

Quantitative Classification of Parkinsonian Gait Disturbances Using Telemetry: Differentiating Akinetic Freezing and Inefficient Tremulous Gait

Zhenghua Li^{1,2} and Kenichi Yamamura^{1,2*}

¹Institute of Resource Development and Analysis,
Kumamoto University, Kumamoto, Japan

²Transgenic Group, Inc., Fukuoka, Japan

*Corresponding Author

Kenichi Yamamura, Institute of Resource Development and Analysis,
Kumamoto University, Kumamoto, Japan.

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Abstract

Background: We previously demonstrated that freezing of gait (FOG) in Parkinson's disease (PD) can be objectively assessed using consumer smartwatch telemetry and that FOG episodes introduce significant spatial GPS distance distortion. However, parkinsonian gait impairment comprises distinct motor subtypes, notably complete motor arrest (akinetic freezing) and irregular shuffling gait.

Objective: To determine whether these distinct manifestations can be quantitatively evaluated and differentiated using telemetry metrics derived from structured field walking tests.

Methods: We conducted outdoor walking test trials on a standardized park pathway using Apple Watch Ultra 2 (WorkOutDoors and HealthFit). Quantitative telemetry metrics included the Measurement Error Rate (MER: $[(\text{Recorded Distance} - \text{Map Distance}) / \text{Map Distance}] \times 100\%$) and the FOG Ratio (Freezing Time / Total Time).

Results: FOG Ratio strongly correlated with walking speed ($r = -0.869$, $p < 0.001$) and cadence ($r = -0.848$, $p < 0.001$). Crucially, MER showed no correlation with FOG Ratio ($r = 0.135$, $p = 0.659$) or walking speed ($r = -0.096$, $p = 0.755$).

Conclusion: FOG Ratio and MER represent orthogonal dimensions of gait impairment. This decoupling establishes a quantitative classification differentiating Akinetic Freezing (high FOG Ratio, low MER) from Inefficient Tremulous Gait (high MER), providing a refined framework for digital gait telemetry.

1. Introduction

Freezing of gait (FOG) is a paroxysmal, disabling symptom in Parkinson's disease (PD) characterized by brief episodes of inability to produce effective forward stepping [1]. Wearable sensor technology and consumer smartwatches have gained rapid popularity in clinical research for objective, real-world gait telemetry [2-6]. In our previous published study, we demonstrated that FOG in PD can be quantitatively evaluated using smartwatch telemetry, establishing the sensitivity of the FOG Ratio and uncovering FOG-induced GPS trajectory inflation (~32%) during stationary motor arrests [7]. Furthermore, our long-term

digital phenotyping studies established the utility of continuous Apple Health tracking for assessing disease progression and pharmacological interference [8,9]. Building directly upon these findings, the present study addresses a persistent clinical and technical challenge: commercial wearable devices often aggregate heterogeneous gait abnormalities into generic distance metrics without distinguishing underlying motor subtypes [4]. Specifically, high-frequency, low-amplitude movements (micro-shuffling or tremulous leg motions) can artificially inflate recorded distance via accelerometric over-counting or GPS jitter [5]. To resolve these measurement ambiguities, we propose a quantitative sub-

classification of parkinsonian gait disturbances—differentiating true temporal gait arrest (Akinetic Freezing) from spatial artifact-driven gait inefficiency (Inefficient Tremulous Gait)—using two complementary telemetry metrics: the Measurement Error Rate (MER) and the FOG Ratio.

2. Methods

2.1. Trial Design and Environment

Thirteen field walking tests (N = 13) were performed on a signal-free, level, standardized paved jogging path at Starlin Park (Harbin, China) to control for environmental variations.

2.2. Instrumentation and Data Collection

A smartwatch (Apple Watch Ultra 2, worn on the left wrist) running WorkOutDoors and HealthFit applications recorded continuous spatial and temporal parameters, including Recorded Distance (RD), Total Time (TT), Moving Time (MT), Walking Speed, Cadence, and Step Length. True geographic distance (Map Distance, MD) was established via high-precision map calibration.

