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Computerized spiral analysis using the iPad

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HIGHLIGHTS

- The iPad offers a precise and mobile option for computerized spiral analysis.
- This modality provides an easy method for intraoperative and potentially at-home data collection.
- This method is comparable to established digital spiral acquisition techniques.

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ABSTRACT

Background: Digital analysis of writing and drawing has become a valuable research and clinical tool for the study of upper limb motor dysfunction in patients with essential tremor, Parkinson's disease, dystonia, and related disorders. We developed a validated method of computerized spiral analysis of hand-drawn Archimedean spirals that provides insight into movement dynamics beyond subjective visual assessment using a Wacom graphics tablet. While the Wacom tablet method provides robust data, more widely available mobile technology platforms exist.
New method: We introduce a novel adaptation of the Wacom-based method for the collection of hand-drawn kinematic data using an Apple iPad. This iPad-based system is stand-alone, easy-to-use, can capture drawing data with either a finger or capacitive stylus, is precise, and potentially ubiquitous.
Results: The iPad-based system acquires position and time data that is fully compatible with our original spiral analysis program. All of the important indices including degree of severity, speed, presence of tremor, tremor amplitude, tremor frequency, variability of pressure, and tightness are calculated from the digital spiral data, which the application is able to transmit.
Comparison with existing method: While the iPad method is limited by current touch screen technology, it does collect data with acceptable congruence compared to the current Wacom-based method while providing the advantages of accessibility and ease of use.
Conclusions: The iPad is capable of capturing precise digital spiral data for analysis of motor dysfunction while also providing a convenient, easy-to-use modality in clinics and potentially at home.

1. Introduction

Computerized spiral analysis (CSA) has been in use for many years as a clinical tool to evaluate movement disorders, particularly upper limb tremors such as those found in Parkinson's disease (PD), essential tremor (ET), dystonia, and cerebellar disorders (Pullman, 1998; Saunders-Pullman et al., 2008). Traditionally, a clinician visually analyzes spirals and subjectively scores its severity, e.g. with a five point rating scale (0–4). While easily performed, rating scales are examiner-dependent, vulnerable to inter-rater bias (e.g. UPDRS: Post et al., 2005) and relatively insensitive to small changes. By contrast, CSA analyzes spirals digitally and is thereby able to objectively and precisely calculate detailed measurements such as drawing motor control, spiral tightness, spiral loop width variation, speed, tremor frequency, amplitude, and direction (Elble et al., 2006; Pullman, 1998). These measures provide greater insight into the motor kinematics and dynamics of patients with upper limb disorders (e.g. Hess et al., 2014) and allow clinicians to

Abbreviations: CSA, computerized spiral analysis; DoS, degree of severity.

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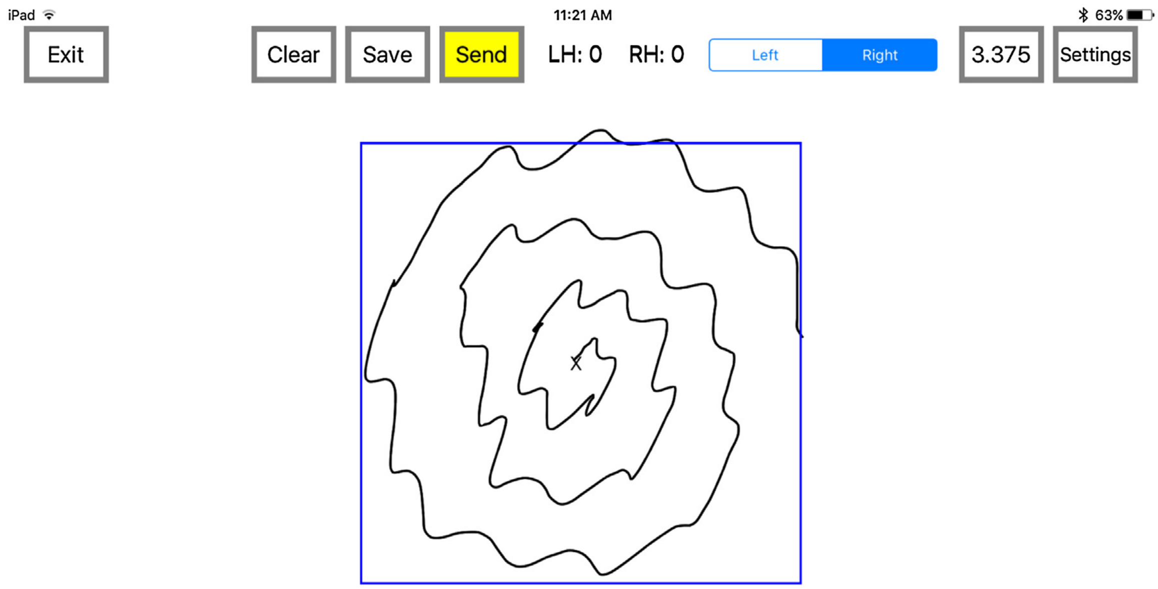

