Spiral Analysis: A New Technique for Measuring Tremor With a Digitizing Tablet

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Summary: A new computational method for quantification of tremor and other aspects of motor dysfunction is described. By using a digitizing tablet connected to a microcomputer, this analysis is derived from the handwritten Archimedean spiral. This technique extends the standard clinical neurologic test of spiral drawing into an objective and accurate measure that can automatically detect, characterize, and quantify motor dysfunction in patients with movement disorders. Further, it is safe, inexpensive, fast, portable, noninvasive, and can be administered to a large cohort of patients without the need for wires or other attachments. Spiral data are collected in the X, Y, and pressure axes, providing virtual "triaxial" recordings. Spiral analysis is shown to be capable of assessing subtle motor abnormalities potentially indicative of clinical problems in their earliest stages, and thus allow the most rational forms of genetic testing, treatment, or prevention. Spiral analysis may be useful as an initial marker of clinical involvement or serve as an objective gauge of change after therapeutic intervention. **Key Words:** Tremor—Motor control—Digitizing tablet—Mathematical modeling.

The increased power and speed of microprocessors now enable clinical laboratories to quantify tremor and other aspects of motor disability with accuracy and precision not possible a decade ago. Advances in measurement techniques also allow detailed analyses in the time and frequency domains of virtually all meaningful kinematic and physiologic features of normal and deranged movement. There are several different techniques for measuring tremor. One of the most popular and sensitive methods uses accelerometers,[1,2] but these devices are relatively expensive, must be set up and interpreted properly, and some varieties produce poor response signals at clinically important low frequencies.

Digitizing tablets offer an alternative method of recording and quantifying aspects of movement control of the arms not attainable by accelerometer or other means. Handwritten lines or Archimedean spirals, which up to now have been interpreted subjectively and not easily standardized across subjects, can be digitized to offer graphic evidence of tremor activity by using a digitizing tablet connected to a microcomputer. This approach is new, safe, inexpensive, fast, portable, noninvasive, and can detect, characterize, and quantify motor dysfunction without wires or other attachments. Measurements can be collected not only in the X–Y plane, but also in the pressure axis, providing virtual "triaxial" acquisition. Digitizing tablets are limited to assessments of writing and drawing, but these are among the most affected by tremor or task-specific arm dysfunction, and therefore cover a variety of clinically important issues.

METHODS

We developed a method of analyzing tremor and other kinematic features of arm behavior derived from handwritten Archimedean spirals recorded on a digitizing tablet (Kurta Corporation, Phoenix, AZ, U.S.A.). This tablet has a resolution of 2540 points/inch (100 points/mm) with an accuracy of ±0.005 in. (0.127 mm), an output rate of 200 points per second (which translates into 65–70 Hz per axis), and 256 levels of measurable pressure (2.5 g/level). Although still in its preliminary stages, spiral analysis has proven to be highly informative, easy to perform, and extremely well tolerated by all subjects. Spiral data are collected in a virtual triaxial setup (X, Y, and pressure) with subjects seated comfortably at a digitizing tablet. A writing pen is held in a normal fashion without constraints to allow the most clinically meaning-

ful results. Ten spirals are collected from each hand, and all tracings are monitored on-line for error control.

Several steps went into the development of spiral analysis, the first of which was establishing a means of transforming a freely drawn spiral into an extractable equation for mathematical analysis without loss of fidelity. We accomplished this by "unraveling" the spiral into a linear format. An ideal spiral can be described as:

$$x = a\theta \cos(\theta + c) \quad (1)$$

$$y = a\theta \cos(\theta + c) \quad (2)$$

where x, y are the Cartesian coordinates, a is a constant parameter, θ is an angle parameter, and c is a constant representing the initial angle. The polar expression, however, of an ideal spiral can be expressed simply as:

$$r = a\theta$$
$$\text{where } r = \sqrt{x^2 + y^2} \quad (3)$$

This transformation into a linear relation between r and θ sets the stage for clinical analysis.