2.3. Derived Quantitative Metrics

- Measurement Error Rate (MER, %): $MER = [(RD) - (MD) / (MD) \times 100$
- FOG Ratio: {FOG Ratio} = Freezing Time (FT)/Total Time (TT) x 100
- $= [(TT) - Moving Time (MT)] / TT \times 100$

2.4. Note on Nomenclature:

We specifically designate MER as a "Rate" (Measurement Error Rate) rather than a "Ratio" because it quantifies the magnitude of spatial error relative to a fixed geographic standard (Map Distance), whereas the FOG Ratio represents a true temporal proportion (Freezing Time / Total Time).

2.5. Statistical Analysis

Descriptive statistics (Mean ± SD) were calculated for all walking parameters. Bivariate relationships between MER, FOG Ratio, walking speed, cadence, and step length were assessed using Pearson’s correlation coefficient (r) with significance set at p < 0.05.

3. Results

3.1. Summary of Telemetric Parameters

Across 13 trials, the mean MD was 551.5 m ± 153.2 m, while mean RD reached 752.3 m ± 208.9 m, yielding a mean MER of 38.45 ± 19.92 % (range: 14.29 ± 81.08 %). The mean FOG Ratio was 0.58 ± 0.11 % (range: 0.38 – 0.79 %). Mean walking speed was 1.79 ± 0.50 km/h, mean cadence was 63.62 ± 18.34 steps/min, and mean step length was 48.69 ± 5.09 cm. Raw data for these values are shown in Tabel 1 and 2. Based on these data, FOG in PD patient can be classified into two phenotypes in consumer telemetry:

Test No.	Date Time	Google Maps	WorkOutDoors		Ratio	HealthFit			
		Map distance (MD) (m)	Recorded distance (RD) (m)	Measurment error (MD-RD) (m)	Measurement error ratio (MER) [(MD-RD)/MD] x100 (%)	Total time (TT)	Moving time (MT)	Freezing time (FT) =TT-MT	FOG ratio (FT/TT)
Test 1	260817 15:48-16:05	600	720	120	20.0	0:17:54	0:11:09	0:06:45	0.377
Test 2	260820 17:25-17:54	600	820	220	36.7	0:30:16	0:12:49	0:17:27	0.577
Test 3	260824 14:39-15:05	600	960	360	60	0:26:17	0:14:09	0:12:08	0.462
Test 4	260825 16:01-16:32	600	970	370	61.7	0:31:51	0:14:35	0:17:16	0.542
Test 5	260831 16:29-16:59	600	840	240	40.0	0:30:33	0:11:22	0:19:11	0.628
Test 6	260901 16:21-16:49	600	750	150	25.0	0:29:03	0:10:03	0:19:00	0.654
Test 7	260903 15:28-15:59	600	760	160	26.7	0:31:45	0:10:21	0:21:24	0.674
Test 8	260905-1 16:03-16:16	320	460	140	43.8	0:13:50	0:06:12	0:07:38	0.552
Test 9	260905-2 16:21-16:29	280	330	50	17.9	0:07:56	0:04:32	0:03:24	0.429
Test 10	260908 16:22-16:53	700	1030	330	47.1	0:30:10	0:12:16	0:17:54	0.593
Test 11	260912 15:22-16:04	700	800	100	14.3	0:30:10	0:12:16	0:17:54	0.593
Test 12	260918 15:02-16:11	700	880	180	25.7	0:59:04	0:12:21	0:46:43	0.791
Test 13	260921 17:00-17:32	370	670	300	81.1	0:32:38	0:09:37	0:23:01	0.705

