017, 1–6, https://doi.org/10.1109/ETCM.2017.8247459

10. Arora S, Venkataraman V, Zhan A, Donohue S, Biglan KM, Dorsey ER, et al. Detecting and monitoring the symptoms of Parkinson's disease using smartphones: A pilot study. Parkinsonism Relat Disord. 2015; 21, 650–653. https://doi.org/10.1016/j.parkreldis.2015.02.026 PMID: 25819808

11. Mitsi G, Mendoza EU, Wissel BD, Barbopoulou E, Dwivedi AK, Tsoulos I, et al. Biometric Digital Health Technology for Measuring Motor Function in Parkinson's Disease: Results from a Feasibility and Patient Satisfaction Study. Front Neurol. 2017; 8, 273. https://doi.org/10.3389/fneur.2017.00273 PMID: 28659858

12. Wissel BD, Mitsi G, Dwivedi AK, Papapetropoulos S, Larkin S, López Castellanos JR, et al. Tablet-Based Application for Objective Measurement of Motor Fluctuations in Parkinson Disease. Digit Biomark. 2018; 1, 126–135. https://doi.org/10.1159/000485468 PMID: 32095754

13. Zhang L, Lei L, Zhao Y, Wang R, Zhu Y, Yu Z, et al. Finger Tapping Outperforms the Traditional Scale in Patients With Peripheral Nerve Damage. Front Physiol. 2018; 9, 1361. https://doi.org/10.3389/fphys.2018.01361 PMID: 30327614

14. Lipsmeier F, Taylor KI, Kilchenmann T, Wolf D, Scotland A, Schjodt-Eriksen J, et al. Evaluation of smartphone-based testing to generate exploratory outcome measures in a phase 1 Parkinson's disease clinical trial. Mov Disord. 2018; 33, 1287–1297. https://doi.org/10.1002/mds.27376 PMID: 29701258

15. Prince J, Vos M. A Deep Learning Framework for the Remote Detection of Parkinson's Disease Using Smart-Phone Sensor Data. 2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society. 2018; 3144–3147. https://doi.org/10.1109/EMBC.2018.8512972 PMID: 30441061

16. Alberts JL, Koop MM, McGinley MP, Penko AL, Fernandez HH, Shook S, et al. Use of a Smartphone to Gather Parkinson's Disease Neurological Vital Signs during the COVID-19 Pandemic. *Parkinsons Dis* 2021 5534282. https://doi.org/10.1155/2021/5534282 PMID: 33868630

17. Westmoreland P. A philosophical approach to the concept of handedness: The phenomenology of lived experience in left- and right-handers. Laterality. 2017; 22(2):233–255. https://doi.org/10.1080/1357650X.2016.1164181 PMID: 27026143

18. Prigatano GP, Goncalves C, de Oliveira SB, Denucci SM, Pereira RM, Braga LW. Kinematic recordings while performing a modified version of the Halstead Finger Tapping Test: Age, sex, and education effects. J Clin Exp Neuropsy. 2020; 42(1), 42–54. https://doi.org/10.1080/13803395.2019.1665170 PMID: 31516073

19. Veale JF. Edinburgh Handedness Inventory—Short Form: a revised version based on confirmatory factor analysis. Laterality. 2014; 19(2), 164–177. https://doi.org/10.1080/1357650X.2013.783045 PMID: 23659650

20. Hiraoka K, Igawa K, Kashiwagi M, Nakahara C, Oshima Y, Takakura Y. The laterality of stop and go processes of the motor response in left-handed and right-handed individuals. Laterality. 2018; 23 (1):51–66. https://doi.org/10.1080/1357650X.2017.1311906 PMID: 28378624

21. Morita T, Asada M, Naito E. Right-hemispheric Dominance in Self-body Recognition is Altered in Left-handed Individuals. Neuroscience. 2020; 425:68–89. https://doi.org/10.1016/j.neuroscience.2019.10.056 PMID: 31809726

22. Makai-Bölöni S, Thijssen E, van Brummelen EMJ, Groeneveld GJ, Doll RJ. Touchscreen-based finger tapping: Repeatability and configuration effects on tapping performance. PloS one, 16(12), e0260783. https://doi.org/10.1371/journal.pone.0260783 PMID: 34874977

23. Karlsson EM, Johnstone LT, Carey DP. The depth and breadth of multiple perceptual asymmetries in right handers and non-right handers. Laterality. 2019; 24, 707–739. https://doi.org/10.1080/1357650X.2019.1652308 PMID: 31399020

24. Johnstone LT, Karlsson EM, Carey DP. Left-handers are less lateralized than right-handers for both left and right hemispheric functions. Cereb Cortex. 2021; 31, 3780–3787. https://doi.org/10.1093/cercor/bhab048 PMID: 33884412

25. Teismann H, Schubert R, Reilmann R, Berger K. Effects of age and sex on outcomes of the Q-Motor speeded finger tapping and grasping and lifting tests-findings from the population-based BiDirect Study. Front Neurol. 2022; 13:965031. https://doi.org/10.3389/fneur.2022.965031 PMID: 36247774