This approach allows subjects to create spirals with total clinical freedom to draw in any fashion and for as long as desired. Adapting the polar expression allows the

analysis of any spiral, as illustrated in Figure 1. The ideal spiral is computer generated, but this was an inappropriate template against which human behavior could be compared. To create a more suitable spiral for human analysis, we "trained" our computer setup to learn, by example, how to rate spirals in a manner similar to that of expert movement disorder physicians by using a 0–4 modified United Parkinson's Disease Rating Scale[3] where 0–1 = normal; 1–2 = mildly; 2–3 = moderately; and 3–4 = severely abnormal. Training was accomplished by choosing the 10 "best" physicians' ratings (from Columbia-Presbyterian Movement Disorders Group, excluding the author of this report to prevent bias) of spirals from 60 subjects (15 normal, 15 ET, 15 PD, and 15 dystonia patients), the diagnoses of which were blinded to the physicians. "Best" physician rating scores were determined by the 10 highest r^2 linear regressions derived from each physician's scores in comparison to the average of all other physicians.

We then established a series of mathematical indices extracted from the transformed spiral data for quantification. The first five indices described the shape and physical nature of the spirals. We term these indices first- and second-order "smoothness," "tightness," and first- and second-order "zero crossing." We defined smooth-
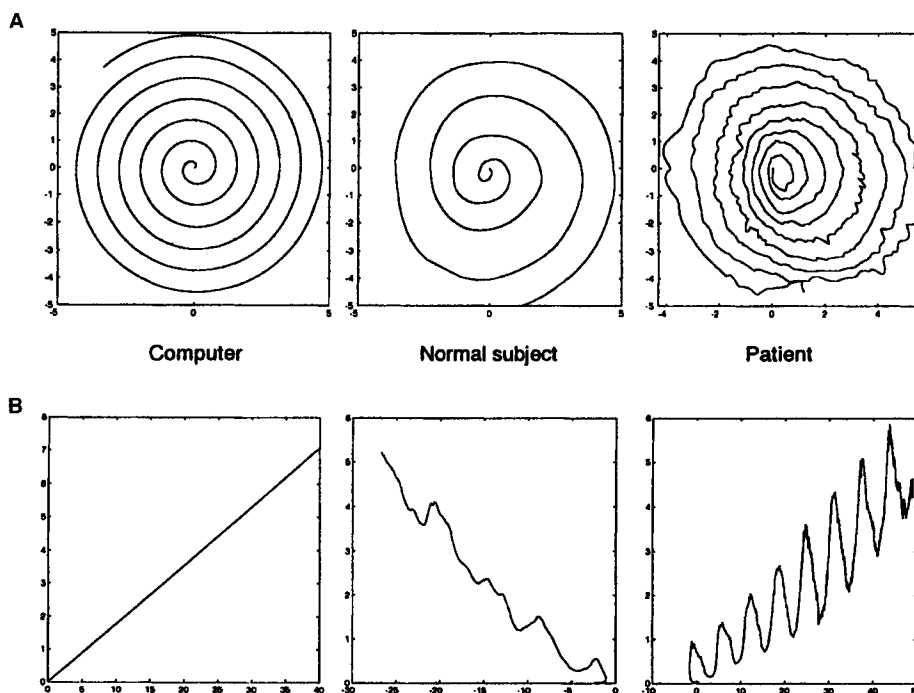

FIG. 1. Reasoning behind spiral analysis. (A) An ideal spiral created by the computer on the upper left, a normal control subject spiral in the middle, and a patient spiral with mild essential tremor (ET) on the right. (B) Corresponding radius-angle transforms. This high-fidelity one-to-one translation allows virtually unlimited analyses on freely drawn spirals. The transform slopes upward or downward, depending on whether the spiral was drawn counterclockwise or clockwise.

ness by how close the linear transform remained to its own mean, as follows:

First-order smoothness

$$i_1 = \frac{1}{\Theta} \sum \left(\frac{\Delta r}{\Delta \theta} - \bar{r}_\theta \right)^2 |\Delta\theta| \qquad (4)$$

$$I_1 = \ln i_1$$

where I1 is the first index, which is the natural log of the formula; Θ is the total angular change; is the average slope of r~θ; and is the difference operator reflecting discrete changes caused by sampling by the digitizing tablet.

Second-order smoothness (first derivative)

$$i_2 = \frac{1}{\Theta} \sum \left(\frac{\Delta \frac{\Delta r}{\Delta\theta}}{\Delta \theta} - d\bar{r}_\theta \right)^2 |\Delta\theta| \qquad (5)$$

$$I_2 = \ln i_2$$

where $d\bar{r}_\theta$ is the average slope of $\frac{\Delta r}{\Delta \theta}$ ~θ

We defined tightness of the spiral by how many turns of the spirals were drawn over its total angular change within a 10-cm square, normalized to 7 (or 14π because each full loop = 2π) and to the largest radius, R, as follows:

