

Diagnostic Value of Synchronous Heart Sound Electrocardiogram in Children with Postural Tachycardia Syndrome

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Background: Postural tachycardia syndrome (POTS) is a common autonomic dysfunction in children. The head-up test (HUT) or head-up tilt test (HUTT) is typically required to confirm the diagnosis of POTS. This study describes a novel approach to diagnosing POTS in children by simultaneous measurement and analysis of heart sounds and electrocardiogram (ECG) signals using a wearable device.

Objective: To evaluate the diagnostic value of synchronous heart sound and ECG monitoring in identifying POTS in children.

Methods: This study included a total of 50 children. Twenty-five children with POTS were admitted to the hospital with symptoms of syncope or orthostatic intolerance, while twenty-five children who came to the hospital for a health checkup were included as the control group. All children underwent synchronous phonocardiography and ECG monitoring with wearable devices to simultaneously record heart sounds and ECG signals. Wavelet analysis was used to automatically analyze heart sounds and ECG signals to determine the Electromechanical Activity Time (EMAT).

Results: In the POTS group, EMAT decreased significantly from supine to upright position (75.71 ± 9.16 ms vs 70.90 ± 10.86 ms, $P = 0.0051$), while the change in the control group was not significant (58.92 ± 4.10 ms vs 55.50 ± 9.89 ms, $P = 0.100$). The difference in EMAT change (upright-supine) was significantly greater in the POTS group (3.39 ± 5.91 ms) than in controls (0.58 ± 5.70 ms, $P = 0.038$). Precision-recall curve (PRC) analysis demonstrated that the average precision (AP) for EMAT in the supine position was 0.84, while the AP for the upright position was 0.88.

Conclusion: Simultaneous heart sound and ECG analysis using a wearable device is a simple, noninvasive approach that aids in the diagnosis of pediatric POTS. EMAT serves as a valuable discriminative marker between patient groups.

Keywords: cardiac function, electromechanical activity time, postural tachycardia syndrome, heart sounds and ECG, wearable cardiac devices

Introduction

In children with Postural tachycardia syndrome (POTS), redistribution of blood upon standing due to gravity, increased sympathetic tone, decreased vagal activity resulting from muscle pump dysfunction, autonomic dysregulation, hyperadrenergic state, and autoimmunity contribute to reduced venous return and cardiac output.¹⁻⁵ These alterations can lead to recurrent syncope, seriously impacting the physical and mental health and quality of life of affected children. Therefore, identifying a simple, feasible, and cost-effective method for diagnosing and monitoring POTS is crucial.⁴⁻⁶ Prior studies have indicated that the intensity of the first heart sound correlates positively with cardiac systolic function and may be used to assess physical activity tolerance in patients.⁷ Evaluation of the relationship between electrocardiogram (ECG) and heart sounds may assist in identifying patients with POTS.⁸

Electromechanical activation time (EMAT) is defined as the interval from the onset of the QRS complex on ECG to the first heart sound (S1, mitral valve closure), reflecting the time from electrical excitation to mechanical contraction of the myocardium.⁹ A shorter EMAT is associated with more efficient myocardial contraction. In this study, we employed a novel wearable patch to simultaneously record heart sounds and ECG signals.¹⁰ Analysis of these signals can help determine correlations with left ventricular ejection fraction.^{11,12}

Research Methods and Resources

Empowerment

This study was approved by the First Affiliated Hospital of the Medical College of Shihezi University Scientific and Technological Ethics Committee. All participants and their guardians provided written informed consent after being fully informed of the study's purpose, content, and methods.

Study Subjects

From December 2022 to September 2024, fifty consecutive outpatients or inpatients were enrolled: 25 children with POTS (diagnosed by head-up tilt test [HUT/HUTT]) and 25 healthy controls.

Inclusion Criteria

- ① POTS was diagnosed according to the Chinese Medical Association's Pediatric Syncope Guidelines (2016 Revision);¹³
- ② Age between 5 and 14 years;
- ③ Complete clinical data;
- ④ Written informed consent from guardians.

Exclusion Criteria

- ① History of surgery, metabolic disease (such as chronic renal failure, hypertension, obesity, diabetes), cardiovascular disease (congenital heart disease, arrhythmia), or neurological disorders;
- ② Use of hormone drugs or renin-angiotensin-aldosterone system inhibitors within 3 months;
- ③ Noncooperation during HUTT;
- ④ Refusal to sign informed consent;
- ⑤ Incomplete clinical data.

