Heart Rate Variability Assessment via Smartwatch Detects Autonomic Dysfunction in Long COVID

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Abstract

This study investigates Postural Orthostatic Tachycardia Syndrome (POTS) as a common manifestation of autonomic dysfunction in Long COVID. We employed calibrated smartwatches for non-invasive heart rate variability (HRV) assessment across three sequential phases. Phase I compared 39 Long COVID patients to 22 healthy controls using the Tilt Test, revealing significantly increased R-R intervals ($p = 0.0136$), reduced HF power ($p = 0.0315$), and elevated LF/HF ratios ($p = 0.0316$). In Phase II, 22 participants completed smartwatch-based protocols simulating postural changes, with the supine-walking-supine protocol demonstrating superior sensitivity for detecting autonomic alterations. To clinically validate our findings, Phase III presents a case study of a 25-year-old Long COVID patient who exhibited marked tachycardia (>170 bpm), elevated LF/HF ratio (23.6), and reduced RMSSD/SDNN during the supine-walking-supine protocol—findings consistent with POTS diagnosis. Collectively, our results support the utility of smartwatches as scalable tools for early detection and remote monitoring of autonomic dysfunction in Long COVID populations.

1. Introduction

The COVID-19 pandemic has led to global research efforts to understand its systemic effects, particularly on cardiovascular autonomic regulation [1,2]. Using the Tilt Test, our group identified reduced high-frequency (HF) spectral power in HRV among Long COVID patients, indicating autonomic dysfunction with sympathetic predominance [3].

A common clinical outcome is Postural Orthostatic Tachycardia Syndrome (POTS), associated with presyncope, fatigue, and syncope. Early detection is essential for proper management. The Tilt Test, the gold standard for evaluating autonomic response, involves a 50-minute protocol divided into three phases (supine, tilted, supine), enabling precise analysis of sympathetic-parasympathetic balance[4].

Given its cost and complexity, this study explores calibrated smartwatches as non-invasive alternatives for detecting HRV abnormalities. Across three phases, Tilt Test data were compared to smartwatch-based protocols. Results showed strong convergence, supporting the feasibility of wearable technologies for early screening and longitudinal monitoring of autonomic dysfunction [3,5].

1.1. Hypothesis and objectives

It is hypothesized that calibrated smartwatches can effectively detect autonomic dysfunctions—particularly Postural Orthostatic Tachycardia Syndrome (POTS)—in individuals with Long COVID, through non-invasive heart rate variability (HRV) monitoring. This wearable-based strategy may demonstrate strong agreement with conventional diagnostic tools, such as the Tilt Table Test.

The objective of this study is to validate the clinical utility of smartwatches for the early identification of POTS by comparing HRV metrics obtained from wearable devices to those from the Tilt Table Test. Additionally, it aims to assess the potential autonomic effects associated with different COVID-19 vaccine platforms, including mRNA, viral vector, and inactivated virus formulations.

2. Materials and Methods

2.1. Materials

The study utilized Smartwatch Samsung Galaxy 4 equipped with photoplethysmography (PPG) sensors sampling at 80 Hz, Application developed and validated by our research team [5]. These consumer-grade devices were calibrated against clinical-grade ECG equipment prior to data collection. While not certified as medical devices, their affordability and accessibility make them suitable for large-scale screening applications.

2.2. Participants

The study included three experimental phases. In Phase I, 61 volunteers participated: 39 individuals with Long COVID and 22 healthy controls. In Phase II, 22 healthy individuals underwent wearable-based HRV protocols. In Phase III, a single case of a 25-year-old female patient with Long COVID was analyzed to demonstrate the clinical application (CEP, CAAE: 64561022.7.0000.5497. 3).

2.3. Inclusion and Exclusion Criteria

Inclusion criteria included: age between 18 and 75 years, no current pregnancy, negative COVID-19 PCR test (when relevant), absence of known cardiovascular or neurological diseases, and no continuous use of medications that affect the autonomic nervous system. Individuals previously infected with COVID-19 were excluded from control and vaccine subgroups.

2.4. Protocol

Phase I: participants completed a 50-minute Tilt Test, with HRV assessed via continuous ECG and blood pressure monitored every minute. Time and frequency domain parameters (SDNN, RMSSD, LF, HF, LF/HF) were analyzed across supine–tilt–recovery phases.