Fig. 1. iPad Application Graphical User Interface (GUI). A simple GUI provides the patient with a 10 × 10 cm workspace in which to draw a spiral. The interface allows the spiral data to be cleared from the device, saved, or sent via email to be analyzed. Button and label layout has been optimized to reduce spiral acquisition time. The application can generate a sample spiral with a radius of 5 cm drawn at a rate of one revolution per second as a demonstration. The patient then draws their own spiral freehand, shown in this figure, attempting to emulate the computer generated spiral as closely as possible.

evaluate the baseline severity, change after treatment, progression of disease (see review: Van Gemmert and Teulings, 2006) as well as serving as possible biomarkers of PD (San Luciano et al., 2016).

Currently, our spiral collection software operates on a Macintosh computer (Apple, Inc, Cupertino, CA) connected to a Wacom drawing tablet (Intuos 4, Wacom technology, Vancouver, WA) (Pullman, 1998). Patients are given a stylus with a ballpoint pen tip and an 8.5 × 11" paper that is placed on the graphics tablet. They are first shown a template Archimedean spiral in a 10 × 10 cm box outlined on the paper. After the patient is given the opportunity to practice drawing freehand spirals with each hand, we collect 10 spirals from the dominant hand and 10 spirals from the non-dominant hand. Data regarding the x, y position, stylus pressure, and time are collected. Tablet data collection software then places the data into a formatted text file that contains the patient's name, demographics, age, handedness, and raw data from each spiral, which is then processed by off-line analysis software written in MatLab (The Mathworks, Natick, MA) (Pullman, 1998).

The Wacom tablet method has provided robust data for years, but it requires connection to a computer running software that is not widely available, thus limiting its accessibility to subjects outside of a clinical setting. With the emerging importance of telemedicine and the need to diagnose and monitor the progression of movement disorders in patients between hospital or clinic visits, a more portable, accessible, and practical method of acquiring this information would be of great value. The introduction of handheld touch screen technology in both clinical and personal settings is an opportunity for more flexible and less costly evaluation of movement disorders (Stanley et al., 2010). A touch screen approach is self-contained: the device is capable of both recording data and conducting analysis without any additional external hardware. Indeed, this type of integrated and portable approach has already seen success in chronic conditions such as diabetes (Harrison et al., 2014) and hypertension (Omboni and Ferrari, 2015). Because touch screen devices are more mobile and widely distributed than the Wacom tablet, dissemination of this technology throughout patient care centers and homes would be a more practical alternative.

There are some limitations of current touch screen technology that may preclude it from being an alternative to our Wacom method. First, touch screen input is generated by finger movement rather than via a pencil or stylus, an inherently different motor task than drawing with a ballpoint pen or other drawing instrument. Next, drawing with a finger is unnatural or unusual to many users, especially if they have never used touch screen technology before. Furthermore, the larger surface area of a finger renders it less precise than a ballpoint pen and produces a significant force of kinetic friction, which has a dampening effect on tremor. Finally, touch screen devices lack the ability to record pressure measurements, thus reducing the dimensionality of the acquired data.

In spite of these disadvantages, however, given the popularity of mobile touch screen devices, their use provides the profound advantage of accessibility to patients through a combination of portable hardware at reasonable costs and digital distribution platforms such as the Google Play Store or Apple App Store. This method of recording and sending digital data takes advantage of the pervasive availability of mobile devices thereby enabling clinicians to collect large amounts of previously unattainable data with ease. Additionally, implementation of these methods will not only facilitate clinical assessment, but also increase patients' agency and involvement in their own care.