Data Collection

Heart Sound and ECG Signals Were Acquired Synchronously

The study used a wearable synchronous heart sound ECG data sensor acquisition system developed by Wenxin Technology Company (Beijing, China). The device consists of a reusable central component and a single-use patch (Figure 1). The disposable patch is stuck on the central piece and then attached to the chest wall of the patient. The 2 circular patches are the electrodes for the single-lead ECG. The sound sensor is in the center of the reusable part. The device can automatically detect ECG and heart sounds at the same time and digitize the signal and send it to a smartphone or tablet via Bluetooth. The data can also be sent to a cloud-based data center for archiving and analysis (Figures 2 and 3).

Heart Sound and Electrocardiogram Related Indicator Tests

① Mi-Ti: The time between mitral valve closure and tricuspid valve closure. ② Az-P2: Time between aortic valve closure and pulmonary valve closure. ③ EMAT: Heart electromechanical activation time represents the time from the onset of ventricular excitation to mitral valve closure, that is, the time from ORs wave initiation to M1. ④ LVST (left ventricular systolic time): Representing the time interval from S1 to S2 (Figure 2). ⑤ LVET (Left Ventricular Ejection Time) is the duration of blood ejection from the left ventricle into the aorta during systole, reflecting ventricular contractile efficiency and aortic valve function.

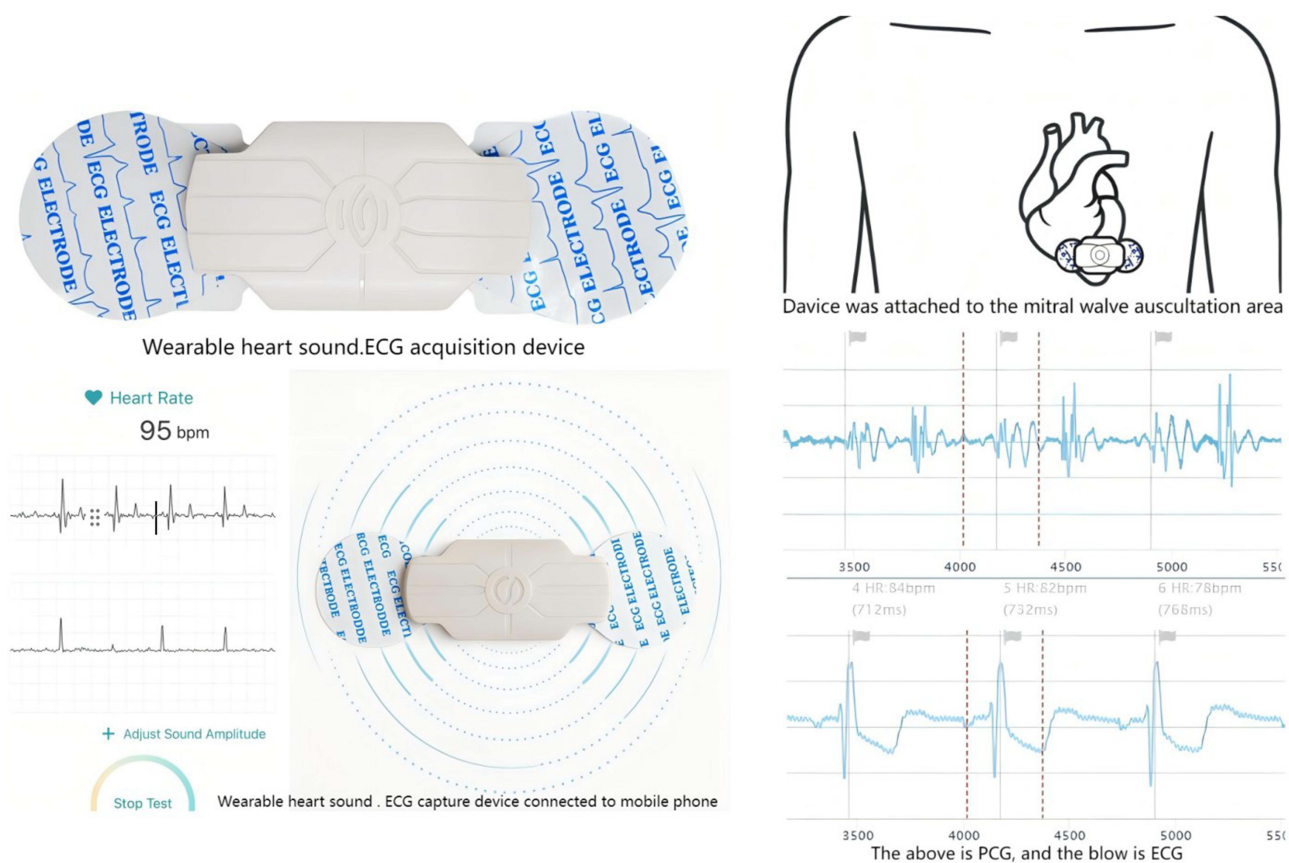


Figure 1 Operation flow of wearable heart-ECG monitoring device.