Phase II: Smartwatch-based protocols simulated everyday activities: Protocol 1 (seated–walking–seated): 6 minutes seated, 6 minutes walking at 3.5 km/h, and 7 minutes seated. Protocol 2 (supine–walking–supine): 6 minutes lying down, 6 minutes walking, and 7 minutes lying down again. These were designed to mimic the autonomic challenge induced by the tilt test. The Protocol 2 was particularly sensitive in replicating postural stress and recovery phases.

Phase III: Smartwatch data collection during light walking to assess cardiovascular response. The protocol is designed to capture physiological metrics—specifically HR, the LF/HF ratio, and time-domain indices (RMSSD/SDNN)—that are indicative of the autonomic patterns associated with POTS.

2.5. Data Processing

All HRV data (ECG and smartwatch-based) were processed using statistical software Jamovi (for tests such as Mann-Whitney, repeated measures ANOVA) and Power BI (for dashboard visualizations integrating demographic, clinical, and HRV data). Time-domain and frequency-domain analyses followed standard signal processing protocols. Wearable data were synchronized with the app and extracted in RR interval format for analysis.

3. Results

The results were structured into three phases based on HRV analysis via smartwatches in Long COVID patients. Phase I involved smartwatch calibration using Tilt Test data to compare Long COVID patients and healthy controls. Phase II tested two smartwatch-based protocols simulating daily activities, with the supine–walking–supine sequence showing higher sensitivity to autonomic alterations. Phase III presented a clinical case consistent with POTS, reinforcing previous findings and the diagnostic potential of wearable technologies.

3.1. Phase I: Calibration

Smartwatches were calibrated against ECG data collected during the Tilt Test.

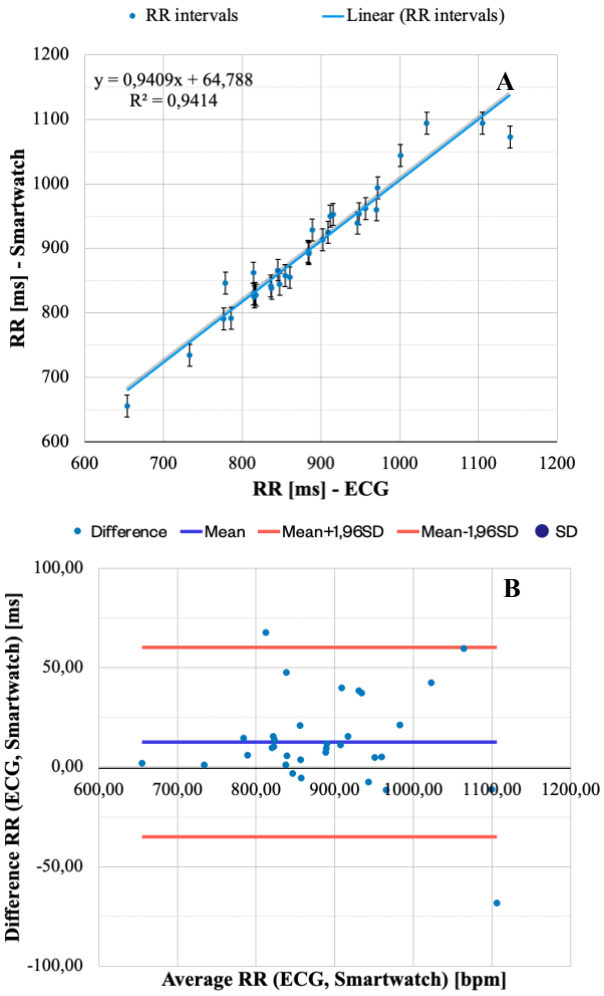

Figure 1. A) RR interval correlation. D) Bland-Altman plot for RR intervals. Source: original data from the author.

The comparison showed strong agreement, with a Pearson correlation coefficient of R = 0.98 and a mean absolute error of approximately 1 bpm. Correlation plots and Bland-Altman diagrams demonstrated accuracy for both heart rate and RR intervals, validating the wearable devices for clinical HRV assessment (Figure 1). The application used in the smartwatch operated at a high sampling rate, and data visualization was performed using dynamic dashboards in Power BI and Python.

