

# Noninvasive and quantitative evaluation of movement disorder disability using an infrared depth sensor

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## Research Article

**Keywords:** gait analysis, cerebellar ataxia, Parkinson's disease, stride length, feet interval, gait rhythm

**Posted Date:** February 18th, 2019

**DOI:** <https://doi.org/10.21203/rs.2.351/v1>

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**Version of Record:** A version of this preprint was published at Journal of Clinical Neuroscience on January 1st, 2020. See the published version at <https://doi.org/10.1016/j.jocn.2019.08.101>.

# Abstract

**Background:** Cerebellar ataxia including spinocerebellar ataxia and Parkinson's disease are neurodegenerative disorders clinically characterized by motor disabilities including gait disturbance. This study aimed to investigate the usefulness of an infrared depth sensor device to quantitatively evaluate gait disturbances and assess its cost effectiveness in patients with movement disorders.

**Methods:** Twenty five ataxic, twenty five Parkinson's disease, and twenty five control subjects were enrolled and evaluated their walk over a short distance. Stride length, feet interval, gait rhythm, and a ratio of the actual walking route length to the linear distance between the start and goal points (A/L ratio) were assessed and compared between ataxic or Parkinson's disease subjects and control subjects. Outcome correlations with clinical scales were also analyzed in the disease groups.

**Results:** The average stride length was shorter in ataxic subjects or Parkinson's disease subjects than in control subjects. The average feet interval was larger in ataxic subjects than in control subjects. The stride length coefficient of variation (CV), gait rhythm CV, and average and standard deviations of the A/L ratio were larger in ataxic or Parkinson's disease subjects than in control subjects. Ataxic subjects exhibited significant positive correlations between the CV of stride length or average feet interval and scale for the assessment and rating of ataxia scores or international cooperative ataxia rating scale scores. Parkinson's disease subjects exhibited a significant correlation between the average stride length, CV of stride length, or standard deviation of A/L ratio and unified Parkinson's disease rating scale score.

**Conclusion:** The device used in this study differentiated the characteristics of gait disturbance in each movement disorder and quantitatively evaluated ataxia or Parkinson's disease severity, indicating its potential clinical utility across applications.

## Background

Cerebellar ataxia is clinically characterized by progressive limb and truncal ataxia, dysarthria, and gait disturbance due to neurodegeneration in the cerebellum and cerebellar systems [1,2]. Parkinson's disease is another neurodegenerative disorder, clinically characterized by rigidity, bradykinesia, tremor, impairment of righting reflexes, and gait disturbances [3]. Both cerebellar ataxia and Parkinson's disease result in reduced mobility and activities of daily living with stage advancement. The detailed molecular pathogenesis of these devastating disorders, as well as fundamental therapies for them, have not yet been elucidated. To develop an effective disease modifying therapy for these disorders, clinical trials must be conducted in which reliable parameters are measured. Previous clinical trials have evaluated disabilities in cerebellar ataxia or Parkinson's disease quantitatively, however, these were not useful from the perspective of cost effectiveness and portability [4,5]. To access the broadest clinical population, a simple, ideally portable device with high cost effectiveness should be used.

In the present study, motor disabilities in cerebellar ataxia and Parkinson's disease were assessed using a device equipped with an infrared depth sensor.

# Methods

## 1. Subjects

A total of twenty five patients with ataxic diseases, including degenerative ataxias such as Machado-Joseph disease/ spinocerebellar ataxia types 3 and 6, dentatorubral-pallidolusian atrophy (DRPLA), familial but genetically undiagnosed ataxia, sporadic cerebellar ataxia, acute cerebellitis, and multiple system atrophy with predominant cerebellar ataxia (MSA-C) participated in the present study. In addition, twenty five Parkinson's disease patients and twenty five controls without gait disturbance or any neurological disorders participated (Table. 1). Sporadic cerebellar ataxia patients who fulfilled the Abele's diagnostic criteria, MSA patients who fulfilled the second consensus criteria for "probable" disease, and Parkinson's disease patients who fulfilled Movement Disorder Society clinical diagnostic criteria for Parkinson's disease were enrolled in the present study [6-9]. Patients with Machado-Joseph disease did not have a neuropathy, DRPLA patient did not show involuntary movements, and acute cerebellitis patient did not have remarkable laterality.