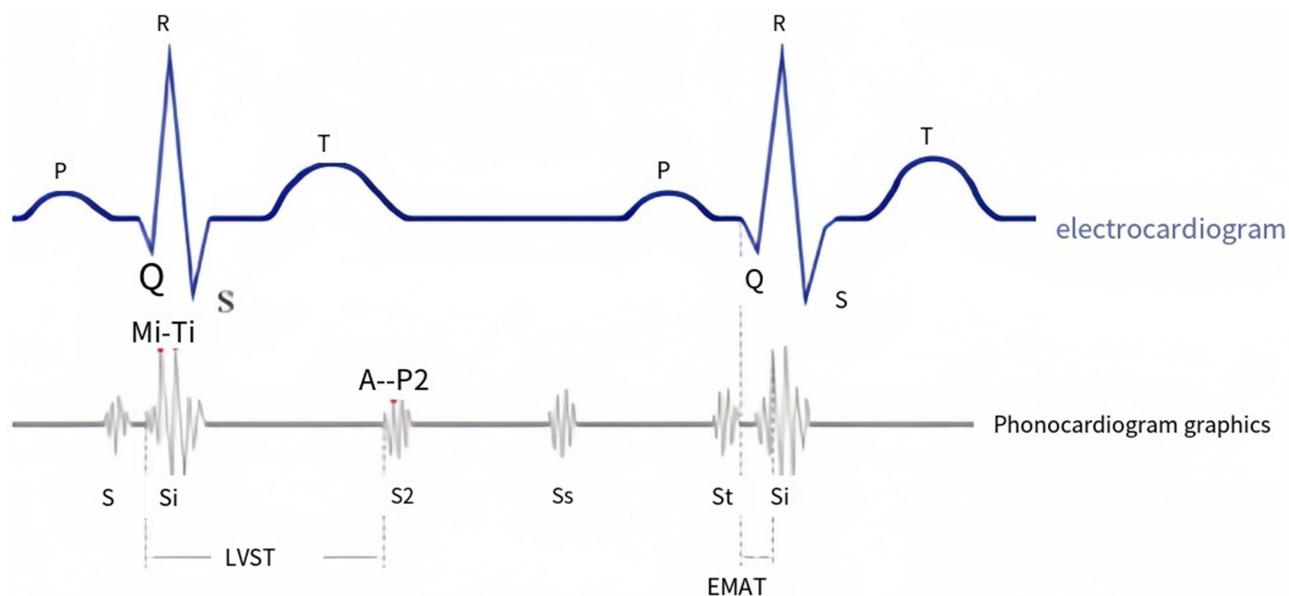


Figure 2 Example heart sound ECG. Mi-Ti: The time between mitral valve closure and tricuspid valve closure. Az-P2: Time between aortic valve closure and pulmonary valve closure. EMAT: Heart electromechanical activation time (electromechanical activation time) represents the time from the onset of ventricular excitation to mitral valve closure, that is, the time from ORs wave initiation to MI. LVST: left ventricular systolic time, representing the time interval from S1to S2.