Following calibration, the Tilt Test was applied to 61 participants (39 Long COVID patients and 22 healthy controls). The Long COVID group exhibited significantly increased mean R-R interval (p = 0.0136), reduced high-frequency (HF) power (p = 0.0315), and an elevated LF/HF ratio (p = 0.0316), indicating autonomic imbalance with sympathetic predominance and parasympathetic withdrawal. Intra-group analysis also revealed impaired autonomic recovery following the orthostatic phase, with persistent RR instability and incomplete normalization of LF and HF components ($p < 0.0001$), as illustrated in the spectral HRV comparisons (Table 1).

Table 1. HRV parameters. (1) in [s]; (2) in [%]; (3) normalized value, (*) p-value < 0.05.

	Supine		Up-right		Recovery	
	CG	SG	CG	SG	CG	SG
Mean RR[1]	0.90 ±0.15	0.92 ±0.12	0.70* ±0.07	0.78* ±0.14	0.93 ±0.16	0.96 ±0.12
SDNN[1]	0.06 ±0.03	0.04 ±0.03	0.04 ±0.01	0.04 ±0.02	0.055 ±0.03	0.058 ±0.04
RMSSD[1]	0.04 ±0.03	0.03 ±0.01	0.019 ±0.01	0.022 ±0.02	0.03 ±0.01	0.03 ±0.01
pNN50[2]	17.7 ±15.8	11.9 ±14.1	3.27 ±3.95	6.18 ±11.1	17.8 ±14.3	16.2 ±15.8
Triangular Index	14.0 ±5.7	11.4 ±4.3	11.5 ±3.8	10.8 ±4.6	13.0 ±4.3	13.7 ±5.4
TINN[1]	0.20 ±0.08	0.17 ±0.06	0.17 ±0.06	0.16 ±0.07	0.20 ±0.07	0.20 ±0.07
LF[3]	53.2 ±17.3	57.8 ±14.1	79.3* ±10.1	70.4* ±19.5	54.7 ±14.0	56.6 ±17.3
HF[3]	46.8 ±17.3	42.1 ±14.1	20.7* ±10.14	29.7* ±19.6	45.3 ±14.1	43.4 ±17.3
LF/HF	1.49 ±1.10	1.73 ±1.28	5.80* ± 5.10	4.21* ±3.48	1.44 ±0.82	1.96 ±2.06

3.2. Phase II: Everyday Activities

To assess autonomic responses in daily-life conditions, two smartwatch-based protocols of 21 minutes each were applied to 22 healthy participants, following prior calibration using the standard Tilt Test. Protocol 1 consisted of seated – walking – seated, whereas Protocol 2 involved supine – walking – supine. Due to the postural shifts from supine to standing, Protocol 2 elicited stronger autonomic activation, as expected from the physiological demands of venous return and baroreflex engagement.

As shown in Figure 2 (A–D), control participants (Panels A and B) exhibited smooth and physiologically consistent RR interval transitions across phases. In contrast, Long COVID participants (Panels C and D) demonstrated reduced modulation and abrupt transitions, particularly during the walking phase, suggesting impaired autonomic adaptability. These alterations mirror the blunted vagal recovery and exaggerated sympathetic dominance commonly observed in the Tilt Test during Phase I in Long COVID patients, reinforcing the presence of autonomic dysregulation.

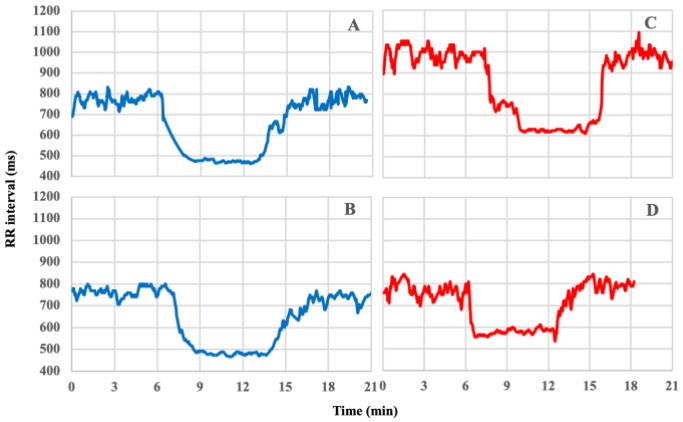

Figure 2. RR interval dynamics during smartwatch-based monitoring. (A) Control group, male (CG-M); (B) Control group, female (CG-F); (C) Long COVID group, male (LC-M); (D) Long COVID group, female (LC-F). Protocol structure: Phase 1 (rest), Phase 2 (walking), Phase 3 (recovery).