There were no significant differences between ataxic and control subjects or between Parkinson's disease and control subjects in participants' ages and body height at examination (Table. 1). Individuals who were prescribed medicines that might affect their ability to walk and those who required a cane or walker were excluded. All patients and control subjects who were enrolled provided written informed consent. This study was approved by the Gunma University Graduate School of Medicine's institutional review board.

## 2. Motion capture device with an infrared depth sensor and analysis system

Gait performance was evaluated by an apparatus equipped with a Microsoft Kinect V2 sensor (Microsoft, WA, USA), which is easy to apply because of its inexpensive and markerless system (Fig. 1A). It is a motion capture device that features a depth sensor and an infrared ray sensor and can detect feature points on the body using Time of Flight (ToF) technology. ToF technology calculates distances by measuring the amount of time that elapses between emission of a light and its return after being reflected by an object. The Kinect V2 functionally tracks points on 25 skeletal joints in real time. X, Y, and Z coordinates are provided for each joint position. It is possible to acquire depth information in the range of 0.5 to 8.0 m, relative to the position of the Kinect V2, and joint information in the range of 0.5 to 4.5 m [10-12].

The 3D depth camera used in the present study was placed at a height of 1.2 m. Each subject was required to undergo three trials (4.0 m each) of round walking at the regular speed toward the camera (Fig. 1B). The measurements excluded the first and last steps to eliminate the influence of acceleration and deceleration.

The Kinect V2 obtained the 3D position of each joint without using markers. Signal and image processing were performed independently using the Kinect V2 Software Development Kit (Microsoft, WA,

USA). Data were analyzed using a software packaged developed by our group. This program automatically detects body movements and displays them from multiple angles using the 3D, real-time data acquired from 25 joints (Fig. 1C). From these data, we could quantitatively calculate gait parameters, such as stride length, feet interval, and time intervals for every step.

### 3. Evaluation items

Data for the following parameters were collected in the present study.

- I. Stride length: A distance in the longitudinal axis (Z-axis) between the left and the right heel points for each step (Fig. 1D-(1)).
- II. Feet interval: A distance in the horizontal axis (X-axis) between the left and the right heel points for each step (Fig. 1D-(2)).
- III. Gait rhythm: Time intervals for each step. Stride length, feet interval, and gait rhythm were evaluated based on actual measurements, and coefficients of variation (CV).
- IV. The ratio of the actual walking route length to the linear distance between the start and goal points (A/L ratio) and its standard deviations (SD) were also evaluated. This parameter was expressed as a deviation from the ideal walking route (Fig. 1E). The actual walking route was measured by adding the straight-line distance of each frame (30 frames/s).
- V. The scale for the assessment and rating of ataxia (SARA) and the international cooperative ataxia rating scale (ICARS) were measured in patients with ataxic subjects, and the unified Parkinson's disease rating scale (UPDRS) was measured in patients with Parkinson's disease subjects.

### 4. Statistical analyses

The following items were analyzed, and statistical analyses were performed on them using SPSS 25 software (SPSS Inc., IL, USA). Each item was compared between ataxic or Parkinson's disease subjects and control subjects.  $p < 0.05$  was used to establish statistical significance in all comparisons among the groups. Data normality was analyzed using the Kolmogorov-Smirnov test. The paired sample t-test or Mann-Whitney U test was used to calculate the differences.

Correlations between each item and conventional clinical scales [e.g. SARA or ICARS] were analyzed using Pearson's correlation coefficient in ataxic subjects [13,14]. Similar analyses were performed in Parkinson's disease subjects by comparing each evaluation item to clinical scale ratings on UPDRS or UPDRS Part 2 [15].

