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. Using calibrated smartwatches for non-invasive heart rate variability (HRV) assessment, the study was conducted in three phases. Phase I compared 39 Long COVID patients to 22 healthy controls via Tilt Test, revealing 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 showing greatest sensitivity. Phase III reported a case of a 25-year-old Long COVID patient with tachycardia >170 bpm, LF/HF = 23.6, and reduced RMSSD/SDNN—findings consistent with POTS. Results support the utility of smartwatches as scalable tools for early detection and remote monitoring of autonomic dysfunction.

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.

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 (FAPESP Project 21/14231-0)

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

Follow the information given in Table 1 for all font print sizes and styles.

2.2 Sample

The study included three experimental phases. In Phase I,

61 volunteers participated: 39 individuals with Long COVID and 22 healthy controls. For the vaccine subanalysis, 29 healthy individuals (no prior COVID-19) were divided into three groups according to the vaccine type received: viral vector (n=9), inactivated virus (n=10), and mRNA (n=10). 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.

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

In 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.

In 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.

In Phase III, smartwatch data from the female patient during Protocol 2 revealed HR >170 bpm during light walking (~88% of predicted max HR), with significant LF/HF elevation (23.6) and RMSSD/SDNN reductions — indicating sympathetic overactivation consistent 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 1 - Tilt Test Calibration and Comparative Assessment of Autonomic Dysfunction in Long COVID Patients

In Phase I, smartwatches were calibrated against electrocardiogram (ECG) data collected during the Tilt Test. 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).

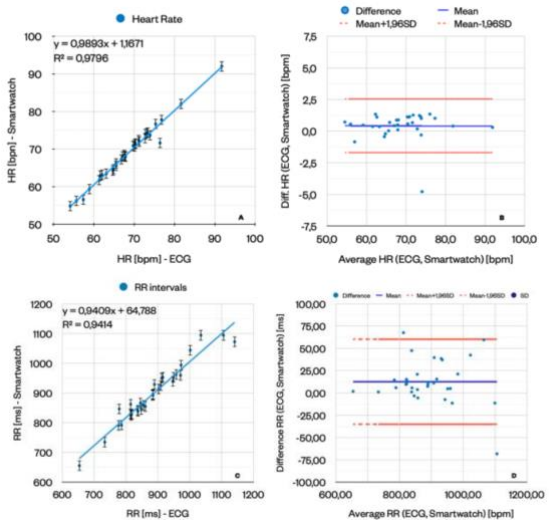

Figure 1. Smartwatch Calibration vs ECG: A) Heart rate correlation. B) Bland-Altman plot for heart rate. C) RR interval correlation. D) Bland-Altman plot for RR intervals. Source: original data from the author.

Table 1. HRV parameters.

	Phase 1			Phase 2			Phase 3		
	Control	Long Covid-19		Control	Long Covid-19		Control	Long Covid-19	
	Mean (CI95%)	Mean (CI95%)	p (value)	Mean (CI95%)	Mean (CI95%)	p (value)	Mean (CI95%)	Mean (CI95%)	P (value)
	Time Domain								
Mean RR	0.9155 (0.8458 - 0.9853)	0.9329 (0.8918 - 0.9740)	0.5374	0.7005 (0.6672 - 0.7337)	0.7825 (0.7370 - 0.8280)	0.0136 (*)	0.9421 (0.8694 - 1.015)	0.9665 (0.9266 - 1.007)	0.3976
SDNN	0.0600 (0.0437 - 0.0763)	0.04910 (0.0402 - 0.0580)	0.2959	0.0433 (0.0369 - 0.0498)	0.04299 (0.0356 - 0.0503)	0.4416	0.0555 (0.0435 - 0.0676)	0.0596 (0.0479 - 0.0713)	0.7667
RMSSD	0.0359 (0.0289 -0.0428)	0.0304 (0.0253 - 0.0355)	0.1606	0.0196 (0.0160 - 0.0233)	0.0229 (0.0184 - 0.0275)	0.5994	0.03680 (0.0304 - 0.0432)	0.03557 (0.0300 - 0.0411)	0.6425
pNN50	18.51 (11.33 - 25.68)	12.74 (8.014 - 17.47)	0.1653	3.383 (1.566 - 5.200)	6.663 (2.910 - 10.42)	0.9425	18.32 (11.78 - 24.87)	17.19 (11.96 - 22.42)	0.6288
Triangular Index	14.00 (11.42 - 16.59)	11.69 (10.26 - 13.11)	0.2306	11.42 (9.672 - 13.17)	11.05 (9.503 - 12.59)	0.4529	12.85 (10.87 - 14.84)	14.07 (12.32 - 15.83)	0.2889
TINN	0.2097 (0.1702 - 0.2492)	0.1724 (0.1518 - 0.1930)	0.1845	0.1737 (0.1452 - 0.2022)	0.1684 (0.1431 - 0.1937)	0.4391	0.1944 (0.1605 - 0.2284)	0.2091 (0.1839 - 0.2343)	0.3191
	Frequency Domain								
LF[n]	52.94 (44.92 - 60.96)	56.44 (52.11 - 60.77)	0.3035	79.06 (74.37 - 83.74)	68.87 (62.55 - 75.19)	0.0316 (*)	54.70 (48.18 - 61.22)	55.45 (49.55 - 60.96)	0.5000
HF[n]	47.06 (39.04 - 55.08)	43.56 (39.23 - 47.89)	0.3035	20.94 (16.26 - 25.63)	31.13 (24.81 - 37.45)	0.0315 (*)	45.30 (38.78 - 51.82)	44.55 (39.04 - 50.05)	0.5000
LF/HF	1.507 (1.000 - 2.014)	1.550 (1.239 -1.861)	0.3035	5.908 (3.549 - 8.267)	3.808 (2.776 - 4.841)	0.0316 (*)	1.454 (1.071 - 1.837)	1.846 (1.184 - 2.508)	0.5000