2. Experimental methods

2.1. Design

The application was written in the Objective-C programming language using Xcode, an integrated developer environment provided by Apple, Inc that contains a suite of tools for the development of iOS and OS X applications. Xcode and Objective-C implement the model-view-controller (MVC) architectural pattern in their graphical user interface; the application controller mediates between the view (what the user sees) and the internal workings of the program (the model). Our program contains two main views: one for inputting patient data, the other for drawing and collecting graphonomic data. The first view contains input areas for various identifier variables, such as name, age, technician, handedness, gender, category (control or subject), and any additional demographic and clinical data. The layout of the second view is optimized for collecting hand drawn spiral data. UI elements (clearing, saving, and sending spiral data, a switch for recording which hand each spiral is drawn, a counter for the number of spirals drawn with each hand, a button to automatically draw an ideal template spiral, and a settings button for additional options) were all organized on a bar on the top of the screen where they were easily accessible to a subject or technician. The drawing area of this view was located just below the user interface. By default, the application displays a 10 × 10 cm blue square, designed to mimic the paper template that is used for our Wacom tablet version of CSA (see Fig. 1). A target is displayed in the center of the drawing area indicating where the spiral drawing should begin. Before subjects begin drawing, the application is capable of drawing an ideal five revolution Archimedean spiral at a rate of 1 revolution per second with a maximum diameter of 10 cm that they are instructed to emulate in their drawing to ensure standardization of the spiral data across multiple subjects.

2.2. Data collection

Hand-drawn Archimedean spirals were collected from 31 subjects (15 healthy controls and 16 patients with movement disorders seen at Columbia University Medical Center out-patient clinics) on both the iPad and Wacom tablet systems. Subjects used their index finger on the iPad and a ballpoint pen stylus on the Wacom tablet as inputs. Each subject drew 10 spirals with their dominant hand and 10 spirals with their non-dominant hand on each device. All subjects gave informed consent and the study was conducted in accordance with the Institutional Review Board (IRB) of Columbia University Medical Center. Input was received from a finger or capacitive stylus. The path for each input was drawn on a superimposed view in the draw view, which utilized the UIBezierPath class for drawing. For efficiency and maximization of the rate at which position data were collected, the UIBezierPath is cached at regular time intervals. The frequency of data received via capacitive input in most touch screen devices did not exceed the screen refresh rate of 60 Hz. Apple does not publish specific technical specifications regarding the precision of the iPad's capacitive touch screen so the exact x, y position accuracy of the application was not known.

After a subject completed drawing a spiral, there was the option of saving or clearing the data. All saved data were then formatted. Position data were converted into millimeters and centered on the first point. Pressure, if available, was converted to a percentage of the input's maximum, since this depends on the stylus used. Finally, time was measured in milliseconds from the initial point of contact. Spiral data could then be sent either as a JSONObject or as text attachments to a secure email address. Each spiral was recorded as its own text file. The software keeps a counter of the number of spirals obtained for each hand for a particular subject. To ensure privacy, all data were wiped from the iPad device upon exiting the draw view.

2.3. Analysis

While most of the spiral analysis was performed off-line, the application implemented an optional modified algorithm that calculated the Degree of Severity (DoS), a unitless composite index that measured overall spiral execution and spatial irregularity. It has been designed as the computerized equivalent of a standard five-point clinical rating scale (0–4) of handwritten spirals where 0–1 = normal, 1–2 = mild, 2–3 = moderate, and 3–4 = severely abnormal (Pullman, 1998). This provided an immediate, objective, and already clinically validated method of spiral assessment. The application accomplished this by first converting all position data from Cartesian coordinates into polar coordinates. It then calculated the linear regression of the radius of each point plotted against the cumulative change in angle. The difference between the patient's drawing curve and the linear curve of best fit give an estimation of the spatial error that the patient made when drawing the spiral, which we call the first order smoothness. Next, first and second order zero crossing, which describe the amount and rate, respectively, at which the unraveled spiral crosses the line of best fit, is also calculated. Finally, a nonlinear combination of these indices is calculated to derive the DoS using a modified version of the equation described in the original CSA paper (Pullman, 1998). Over 70 indices were calculated including DoS, speed, presence of tremor, tremor amplitude, tremor frequency, and variability of pressure and tightness using MatLab analysis software, which takes into account differences between devices such as sampling rate and tablet resolution. Averages ± standard deviations of each index, and linear regression models using STATA14 (StataCorp, College Station, TX) were then used to make comparisons between the iPad and Wacom systems. Of the 70 indices calculated, nine of the most clinically meaningful indices (Hsu et al., 2009) were analyzed for this study.