## Results

Evaluation items are summarized by box-plots as shown in Fig. 2. The average stride length differed significantly between ataxic or Parkinson's disease subjects and control subjects (Fig. 2A, left panel). The

average stride length was shorter in ataxic subjects or Parkinson's disease subjects than in control subjects. Parkinson's disease subjects exhibited the short stride length, reflecting the short-stepped gait typical of parkinsonism. As for the CV of the stride length, ataxic subjects or Parkinson's disease subjects exhibited the greater stride length fluctuation than the control subjects with statistically significant differences (Fig. 2A, right panel). The average feet interval was larger in the ataxic group, significantly differing from controls and reflecting the wide gait often exhibited by these patients due to their truncal instability (Fig. 2B, left panel). The CV of the feet interval did not statistically differ between ataxic or Parkinson's disease subjects and control subjects (Fig. 2B, right panel). The Parkinson's disease subjects exhibited a longer time interval per step than the control subjects (Fig. 2C, left panel), likely reflecting akinesia and gait freezing common to parkinsonism, although there were no statistically significant differences among the groups. Gait rhythm CV was significantly larger in ataxic and Parkinson's disease subjects than in control subjects (Fig. 2C, right panel). The A/L ratio was significantly larger in ataxic subjects or Parkinson's disease subjects than in control subjects in terms of both average values and SDs (Fig. 2D).

Correlations between all gait parameters and the SARA or ICARS scores in ataxic subjects and the UPDRS or UPDRS Part 2 scores in Parkinson's disease subjects were also analyzed and depicted in scatterplots (Fig. 3). Average stride lengths did not statistically correlate with the SARA or ICARS scores in ataxic subjects (Fig. 3A, upper left row). In Parkinson's disease subjects, however, significant negative correlations were observed between the average stride length and the UPDRS or UPDRS Part 2 scores (Fig. 3A, upper right row). The stride length CV exhibited significant positive correlations with the SARA or ICARS scores in ataxic subjects (Fig. 3A, bottom left row), and with the UPDRS or UPDRS Part 2 scores in Parkinson's disease subjects (Fig. 3A, bottom right row). As for the average feet interval findings in the present study, these were significantly and positively correlated with the SARA or ICARS scores (Fig. 3B, left). No correlation was found between the average feet interval and the UPDRS or UPDRS Part 2 scores in Parkinson's disease subjects, however (Fig. 3B, right). There were positive correlations between Parkinson's disease subjects' average A/L ratios and the UPDRS or UPDRS Part 2 scores, although no such correlation was found between average A/L ratios and the SARA or ICARS scores in ataxic subjects (Fig. 3C, upper rows). The SD of A/L ratios were positively correlated with the SARA scores among ataxic subjects (Fig. 3C, bottom left row), as well as with the UPDRS or UPDRS Part 2 scores in Parkinson's disease subjects (Fig. 3C, bottom right row).

## Discussion

Clinical scales used to evaluate the severity of motor disturbances, such as the SARA and ICARS for cerebellar ataxia and the UPDRS for Parkinson's disease, are broadly accepted but difficult to quantify because each is interpreted according to a sum graded score despite interrater variability. These clinical scales were developed for evaluating of disease-specific disturbances, but are not used to compare motor impairments between and across different disease populations. The device used in the present study, which is equipped with an infrared Kinect V2 depth sensor, which was developed by Microsoft Inc., may be a valuable tool for resolving these challenges. This tool enables the non-invasive, quantitative,

objective, and accurate evaluation of motor impairments. Previously, gait analyses using Kinect V2 were reported in stroke or Parkinson's disease subjects, although subjects with cerebellar ataxia have not been similarly assessed with the exception of one study that analyzed juvenile and infantile-onset cerebellar ataxia [16-21].

The average values and CV of the stride length, CV of the gait rhythm, and average A/L ratio and its SD significantly differed between ataxic or Parkinson's disease subjects and control subjects. The average feet interval significantly differed between ataxic subjects and control subjects. These parameters represent major aspects of gait performance and significant changes in them may correspond to the truncal ataxia, short step length, and gait freezing which are critical components of Parkinson's disease.