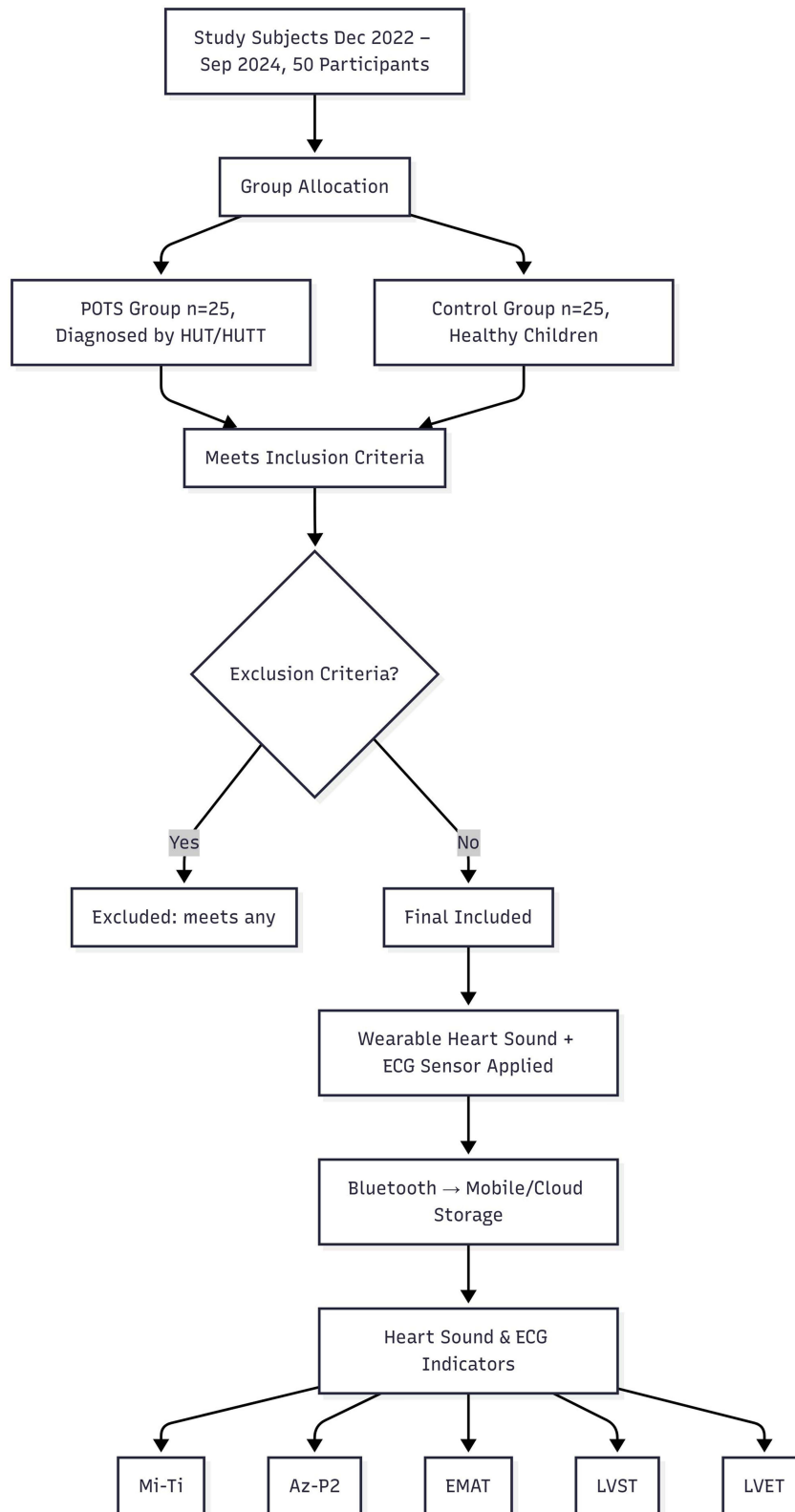


Figure 3 Flow chart.

Statistical Analysis

Based on the results of the normality test of the data, intergroup comparisons between the experimental and control groups were performed as follows: if the data conformed to a normal distribution (verified by the Shapiro–Wilk test), an independent samples *t*-test was used and expressed as the mean±standard deviation ($\bar{x} \pm s$); if the data were not normally distributed, a Mann–Whitney *U*-test was used, and the distribution was characterized by the median and interquartile range (IQR) to characterize the distribution. Two-way ANOVA was used to evaluate the effects of different groups (POTS vs control) and body positions (supine vs upright) on EMAT values. Precision-recall curve (PRC) was used for parameters associated with the diagnosis of postural tachycardia syndrome. SPSS 26.0 software (IBM, USA) was used for statistical analysis. $P < 0.05$ was considered statistically significant.

Results

Comparison of Gender, Age and Body Mass Index (BMI) Between POTS Group and Control Group

Age Characteristics

The age distribution was similar in both groups, with a mean age of 9 ± 5 years (median 11 years, interquartile distance 4) in the POTS group and 9 ± 5 years (median 10 years, interquartile distance 3) in the control group. The Mann–Whitney *U*-test showed no statistical difference in age between the two groups ($U = 261.5$, $p = 0.317$) (Table 1).