Table 1
Mean ± SD from nine indices obtained from both hands of all subjects using both iPad and Wacom systems. Values were averaged over 10 trials for each hand. *Correlation in linear regression models indicating that all were significant to the level of $p < 0.001$.

	iPad	Wacom	R^2 *
DoS	1.139 ± 1.168	1.360 ± 1.958	0.8993
1st order smoothness	−0.490 ± 1.513	−0.667 ± 1.533	0.8955
2nd order smoothness	−3.139 ± 1.513	−3.203 ± 3.054	0.8698
Tightness	1.088 ± 0.259	1.087 ± 0.337	0.6161
1st order zero crossing	5.211 ± 1.459	5.335 ± 1.927	0.5154
2nd order zero crossing	31.602 ± 7.455	32.087 ± 9.463	0.5988
Speed mean	19.530 ± 7.347	19.534 ± 8.277	0.7882
Overall average of widths	0.868 ± 0.248	0.880 ± 0.259	0.6121
Width variation	0.301 ± 0.127	0.309 ± 0.142	0.6341

3. Results

A total of 1240 hand-drawn Archimedean spirals from both hands of 31 subjects: 15 healthy controls (average age = 48.7 ± 20.1 years) and 16 patients with movement disorders: ET (n = 4, age 79.7 ± 12.8 years), PD (n = 9, age 64.2 ± 10.4 years), and brachial dystonia (n = 2, age 58.5 ± 17.7 years) were collected and analyzed. In the linear regression models, all nine of the selected indices from the iPad and Wacom were correlated (all $p < 0.001$), and are shown in Table 1. However, the correlation coefficients between the iPad and the Wacom varied with DoS the most highly correlated, and 1st order zero crossing the least correlated, of the indices.

3.1. Visual output

Fig. 2 presents a side-by-side comparison of a portion of the available visual output taken from two example subjects, a normal control and an ET patient drawing spirals on both devices. The right and left hemispheres of the spiral were differentiated by the colors magenta and blue respectively, to facilitate data interpretation across all graphs.

3.2. Comparison between iPad and Wacom tablet

Results from the nine selected indices from the 1240 spirals drawn by all subjects using both hands on each device are shown in Table 1.

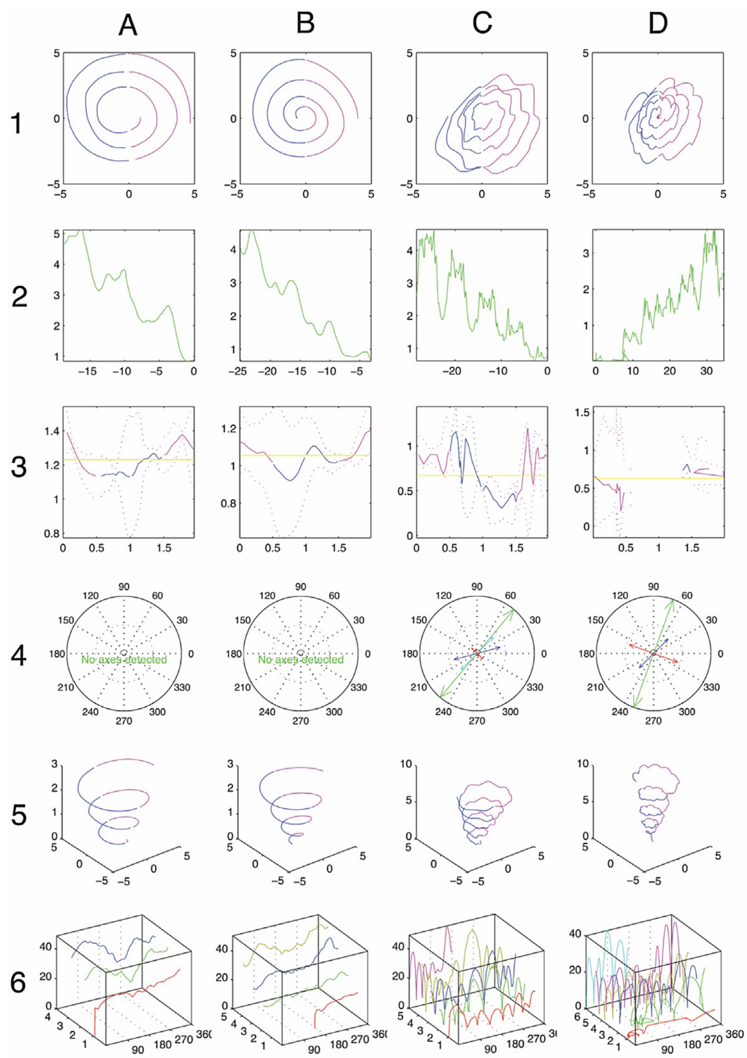

Fig. 2. Graphical representation of spiral data acquired from one control and one ET patient on both the iPad and Wacom tablet. Column A contains data from a control on the iPad and Column B contains data from the same control patient on the Wacom. Column C contains data from an ET patient on the iPad and Column D contains data from the same patient on the Wacom. Rows contain data as follows: 1. Raw spiral graphic; 2. Radius-angle transforms; 3. Spiral widths; 4. Tremor axes; 5. Time vs. trace; 6. Speed vs. angle.