Tightness

$$I_3 = (\Theta/R - 14\pi) / 2\pi \qquad (6)$$

Zero-crossing rates are measures of how frequently the linear transform crosses its own mean and are indicators of spiral irregularity. They are the rates $\Delta r/\Delta\theta$ crosses and can be expressed as follows:

Zero crossing rate

$$I_4 = \frac{1}{2(J-1)} \sum_{j=1}^{j-1} sign\left(\frac{\Delta r}{\Delta\theta} \bigg| j+1 - \bar{r}_\theta \right)$$

$$- \sin n\left(\frac{\Delta r}{\Delta\theta} \bigg| j - \bar{r}_\theta \right) |.100\% \qquad (7)$$

where j is the total number of points collected, sign is a sign function defined by

$$y = sign(x) = \begin{cases} 1 & x > 0 \\ 0 & x = 0 \\ -1 & x < 0 \end{cases} \qquad (8)$$

Second-order zero-crossing rate (first derivative)

$$I_5 = \frac{1}{2(J-1)} \sum_{j=1}^{j-1} \left| sign\left(\frac{\Delta \frac{\Delta r}{\Delta\theta}}{\Delta \theta} \bigg| j+1 - d\bar{r}_\theta \right) \right.$$

$$\left. - sign\left(\frac{\Delta \frac{\Delta r}{\Delta\theta}}{\Delta \theta} \bigg| j - \bar{r}_\theta \right) |100\% \qquad (9)$$

RESULTS

These indices, along with several kinematic measures such as the peak frequency and power in the X, Y, and pressure axes, were used to train the computer to rate spirals in the same manner as expert physicians. Simple linear and second-order polynomial regressions (to look for interactions between indices) were performed for each index against the 10-physician average. Those indices with the most significance, highest r^2, and lowest residuals (I_1, I_2, and I_5) were then used to create a "degree of severity" equation (DOS), the output of which is a clinically relevant score from 0–4:

$$DOS = 0.4615 * I_1 + 0.0544 * I_5 - 0.2331 * I_1^2$$
$$- 0.0726 * I_2^2 - 0.001 * I_5^2 + 0.2539 * I_1 * I_2$$
$$+ 1.3668$$

This DOS formula and the results from other indices provided a wealth of information about motor control in the arms (Fig. 2) and have been successful in quantifying spiral severity that directly correlates with clinical disease.[4] Simple regression of the original 10-physician spiral scores, as well as new or "untrained" spirals, when compared with the computer's DOS, consistently yielded remarkably significant correlations ($r^2 = 0.91$; $p < 0.001$).

In a study of Parkinson's disease (PD) patients, spiral analysis revealed that PD patients exert significantly ($p < 0.03$) less pressure on one hemispiral than on the other[5] in 85% of the cases studied ($n = 62$). The pattern of low and high pressure was the same whichever hand was used, similar to hemianopsia in the visual system. Moreover, the "low-pressure" side of the spiral consistently corresponded to the side of the body more affected by PD.