Gender Composition

The male-to-female ratio was 13:12 in the POTS group and 15:10 in the control group, and the gender distribution was generally balanced between the two groups (Table 1).

Bmi

The mean value of BMI was 13.8 ± 1.2 kg/m² (median 14.0, IQR 12.5–15.0) in the POTS group and 13.7 ± 1.1 kg/m² (median 13.8, IQR 12.5–14.9) in the control group. Statistical analysis based on non-parametric tests showed that the difference in BMI between the two groups was not statistically significant ($U = 301.0$, $P = 0.682$) (Table 1).

The POTS group and the control group were comparable in terms of baseline characteristics such as age, gender and BMI ($P > 0.05$), which met the balanced requirements for case-control studies (Table 1).

Table 1 Comparison of Age, Gender and BMI Between POTS Group and Control Group

	POTS Group	Control Group
Number of cases (n)	25	25
Age ($\bar{x} \pm s$) years	9 ± 5	9 ± 5
Gender (female/male)	12/13	10/15
Age Median	11	10
Age IQR	13 - 9 = 4	12 - 9 = 3
Age U value (POTS-Control group)	261.5	
Age P value (POTS-Control group)	0.317	
BMI ($\bar{x} \pm s$) (kg/m ²)	13.8 ± 1.2	13.7 ± 1.1
BMI Median	14.0	13.8
BMI IQR	12.5–15.0	12.5–14.9
BMI U value (POTS-Control group)	301.0	
BMI P value (POTS-Control group)	0.682	

The control group showed no significant orthostatic tachycardia, with mean supine and upright heart rates of 78.38 ± 9.56 bpm and 78.08 ± 13.63 bpm, respectively ($P = 0.8434$), whereas the POTS group exhibited a dramatic increase on standing from 81.04 ± 9.88 bpm to 111.04 ± 9.88 bpm ($P < 0.0001$) (Table 2).

Details electromechanical intervals in POTS patients ($n = 25$): EMAT shortened significantly from 75.71 ± 9.16 ms supine to 70.90 ± 10.86 ms upright ($P = 0.0051$), and EMAT% rose from $9.18 \pm 1.43\%$ to $11.58 \pm 1.50\%$ ($P < 0.001$). Left ventricular ejection time (LVET) fell from 277.58 ± 23.18 ms to 231.44 ± 29.07 ms ($P < 0.001$), and corrected LVET decreased from 2366.25 ± 220.35 to 2293.78 ± 266.40 ($P = 0.043$) (Table 3).

Control subjects also experienced a non-significant reduction in EMAT (58.92 ± 4.10 ms to 55.50 ± 9.89 ms; $P = 0.100$) and a modest rise in EMAT% ($10.04 \pm 1.41\%$ to $10.83 \pm 0.72\%$; $P = 0.022$) on standing. LVET shortened markedly from 257.67 ± 23.43 ms to 217.58 ± 17.30 ms ($P < 0.001$), and corrected LVET declined from 2591.33 ± 193.61 to 2371.92 ± 186.95 ($P < 0.001$) (Table 4).

Compared to POTS versus controls: raw EMAT was significantly longer in POTS than controls in both supine and upright positions ($P < 0.001$), while EMAT% differences ($P = 0.154$ supine, 0.147 upright) and upright LVET ($P = 0.188$) were not significant. Supine LVET ($P = 0.048$) and supine corrected LVET ($P = 0.014$) did differ between groups (Table 5).

Table 2 Comparison of Supine and Upright Heart Rates Between Control and POTS Groups

Group	Supine Heart Rate (bpm)	Upright Heart Rate (bpm)	P-Value
Control	78.38 ± 9.56	78.08 ± 13.63	0.8434
POTS	81.04 ± 9.88	111.04 ± 9.88	<0.0001

Table 3 POTS Group ($n=25$)

	Supine	Upright	Supine-Upright P Value
EMAT (milliseconds, ms)	75.71 ± 9.16	70.90 ± 10.86	0.0051
EMAT%	9.18 ± 1.43	11.58 ± 1.50	<0.001
LVET (ms)	277.58 ± 23.18	231.44 ± 29.07	<0.001
LVET Correction	2366.25 ± 220.35	2293.78 ± 266.40	0.043

Table 4 Control Group ($n=25$)