Table 1

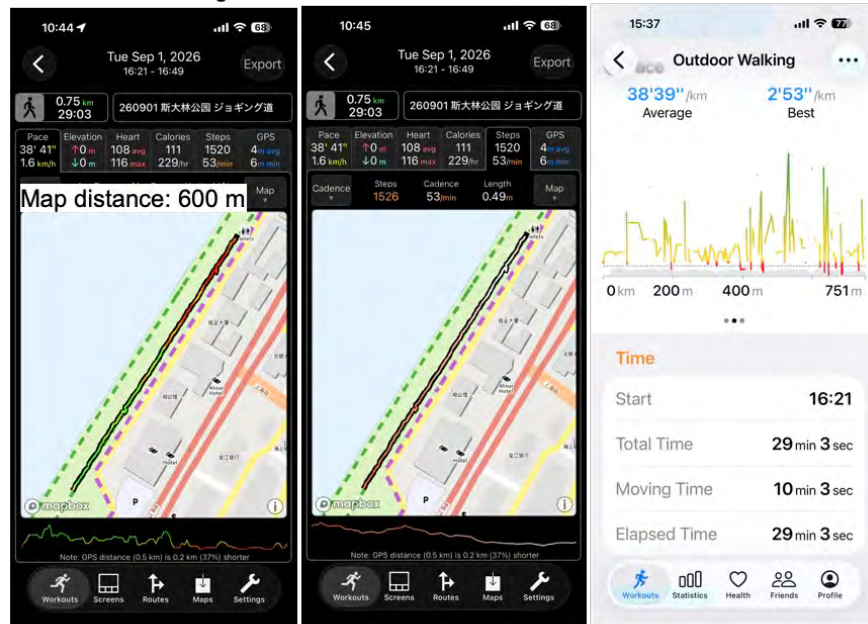
Table 2. Various walking parameters					
	Date Time	Walking speed (km/h)	Step count	Cadence (steps/min)	Step length (cm)
Test 1	260817 15:48-16:05	2.4	1665	94	43
Test 2	260820 17:25-17:54	1.6	1746	59	46
Test 3	260824 14:39-15:05	2.2	2043	79	47
Test 4	260825 16:01-16:32	1.8	1997	63	63
Test 5	260831 16:29-16:59	1.6	1674	55	50
Test 6	260901 16:21-16:49	1.6	1520	63	49
Test 7	260903 15:28-15:59	1.4	1541	49	49
Test 8	260905-1 16:03-16:16	2.0	937	68	49
Test 9	260905-2 16:21-16:29	2.5	611	77	53
Test 10	260908 16:22-16:53	2.5	2216	91	47
Test 11	260912 15:22-16:04	1.6	1726	57	46
Test 12	260918 15:02-16:11	0.9	1802	31	48
Test 13	260921 17:00-17:32	1.2	1398	41	43

- Akinetic Freezing (High FOG Ratio, Low MER):
Characterized by prolonged physical motor arrest (FOG Ratio > 0.55) accompanied by low spatial overestimation (MER < 25 %) (for example: Test 6, Figure 1A). In this state, the patient is stationary, and GPS/accelerometer algorithms correctly recognize zero distance accumulation during arrests.
- Inefficient Tremulous Gait (High MER, Variable FOG Ratio):

Characterized by severe distance inflation (MER > 40 %) (for example: Test 10, Figure 2). Micro-shuffling, leg tremors, or postural adjustments while standing or slow shuffling generate low-amplitude wrist accelerations and GPS jitter, causing the device to erroneously record distance while forward progress is minimal.