DISCUSSION

We showed that a digitizing tablet can be used to acquire data to analyze tremors, movement speed, writing pressure, smoothness, tightness, and a series of mathematically derived kinematic parameters. Further, this method can be used automatically to detect, characterize,
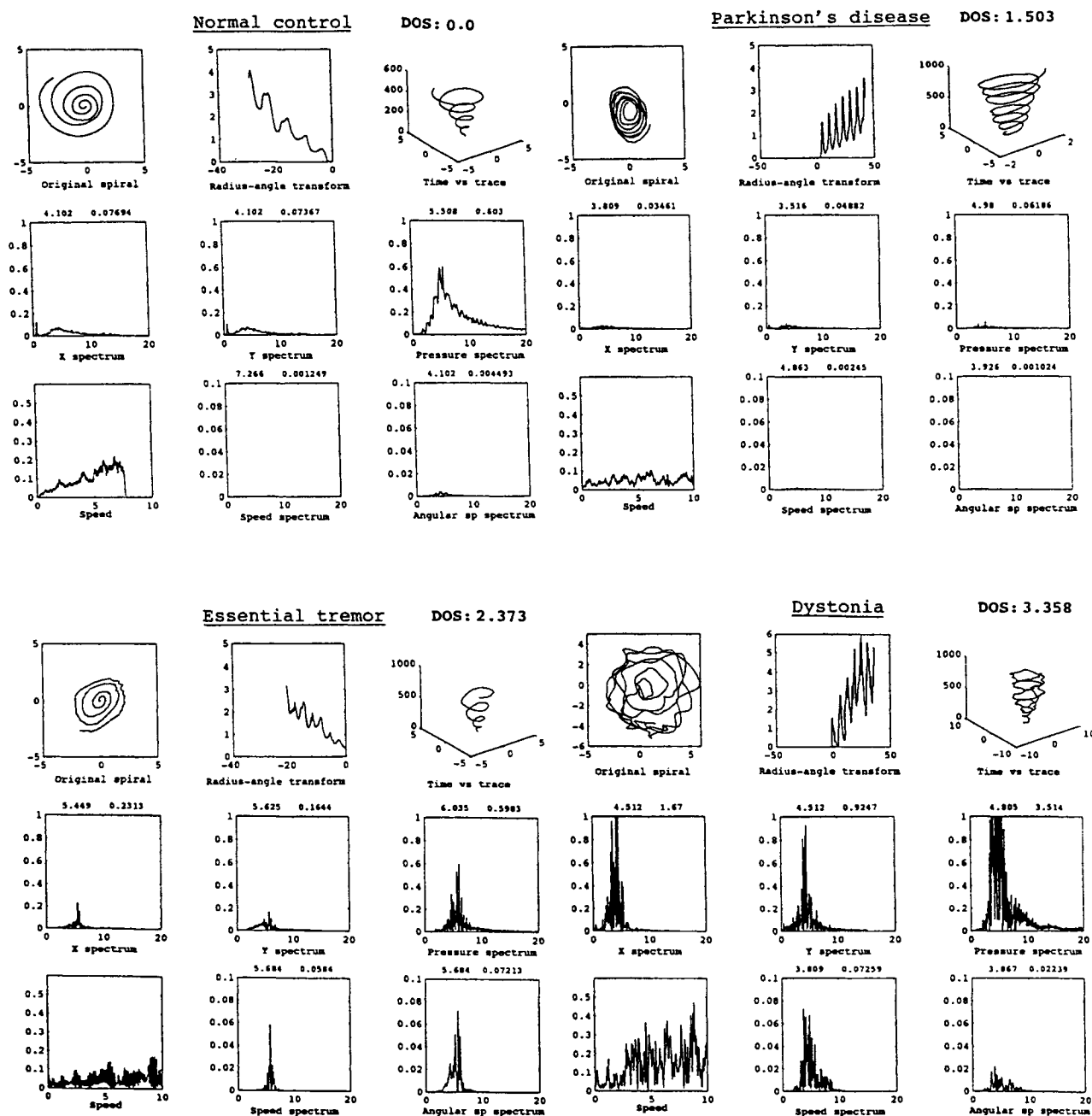
FIG. 2. Preliminary results from four sets of spiral analyses with degree of severity (DOS) ratings listed at the top. The nine figures for each subject reveal some of the basic computational information derived from spirals, starting with a digitized rendering of the original spiral on the upper left, the radius-angle transformation and an X–Y vs. time tracing across to the right. The middle set of tracings reflect Fourier transforms of each of the triaxial dimensions X, Y, and pressure. The lower three figures for each subject reflect speed and angular-speed analyses. Corresponding figures are normalized in each axis. Peak frequency and power are listed above each frequency spectrum. Upper left: a normal control subject with a relative absence of spectral peaks other than pressure and the linearly increasing speed with time. Upper right: a patient with mild Parkinson's disease (PD) with no evidence for writing tremor and low, unchanging linear speed. Lower left: a patient with moderate ET, showing sharp spectral peaks in the X and Y axes, and with even more power in the pressure axis. Note also the oscillation in speed and the sharp spectral peaks of both linear and angular speeds. Lower right: a patient with dystonia with irregular X, Y, and pressure spectra and highly erratic speed tracings.

and quantify motor dysfunction in patients with a variety of movement disorders. A digitizing tablet acquisition system is safe, inexpensive, fast, portable, and noninvasive and has the potential to be administered to a large cohort of patients. One major significance of this method will be in its ability to assess motor abnormalities in their earliest stages, and thus allow the most rational forms of genetic testing, treatment, or prevention. As genetic studies are opening up new horizons in the clinical detection of neurodegenerative diseases, and new drugs are continually developed, spiral analysis with a digitizing tablet may be useful as an initial marker of clinical involvement or serve as an objective gauge of change after therapeutic intervention. Finally, as the bilateral pressure findings suggest for PD, spiral analysis may be useful not only as a diagnostic tool but also for providing insight into higher cortical mechanisms involved.

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