Ataxic subjects exhibited significant and positive correlations between stride length CV and the SARA or ICARS scores, average feet interval and the SARA or ICARS scores, and the SD of the A/L ratio and the SARA scores. Ataxic gait is clinically characterized by a wide-based stance and truncal instability. The device used in the present study allowed for the quantitative evaluation of disabilities in ataxic subjects. In Parkinson's disease subjects, significant negative correlations were identified between the average stride length and the UPDRS or UPDRS Part 2 scores, significant positive correlations were identified between the stride length CV and the UPDRS or UPDRS Part 2 scores, the average and SD of the A/L ratio and the UPDRS or UPDRS Part 2 scores. Gait disturbance in Parkinson's disease is clinically characterized by a short step length and gait freezing. Thus, the device used in the present study adequately, reliably, and quantifiably identified these gait features in a way that agreed with clinical assessments. Among parts 1, 2, 3, and 4 of the UPDRS subscales, part 2 scores capture motor elements of activities of daily living better than the others.

The device used in the present study, which was equipped with a Kinect V2, allowed for the successful assessment of gait disturbance characteristics across patients with multiple neurodegenerative disorders. This provides evidence that this tool, which is highly portable and affordable, might be useful for the evaluation of cerebellar ataxia or Parkinson's disease severity in clinical populations.

## **Conclusion**

The infrared depth sensor device assessed in the present study is expected to contribute to future clinical studies of various, potential therapies for cerebellar ataxia, Parkinson's disease, and similar mobility-limiting disorders due to its high portability and affordability.

## **Declarations**

### **Ethics approval and consent to participate**

All patients and control subjects who were enrolled provided written informed consent. This study was approved by the Gunma University Graduate School of Medicine's institutional review board.

## Consent for publication

Not applicable.

## Availability of data and materials

All data used and analyzed during the current study are available from the corresponding author on reasonable request.

## Competing interests

Not applicable.

## Funding

This study was supported by Grants-in-Aid for Scientific Research (C) from the Ministry of Education, Culture, Sports, Science and Technology, Japan [grant number 16K09665] (to Y.I.); Grants-in-Aid from the Research Committee for Ataxic Disease from the Ministry of Health, Labour and Welfare, Japan (to Y.I.); and the Gunma University Medical Innovation Project (to Y.Y.). The funders had no role in design of study and data collection, analysis, and interpretation of data and in writing the manuscript.

## Authors' contributions

ST analyzed data and wrote the manuscript. MF, KH, and NF contributed to data collection. SN, MF, and YY contributed to data analysis. YY also developed the data analyzing system. YI developed the study concept and contributed to the study design. He also supervised the study, and contributed to drafting and revising the manuscript. All authors critically read and approved the final manuscript.

## Acknowledgements

We would like to thank all the patients who participated in this study, and would like to thank Drs. Masaki Ikeda, Masami Ikeda, Yukio Fujita, Kazuaki Nagashima, Hiroo Kasahara, Kunihiro Ishizawa, Masayuki Sato, and Makoto Shibata for patient enrollment.

## Abbreviations

DRPLA: dentatorubral-pallidoluysian atrophy; MSA-C: multiple system atrophy with predominant cerebellar ataxia; ToF: Time of Flight; CV: coefficients of variation; A/L ratio: ratio of the actual walking route length to the linear distance between the start and goal points; SD: standard deviation; SARA: scale for the assessment and rating of ataxia; ICARS: international cooperative ataxia rating scale; UPDRS: unified Parkinson's disease rating scale