HRV parameters extracted from ECG, SW-P1, and SW-P2 signals were compared across the three phases of the protocol (Baseline, Walking, and Return). During Baseline, mean RR intervals were comparable across methods (ECG: 0.81 s; SW-P1: 0.79 s; SW-P2: 0.75 s), although variability indices (SDNN and RMSSD) were systematically reduced in smartwatch signals, indicating an underestimation of beat-to-beat fluctuations. In the Walking phase, mean RR intervals decreased across all systems (ECG: 0.57 s; SW-P1: 0.50 s; SW-P2: 0.46 s).

However, RMSSD from smartwatch measurements severely approached zero, suggesting substantial signal smoothing or loss of high-frequency dynamics in motion. In the Return phase, ECG values showed recovery (Mean RR: 0.89 s; RMSSD: 0.03 s), while smartwatch recordings demonstrated lower HRV estimates (RMSSD ≈ 0.01 s).

Spectral indices consistently showed that smartwatch-derived signals reported higher LF power and lower HF power, resulting in markedly elevated LF/HF ratios (e.g., Baseline LF/HF: ECG 1.85 vs. SW-P1 5.61 and SW-P2 8.61), suggesting a systematic bias toward sympathetic dominance. Overall, compared to ECG, smartwatch-derived HRV signals reproduced global heart rate trends, but underestimated HRV amplitude and overestimated the LF/HF ratio, particularly under movement conditions.

Importantly, no statistically significant differences were observed between the smartwatch and ECG measures across the three phases, indicating that both smartwatch protocols can reliably capture autonomic patterns associated with postural and activity transitions.

3.3. Phase III: Case POTS

It was implemented a structured remote monitoring protocol using a consumer-grade smartwatch enabled the identification of characteristic autonomic dysfunction patterns consistent with POTS in a post-COVID patient. Analysis of the RR interval tachogram obtained through the smartwatch demonstrated a pathological cardiovascular response during the orthostatic challenge phase (i.e., light walking). Specifically, during the light walking phase (3.0 km/h for 7 minutes), the device recorded a marked reduction in RR intervals to 600–800 ms, corresponding to heart rates reaching 171 bpm. This HR represents 87.7% of the theoretical maximum HR for the patient's age, indicating vigorous exercise intensity despite the minimal physical demand of slow walking. Furthermore, the analysis showed elevated LF/HF ratio and reduced RMSSD/SDNN, indicating sympathetic predominance with parasympathetic withdrawal, consistent with the observed clinical syndrome.

4. Discussion

The potential long-term impact of COVID-19 on autonomic regulation remains under investigation. This study employed smartwatch-based protocols simulating postural transitions and identified altered HRV patterns in Long COVID patients, supporting evidence of persistent autonomic dysfunction[5].

The "supine–walking–supine" smartwatch protocol (Protocol 2) demonstrated enhanced physiological sensitivity, particularly during transitions involving orthostatic stress and recovery phases (Figure 3). Healthy individuals exhibited gradual and stable modulation of RR intervals across different phases, consistent with expected sympathetic and parasympathetic responses. In contrast, Long COVID participants showed abrupt fluctuations and reduced HRV amplitude, suggestive of autonomic dysfunction and impaired baroreflex sensitivity. These findings were consistent with standard ECG-based Tilt Test results, reinforcing the clinical relevance of calibrated wearable devices for remote autonomic screening[3,6].

Calibrated smartwatches offer significant advantages for autonomic monitoring, including continuous non-invasive assessment, real-world applicability, and early detection capability for conditions like POTS. Their portability facilitates integration into remote monitoring and rehabilitation programs. Although strong agreement with ECG was observed, confirmation through gold-standard Tilt Testing remains crucial for clinical applications.

Study limitations include the modest sample size and absence of concurrent ECG in all protocols. Future research should focus on algorithm refinement, expanded cohort diversity, and validation of predictive models for personalized autonomic management.

Acknowledgments

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