	Supine	Upright	Supine -Upright P value
EMAT (ms)	58.92 ± 4.1	55.50 ± 9.89	0.100
EMAT%	10.04 ± 1.41	10.83 ± 0.72	0.022
LVET (ms)	257.67 ± 23.43	217.58 ± 17.30	<0.001
LVET Correction	2591.33 ± 193.61	2371.92 ± 186.95	<0.001

Table 5 POTS Group-Control Group P value

	Supine	Upright
EMAT (ms)	<0.001	<0.001
EMAT%	0.154	0.147
LVET (ms)	0.048	0.188
LVET Correction	0.014	0.438

Notes: Values are given as average \pm SD unless otherwise stated. LVET correction= $\sqrt{\text{LVET} \times \text{HR}}$, EMAT%=(QSI/RR)/(QSI/sqrt(RR)).

Abbreviation: LVET, left ventricular ejection time.

Table 6 Comparison of Differences Between Upright and Supine Positions Between Control and POTS Groups

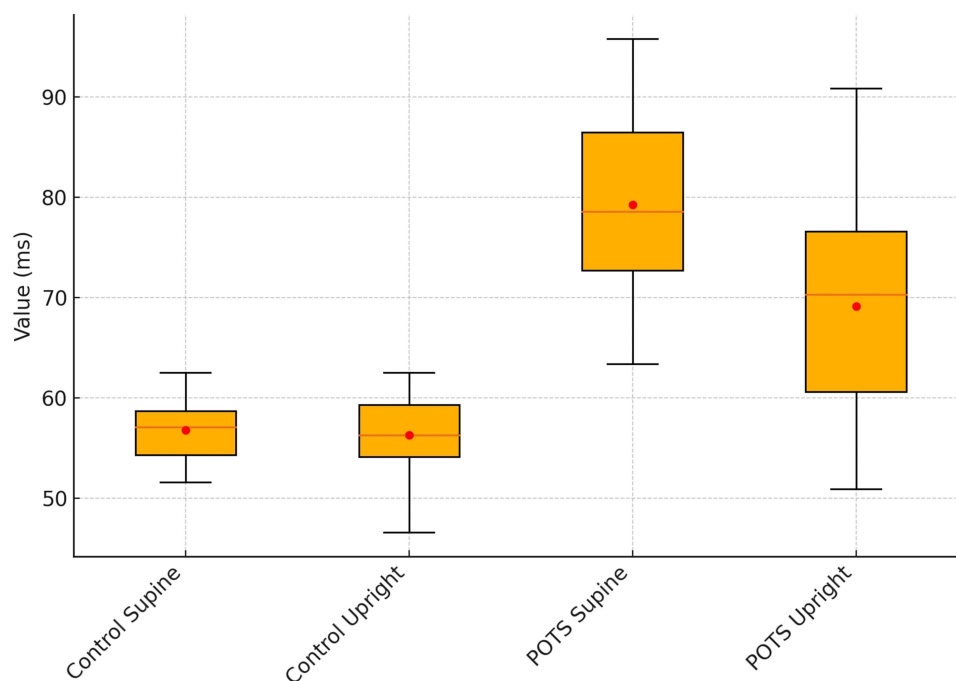
	POTS Group	Control Group
Upright-supine Difference (ms)	3.39 ± 5.91	0.58 ± 5.70
P value	0.0382	

Quantifies orthostatic EMAT change (upright–supine): POTS patients had a mean increase of 3.39 ± 5.91 ms versus 0.58 ± 5.70 ms in controls ($P = 0.038$), underscoring EMAT’s potential value as an orthostatic diagnostic marker (Table 6).

In both positions, the POTS group exhibits higher median and mean values than the control group, with wider interquartile ranges and longer whiskers indicating greater variability. In the supine position, the POTS median (78.5 ms) exceeds the control median (57 ms), and likewise in the upright position (POTS 70 ms vs control 56 ms). Red dots mark group means. This visualization highlights both the main effects of group and position and suggests a pronounced group–position interaction (Figure 4).

Precision–Recall Curves (PRC) for Supine and Upright EMAT in POTS Diagnosis

The supine curve (solid line) achieves an average precision (AP) of 0.84, maintaining high precision even at elevated recall levels. The upright curve (dashed line) yields an AP of 0.88, indicating slightly better overall diagnostic performance. Overlaying both curves highlights that EMAT performs well in both body positions, with the upright measurement offering a marginally higher balance of sensitivity and positive predictive value (Figure 5).