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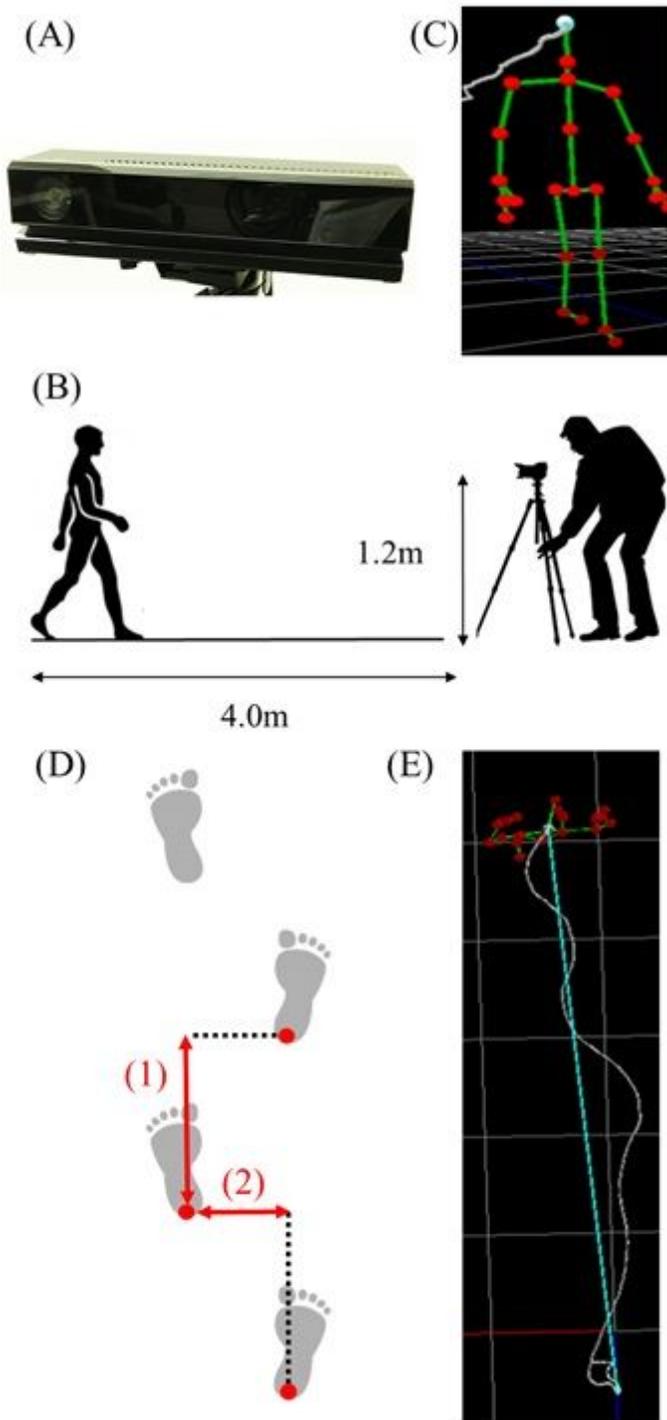
## Tables

**Table. 1** Summarized demographics of ataxic, Parkinson's disease, and control subjects enrolled in the present study.

	Ataxic subjects	Parkinson's disease subjects	Control subjects
Number of cases (Male/Female)	25 (14/11)	25 (10/15)	25 (13/12)
Age at examination (y)	54.1±14.6	68.4±8.1	62.0±13.9
Age at onset (y)	45.4±15.8	61.6±9.6	∅
Body height (cm)	162.5±7.9	158.2±9.0	161.4±7.2
SARA	12.9±3.0	∅	∅
ICARS	35.4±11.1	∅	∅
Hoehn & Yahr stage (on period)	∅	2.8±0.4	∅
UPDRS (on period)	∅	37.1±16.8	∅
UPDRS Part 2 (on period)	∅	9.1±5.1	∅

SARA; scale for the assessment and rating of ataxia, ICARS; international cooperative ataxia rating scale, UPDRS; unified Parkinson's disease rating scale, ∅; not applicable