3.2 Phase II – Smartwatch-Based Daily Activity Protocols

To assess autonomic responses in everyday contexts two 19-minute smartwatch-based protocols were applied to 22 healthy participants, following prior calibration with the Tilt Test. Protocol 1: seated – walking – seated, Protocol 2: supine – walking – supine

Protocol 2 elicited stronger autonomic responses due to the physiological demands of postural transitions. As illustrated in Figure 3, control participants exhibited regular RR interval patterns, while Long COVID individuals showed reduced or abrupt variability, suggesting autonomic dysfunction. These alterations, also reflected in Figure 3, are consistent with those observed in the Tilt Test during Phase I.

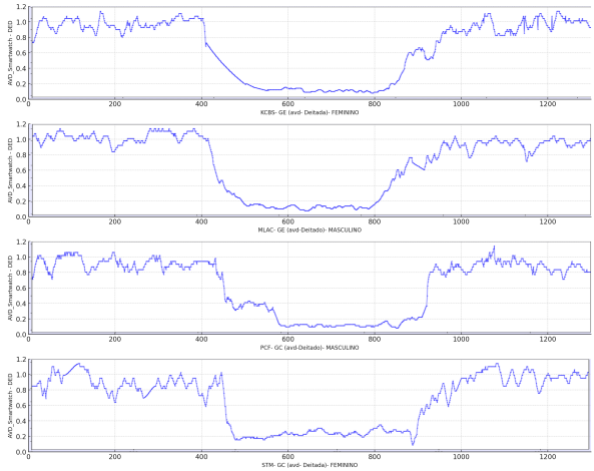

Figure. RR interval.

Figure 3 shows RR interval recordings obtained via smartwatch from four participants: a female with Long COVID (study group), a male with Long COVID (study group), a healthy male (control group), and a healthy female (control group).

3.3. Phase III – Online Detection of POTS: Long COVID Case Study

To enhance our understanding of smartwatch performance in detecting autonomic dysfunction, a 25-year-old female with Long COVID completed the remote supine–walking–supine protocol.

During the walking phase, heart rate peaked at aproximately 171 bpm, representing ~88% of her predicted maximum. Smartwatch data (SW-P2) showed an elevated LF/HF ratio of 23.6, along with reduced RMSSD and SDNN. Similar patterns were confirmed by ECG.

Table 4 compares HRV parameters across ECG, SW-P1, and SW-P2, showing that SW-P1 yielded values more consistent with ECG, particularly in both time and frequency domains.

	Phase 1				Phase 2				Phase 3			
	ECG	SW-P1	SW-P2		ECG	SW-P1	SW-P2		ECG	SW-P1	SW-P2	
	Time - Domain											
Mean RR (ms)	0,81	0,79	0,75		0,57	0,50	0,46		0,89	0,76	0,76	
SDNN (ms)	0,05	0,05	0,04		0,05	0,06	0,02		0,05	0,03	0,05	
RMSSD	0,03	0,01	0,01		0,01	0,003	0		0,03	0,01	0,01	
	Frequency - Domain											
LF (nu)	64,9	84,9	89,6		85,6	85,3	76,4		51,3	94,4	89,8	
HF (nu)	35,1	15,1	10,4		14,4	14,7	23,6		48,7	5,63	10,2	
LF/HF	1,85	5,61	8,61		5,97	5,8	23,6		1,05	16,8	8,79	

Table 4 presents heart rate variability (HRV) parameters of patient CMJ (25 years old, female) obtained through three data collection protocols—ECG,

SW-P1, and SW-P2—across the three experimental phases: Phase 1 (rest), Phase 2 (tilt/walking), and Phase 3 (recovery).

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.

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.

The case study of a 25-year-old female patient further highlighted the diagnostic potential of smartwatch-based monitoring (Figure 4). During low-intensity walking, the patient exhibited marked tachycardia (~171 bpm), reaching approximately 88% of her predicted maximum heart rate. HRV analysis revealed an extremely elevated LF/HF ratio (23.6) and pronounced reductions in RMSSD and SDNN, indicating sympathetic overactivity and parasympathetic withdrawal—a pattern highly consistent with Postural Orthostatic Tachycardia Syndrome (POTS). These alterations were corroborated by ECG data, although with slightly lower intensity, validating the reliability of smartwatch-derived metrics.

The application of calibrated smartwatches in this context offers multiple advantages: continuous, non-invasive monitoring, applicability in real-world settings, and potential for early detection of autonomic conditions such as POTS or orthostatic intolerance. Their portability and ease of use support integration into remote follow-up strategies and rehabilitation programs. Nevertheless, despite the strong convergence between smartwatch and ECG data, confirmation using gold-standard diagnostic protocols such as the Tilt Test remains essential, particularly for clinical decision-making.

Despite promising results, limitations include small sample size and lack of ECG in all wearable protocols. Future studies should refine algorithms, broaden sample diversity, and validate predictive models for personalized autonomic care.

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