**Figure 4** Boxplot of Control vs POTS in Supine and Upright.

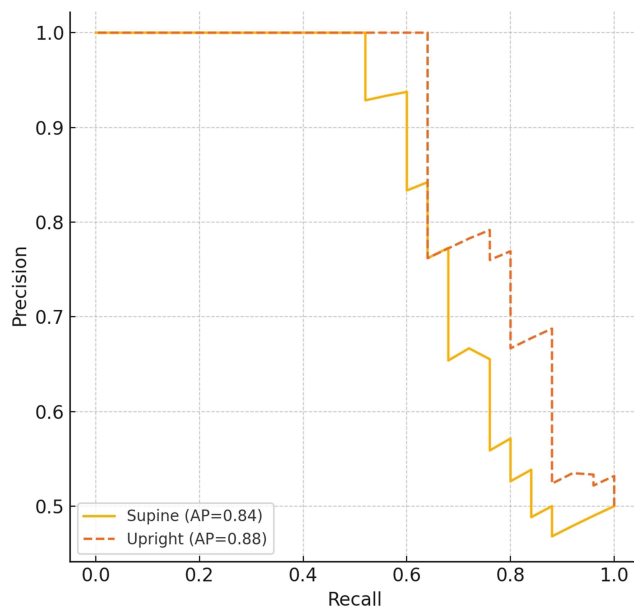


Figure 5 Precision-Recall Curves for EMAT in POTS Diagnosis.

Discussion

The most common clinical methods for assessing postural tachycardia syndrome are the head-up test, the head-up tilt test, and the nitroglycerin-challenged head-up tilt test. These tests are not easily accessible for routine or large-scale screening, as they require a healthcare professional and must be performed in a controlled clinical environment.¹³ Alternatively, heart sounds can be assessed using a stethoscope at various auscultation sites or recorded by specialized transducers and converted into time-series signals, known as phonocardiograms.¹⁴ Phonocardiograms are able to detect heart sound components that are inaudible or difficult to perceive by the human ear. They help distinguish easily confused sounds, determine the timing and characteristics of heart sounds and murmurs, and provide valuable information regarding cardiac hemodynamics, structural integrity, and function. Phonocardiography converts collected sound data into electronic signals, which are then digitized and transmitted to network terminals for automatic analysis, graphical visualization, and storage. This further enhances the clinical utility of heart sound analysis and promotes the development of telemedicine.^{15,16} Acoustic cardiography (ACG) is a new computer-aided diagnosis technology based on the simultaneous acquisition and analysis of ECG and heart sound signals. By placing dual sensing elements in one or both parts of the standard chest leads V2, V3 or V4, the ECG and heart sound signals are simultaneously collected.¹⁷ Computer-aided analysis and automatic report generation offer advantages such as non-invasiveness, ease of operation, cost-effectiveness, and intelligence, while enabling real-time and dynamic ECG monitoring.¹⁸

The researchers found that EMAT and LVST were related to left ventricular pressure changes and myocardial contractility.¹⁹ A shortened LVST or a prolonged EMAT indicates reduced left ventricular systolic function, demonstrating that changes in heart sound features can effectively reflect left ventricular dysfunction and diminished cardiac reserve caused by abnormal cardiac hemodynamic parameters. On the strength of the S1 phonocardiogram were positively correlated with the contraction of the heart function, EMAT is closely related to the cardiac systolic function, which can be used to assess the tolerance of patients to physical activity.²⁰ In this study, a patch device was used to analyze heart sounds and ECG signals. The wearable device can be used not only by health care providers but also by patients themselves outside the hospital to assess cardiac function. The results are helpful for the clinical diagnosis and out-of-hospital monitoring of postural tachycardia syndrome in children.

Yamanouchi et al performed echocardiography on POTS patients and normal controls during baseline supine and upright tilt tests and found that, compared with normal controls, the syncope group had a faster rate of decline in left ventricular end-diastolic volume during tilt and a significant decrease in stroke volume and ejection fraction.²¹ In patients

with POTS, early left ventricular end-systolic pressure and wall stress-corrected shortening of the left internal diameter after HUTT were significantly reduced, indicating a marked decline in cardiac afterload and myocardial contractility.

In this study, EMAT is defined as from ECG Q wave to phonocardiogram S1 first peak period. It reflects the progression from electrical activity to mechanical movement. It can be measured by the time interval between the Q wave of the ECG and the S1 of the heart sound. It was found that there was no statistically significant difference in S1–S2 interval between the POTS and control groups. Based on animal experiments, Kamran et al concluded that EMAT is not related to heart rate and that EMAT values can be directly compared across groups.