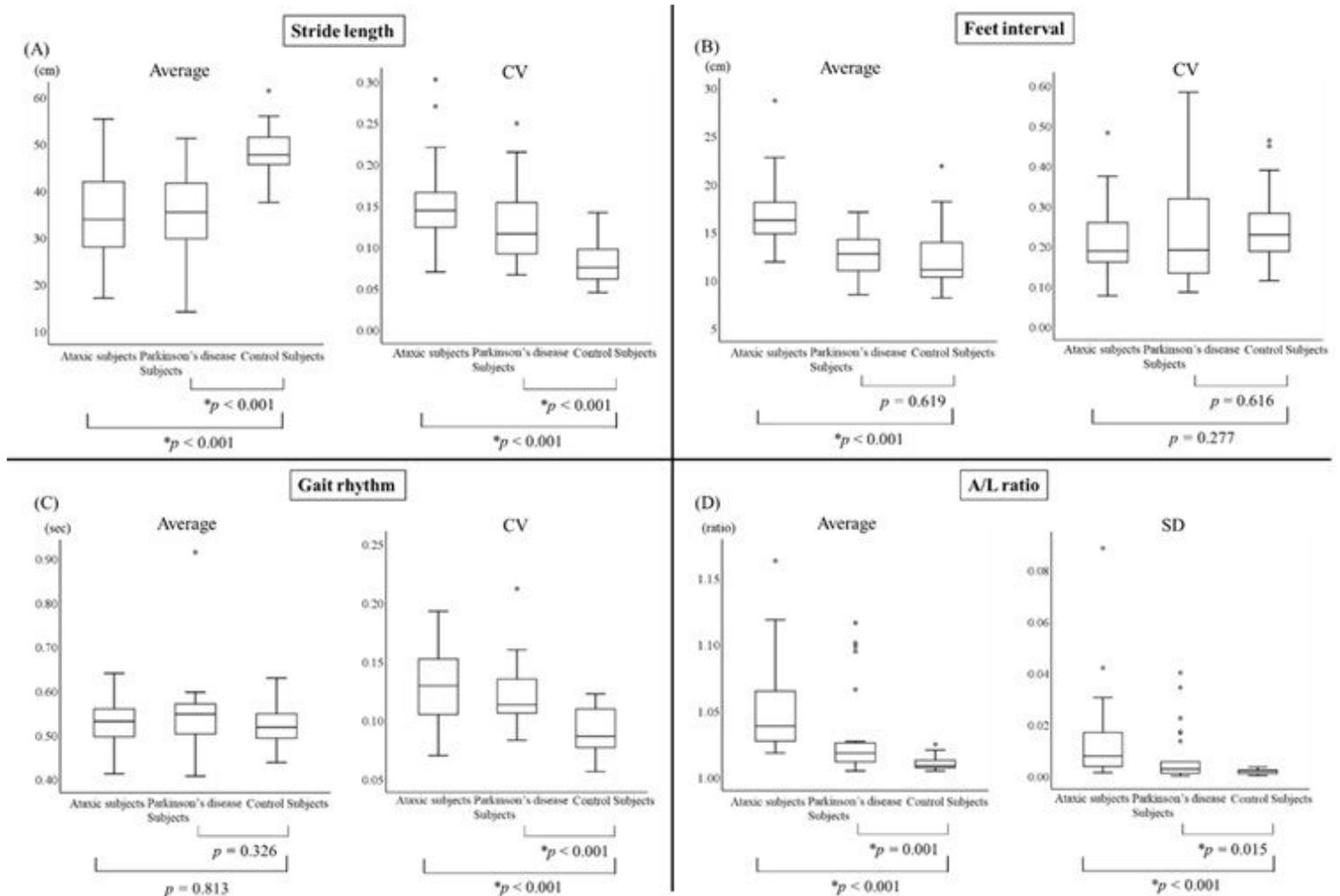
## Figures



**Figure 1**

The device used in the present study, evaluation items, and a picture of a skeletal image. A Kinect V2 camera system and a schematic drawing of the gait analysis used in the present study shown in (A) and (B), respectively (Digital image of silhouettes for public domain retrieved from [https://all-free-download.com/free-vector/download/walking-person-silhouette-clip-art\\_15563.html](https://all-free-download.com/free-vector/download/walking-person-silhouette-clip-art_15563.html) and <https://www.kisscc0.com/clipart/photographer-wedding-photography-fine-art-photogra-6g5u60/> ). A picture of the skeletal image extracted via a 3D-motion analysis system is depicted in (C). Evaluation items of the stride length (1) and feet interval (2) are shown in (D) (Digital image of silhouette for public