Figure 1. Example of two types of FOG

A. Akinetic freezing: Test 6. 260901 16:21-16:49



B. Inefficient Tremulous Gait: Test 10. 260908 16:22-16:53

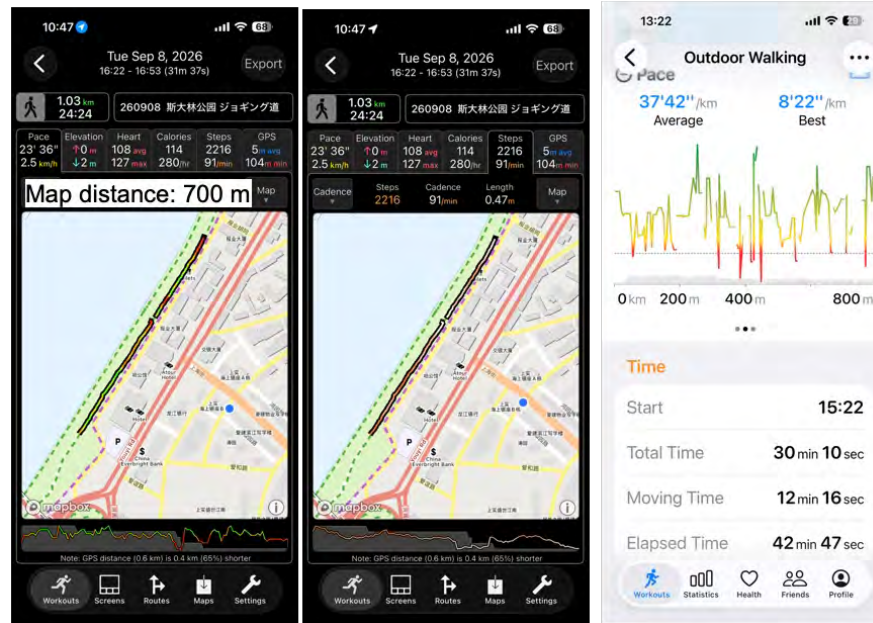


Figure 1: A quantitative sub-classification of parkinsonian gait disturbances can differentiating true temporal gait arrest (Akinetic Freezing) from spatial artifact-driven gait inefficiency (Inefficient Tremulous Gait), using two complementary telemetry metrics: the Measurement Error Rate (MER) and the FOG Ratio.

A. Example of akinetic freezing

B. Example of inefficient tremulous gait

4. Correlation Analysis (Table 3)

• FOG Ratio vs. Gait Dynamics:

FOG Ratio exhibited a very strong negative correlation with both walking speed ($r = -0.869$, $p = 0.0001$) and cadence ($r = -0.848$, $p = 0.0003$).

• MER vs. FOG Ratio:

There was no statistically significant correlation between MER and FOG Ratio ($r = 0.135$, $p = 0.6590$).

• MER vs. Gait Dynamics:

MER did not correlate with walking speed ($r = -0.096$, $p = 0.7545$), cadence ($r = -0.107$, $p = 0.7265$), or step length ($r = 0.106$, $p = 0.7297$).

Table 3. Correlation analysis			
Parameter Pair	Pearson's r	p-value	Clinical Interpretation
FOG Ratio vs. Walking Speed	-0.869	<0.001	Strong temporal validity of FOG Ratio
FOG Ratio vs. Cadence	-0.848	<0.001	Cadence reduction directly reflects freezing duration
MER vs. FOG Ratio	0.135	0.659	Orthogonal metrics; distinct pathophysiology/artifacts
MER vs. Walking Speed	-0.096	0.755	Error rate is speed-independent

5. Discussion

The most critical finding of this study is the complete independence ($r = 0.135$, $p = 0.659$) between MER (spatial error index) and FOG Ratio (temporal gait arrest index). Building upon previous systematic reviews regarding wearable sensor algorithms and our recently published evaluation of FOG telemetry and GPS distance distortion, as well as our long-term digital phenotyping and pharmacological frameworks [6-9], this mathematical orthogonality supports a quantitative two-phenotype classification of parkinsonian gait in consumer telemetry, (1) Akinetic Freezing (High FOG Ratio, Low MER) and (2) Inefficient Tremulous Gait (High MER, Variable FOG Ratio). By decoupling spatial artifacts from temporal freezing duration, researchers can avoid misinterpreting device error as functional mobility, ensuring higher fidelity in remote clinical monitoring.

6. Conclusion

Consumer smartwatch telemetry cannot be interpreted at face value in Parkinson's disease without accounting for spatial measurement artifacts. FOG Ratio and MER provide complementary, non-overlapping diagnostic value. Integrating MER into clinical gait assessments allows investigators to isolate Akinetic Freezing from artifactual Inefficient Tremulous Gait, successfully advancing objective digital health evaluations in PD.

Declarations

- **Author Contributions:** K.Y. conceived the study, interpreted the data, and wrote the manuscript. Z.L. curated the data and contributed to formal analysis. Both authors reviewed and approved the final manuscript.
- **Funding:** This research received no external funding.
- **Competing Interests:** The authors declare no competing interests.
- **Ethics Approval and Consent to Participate:** This study

analyzed anonymized self-collected gait data from a single pD patient and a healthy control. The participants provided informed consent for the use and publication of these data. According to institutional guidelines, analysis of de-identified self-tracked data did not require IRB approval.

- **Consent for Publication:** The participant provided consent for publication.
- **Data Availability:** Data are available from the corresponding author upon reasonable request.
- **Declaration of Generative AI:** During manuscript preparation, the authors utilized Google Gemini to assist with English text editing and structuring. The authors take full responsibility for the published content.

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