The results of this study showed that in the POTS group, heart rate increased significantly from the supine to the upright position (81.04 ± 9.88 bpm vs 111.04 ± 9.88 bpm, $P < 0.0001$), whereas there was no significant difference in heart rate between positions in the control group (78.38 ± 9.56 bpm vs 78.08 ± 13.63 bpm, $P = 0.8434$), confirming the abnormal heart rate response to postural change in children with POTS.

For electromechanical parameters, EMAT in the POTS group was significantly higher than in the control group in both supine and upright positions (75.71 ± 9.16 ms vs 58.92 ± 4.10 ms; 70.90 ± 10.86 ms vs 55.50 ± 9.89 ms, both $P < 0.001$), and the change in EMAT (upright-supine) in the POTS group (3.39 ± 5.91 ms) was greater than that in the control group (0.58 ± 5.70 ms, $P = 0.038$). EMAT% in the POTS group increased significantly in the upright position ($9.18 \pm 1.43\%$ vs $11.58 \pm 1.50\%$, $P < 0.001$), while only a mild increase was observed in the control group. Left ventricular ejection time (LVET) decreased with postural change in both groups, but supine and corrected LVET were significantly lower in the POTS group compared to controls ($P = 0.048$, $P = 0.014$). Precision-recall curve (PRC) analysis showed that the average precision (AP) of EMAT in distinguishing POTS from controls was 0.84 in the supine position and 0.88 in the upright position, indicating good predictive performance.

These data suggest that EMAT and its postural change can serve as sensitive electromechanical indicators of autonomic dysfunction in pediatric POTS. In response to upright stress, POTS patients experience enhanced sympathetic activity, resulting in a marked increase in heart rate and a shortening of EMAT, reflecting abnormal coordination between ventricular filling and contraction. The concurrent changes in EMAT% and LVET further indicate altered timing between mechanical and electrical cardiac events in POTS, closely associated with impaired postural regulation.

Study Limitations

One limitation of our work is that we did not obtain concurrent echocardiographic timing of mitral-valve closure to validate the EMAT interval measured on our synchronized phonocardiogram/ECG recordings. At the time of data collection, real-time echocardiography was not performed in parallel with phonocardiography—equipment and sonographer availability did not allow simultaneous recording of valve motion. Although this technique is good at identifying reduced LV ejection fraction, there are some limitations. Sound is a complex signal. The quality of the collected ACG signal is greatly affected by endogenous and exogenous factors. The endogenous factors include the factors affecting sound transmission such as the degree of obesity of the subject, the presence or lack of lung lesions, pleural and pericardial effusion, and respiratory rhythm, etc. The exogenous factors are mainly the quiet degree of the operating environment. Exogenous factors can be controlled artificially, but the influence of endogenous factors on ACG parameters is still insufficiently studied. Moreover, the heart sound signals collected by different sensors and at different chest standard lead positions are different.

Conclusions

EMAT and its postural variation, measured using a wearable synchronized phonocardiogram-ECG device, are sensitive, noninvasive markers for distinguishing pediatric POTS from healthy controls. Integration of wearable monitoring into clinical practice could facilitate diagnosis and follow-up in pediatric POTS. Larger, prospective studies are warranted to validate and optimize these findings.

Abbreviations

POTS, Postural Tachycardia Syndrome; ECG, Electrocardiogram; EMAT, Electromechanical activity time; BMI, Body mass index; IQR, Interquartile range; ACG, Acoustic cardiography; LVST, Left ventricular systolic time; LVET, Left Ventricular Ejection Time; PRC, Precision-recall curve; HUTT, Head-Up Tilt Test; HUT, Head-Up Test.

Data Sharing Statement

The data supporting the findings of this investigation are available upon reasonable request from the corresponding author.

Ethical Approval and Consent to Participate

This study was conducted in accordance with the principles of the Declaration of Helsinki. Written informed consent was obtained from the parents or legal guardians of all participating children.

Ethical Approval

This study was approved by the Ethics Committee of the First Affiliated Hospital of the Medical College of Shihezi University Scientific and Technological Ethics Committee, approved of the number: KJ2023-178-02.

Consent to Participate

Written informed consent was obtained from the legal guardians of all child participants prior to enrollment in the study.

Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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Disclosure

All authors report no relationships that could be construed as a conflict of interest. All authors take responsibility for all aspects of reliability and freedom from bias of the data presented and their discussed interpretation.

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