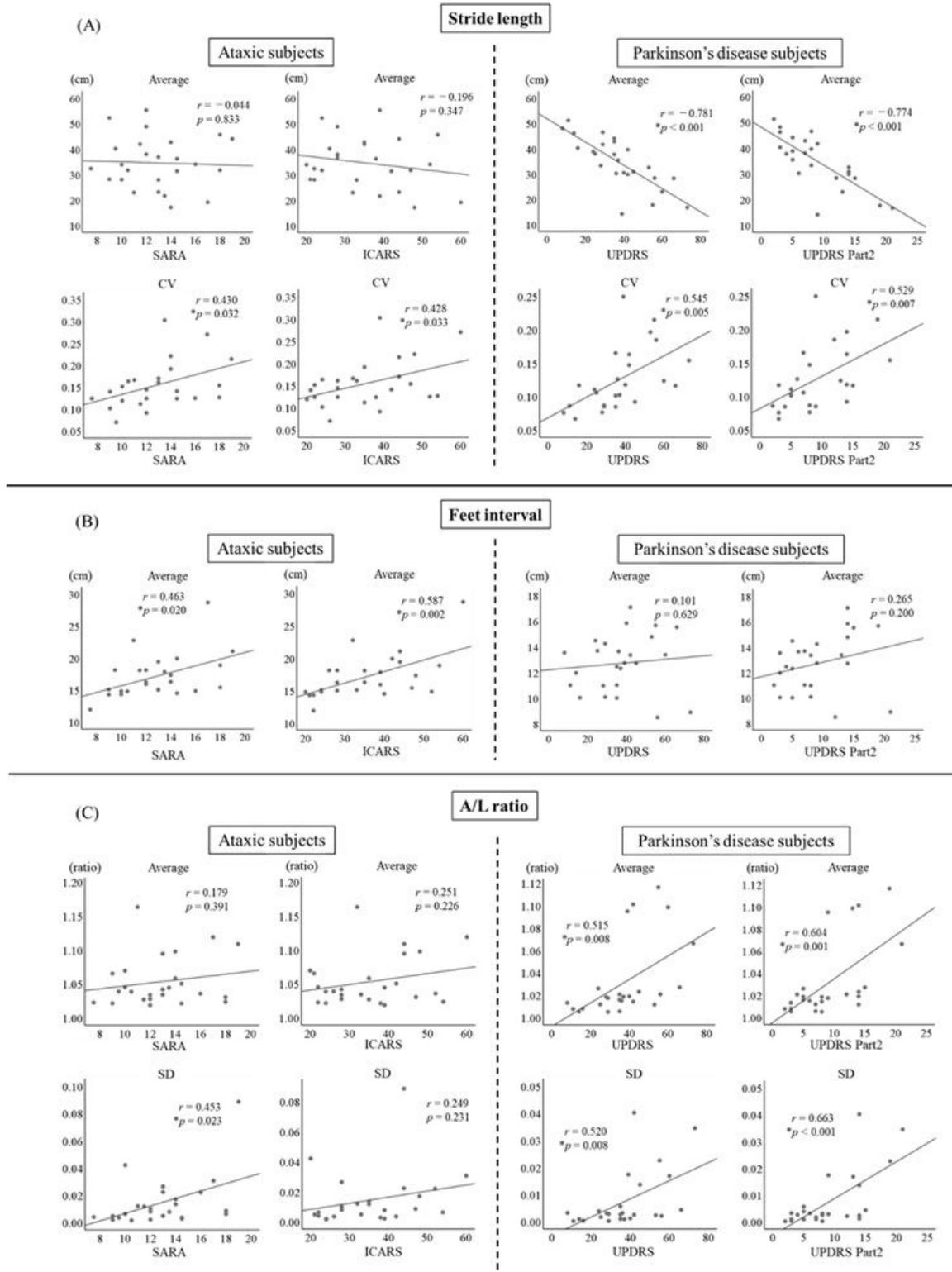
domain retrieved from <http://gahag.net/007099-footprints-footmarks/> ). The 3D-motion analysis system depicted participant routes, from above, as a white curve, and the linear distance of the curve between start and goal points as a blue straight line (E). A ratio of the actual walking route length to the linear distance between the start and goal points (A/L ratio) is distance of white line/blue line.