4. Discussion

We have demonstrated a novel method for recording and analyzing hand-drawn spirals in normal control subjects and patients with movement disorders (PD, ET and brachial dystonia) using an easily accessible and portable iPad device. CSA has been a clinical tool for almost two decades, but has yet to take advantage of the growing trends of portability and convenience seen in mobile devices today so that sophisticated medical tests may be used effectively in the outpatient setting. The iPad CSA application presented here has the potential to enhance the ability to help diagnose and monitor the onset and progression of upper limb dysfunction in a myriad of movement disorders by providing people with an easy, streamlined digital graphonomic data collection method.

Perhaps the greatest benefit to using an iPad application for CSA will be its inherent accessibility. Although the Wacom tablet is available at computer and electronics stores as well as online, the iPad is a more commercially ubiquitous product. The ability for patients to easily record and upload spiral data from their own home may contribute to a greater amount of longitudinal patient data through increased convenience. This has the potential to create large amounts of patient-derived movement disorder data that clinicians would be able to track over time, follow day-to-day, monitor efficacy of new treatment regimens, and automatically detect new subtle abnormalities (as assessed by the calculated indices) before they present in the clinic or hospital at follow-up. Telemedicine and personal, accessible care have contributed to advances in the understanding and treatment of other chronic medical conditions (e.g. Omboni and Ferrari, 2015) and has a large potential for being used in the context of movement disorders. Improvements in touch screen capabilities utilized by our application can empower patients who suffer from movement disorders to more actively participate in their own care.

In addition to the benefits this method may provide to patients at home, the CSA iPad application has potential intraoperative use to measure changes in spiral execution in real time during stereotactic surgery such as deep brain stimulation (DBS) placement. While currently only the DoS is calculated directly on the iPad, more indices can be added in the future to provide more in-depth analysis. A patient will be able to draw a spiral that will give the surgeon immediate feedback during mapping and voltage testing to help optimize DBS electrode placement, thereby improving accuracy and reducing operative time. Similarly, CSA with an iPad could be an efficient method for post-operative DBS patient programming that would allow for precise, reproducible clinical measures of change for each setting.

There are several relevant unresolved issues that should be taken into consideration, however. Standardization of data collection, for example, is imperative in any clinical testing system, and may be less reproducible in the absence of a guiding clinician. A patient's ability to follow instructions and to keep motivation high could be in jeopardy with home-based systems like the iPad CSA. Our method partially addresses this by generating a spiral for the patient before they start drawing their own, but the potential for variability is still a concern, particularly with regards to testing environment. The best way clinicians may be able to help alleviate this will be by providing proper patient education and ensuring that a patient is capable of recording their spiral data in a standardized fashion before having to do so at home. Other educational modalities such as online tutorial videos could also be used to check that patients will be adequately equipped to accurately and consistently record data. Additionally, automatic analysis may have the ability to predict erroneous data and exclude it based on intrinsic characteristics and trends (Hodge and Austin, 2004). One way to do this, for example, would be to look at statistical deviations of outpatient data from data collected in an observed inpatient setting. The difficulty lies in separating these deviations from true pathology or improvement.

Other limitations of this study when comparing CSA data using a Wacom compared to iPad tablets are the input differences inherent to each. Using a finger on a touch screen requires a different motor task when compared to drawing on paper with a ballpoint pen, which may be more familiar to patients, especially in older age groups. Thus, data may not be identical across platforms and comparing the ballpoint tipped stylus of the Wacom with a capacitive stylus warrants additional inquiry. However the lack of a need for specialized equipment and widespread availability of the iPad will allow for the creation of databases with large amounts of control and patient data could be used to standardize these indices and reliably compare a subject's performance against others using the same device when controlled for multiple factors, such as age, gender, and underlying clinical diagnoses.

Along these lines, the ability to collect and analyze spiral data from anywhere in the world may soon allow for the creation of a universal database with de-identified patient information. This could be kept for the purpose of improving disease recognition and tracking treatment paradigms for these patients. Adopting a big data approach to analyzing movement disorder information and create new, more accurate models of motor disabilities may facilitate both our understanding of movement disorders as a disease process and help guide clinical decision-making during the treatment of these conditions.

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Conflicts of interest

The authors report no conflicts of interest.

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