**Figure 2**

Boxplots of each measurement item for ataxic, Parkinson's disease, and control subjects. The average stride length significantly differed between ataxic or Parkinson's disease subjects and control subjects ( $p < 0.001$ , respectively) (A, left panel). The coefficient of variation (CV) of stride length differed significantly between ataxic or Parkinson's disease subjects and control subjects ( $p < 0.001$ , respectively) (A, right panel). The average feet interval differed significantly between control subjects and ataxic subjects ( $p < 0.001$ ), although the CV of this measure did not differ significantly between ataxic or Parkinson's disease subjects and control subjects (B). The average gait rhythm did not differ significantly between ataxic or Parkinson's disease subjects and control subjects (C, left panel). The CV of gait rhythm was significantly larger in ataxic subjects and Parkinson's disease subjects than in control subjects ( $p < 0.001$ , respectively) (C, right panel). The average A/L ratio was significantly longer in ataxic subjects or Parkinson's disease subjects than in control subjects (vs. ataxic:  $p < 0.001$ , vs. Parkinson's disease:  $p = 0.001$ ) (D, left panel).

The standard deviation of the A/L ratio also differed significantly between ataxic or Parkinson's disease subjects and control subjects (vs. ataxic:  $p < 0.001$ , vs. Parkinson's disease:  $p = 0.015$ ) (D, right panel).



**Figure 3**

Scatterplots representing correlations between the measurement items in ataxic or Parkinson's disease subjects and their scores on clinical scales. The average stride length of ataxic subjects did not statistically correlate with the assessment and rating of ataxia (SARA) scores or international cooperative

ataxia rating scale (ICARS) scores (A, upper left row). The CV of stride length in ataxic subjects was significantly and positively correlated with the SARA scores (Pearson's correlation coefficient test:  $r = 0.430$ ,  $p = 0.032$ ) and ICARS scores ( $r = 0.428$ ,  $p = 0.033$ ) (A, bottom left row). Parkinson's disease subjects exhibited a significant and negative correlation between the average stride length and the unified Parkinson's disease rating scale (UPDRS) scores ( $r = -0.781$ ,  $p < 0.001$ ) and UPDRS Part 2 scores ( $r = -0.774$ ,  $p < 0.001$ ) (A, upper right row). The CV of stride length was significantly and positively correlated with the UPDRS scores ( $r = 0.545$ ,  $p = 0.005$ ) and UPDRS Part 2 scores ( $r = 0.529$ ,  $p = 0.007$ ) (A, bottom right row). The average feet interval among ataxic subjects was significantly and positively correlated with the SARA scores ( $r = 0.463$ ,  $p = 0.020$ ) and ICARS scores ( $r = 0.587$ ,  $p = 0.002$ ) (B, left), however, no significant correlation was found in Parkinson's disease subjects with the UPDRS or UPDRS Part 2 scores (B, right). The average A/L ratio in Parkinson's disease subjects was significantly and positively correlated with the UPDRS scores ( $r = 0.515$ ,  $p = 0.008$ ) and UPDRS Part 2 scores ( $r = 0.604$ ,  $p = 0.001$ ), but not with the SARA scores or ICARS scores in ataxic subjects (C, upper rows). The SD of the A/L ratio was significantly and positively correlated in ataxic subjects with the SARA scores ( $r = 0.453$ ,  $p = 0.023$ ) but not with the ICARS scores (C, bottom left row). As for the Parkinson's disease subjects, there was a significant and positive correlation between the SD and the UPDRS ( $r = 0.520$ ,  $p = 0.008$ ) scores and UPDRS Part 2 scores ( $r = 0.663$ ,  $p < 0.001$ ) (C, bottom right row).