Visualizing Cardiac Motion Using Subcutaneously Measured Electrocardiography and Three-Axis Acceleration: Day-to-Day Comparability and Event-Related Changes in Congestive Heart Failure Patients*

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***Abstract*— Continuous monitoring of cardiac motion offers valuable insights into heart failure (HF) progression and management. This study explores a method to visualize heart motion trajectories from a novel subcutaneous sensor by integrating electrocardiogram (ECG) data with data from a three-axis accelerometer. By analysing the area covered by those trajectories during the systolic phase changing cardiac function may be assessed quantitatively. During systole the trajectories clearly showed multi-axial mechanical motion of the contracting chest following the cardiac ejection of blood from the left ventricle into the systemic circulation. Consistent daily trajectory patterns were observed in a stable individual on eight different days as their systolic area covered was comparable in size (0.0140mm^2 ± 0.054mm^2) and orientation. Four Patients that experienced five congestive heart failure events (CHF) showed a reduced systolic plane prior to clinical deterioration as the systolic trajectory area covered was significantly reduced compared to baseline (0.0061mm^2 ± 0.0044mm^2 at the event versus 0.0158mm^2 ± 0.0096mm^2 at baseline, $p<0.05$). Previous research reported qualitatively similar trajectories in healthy volunteers using non-invasive sensors. Additionally, while devices such as other subcutaneous monitoring implants have been evaluated for monitoring ECG and impedance changes in patients with HF, the potential of subcutaneous three-dimensional acceleration measurements remains unexplored. Our findings suggest that this integrated approach could enhance remote monitoring, early detection of decompensation, and personalized treatment strategies for HF patients.**

***Clinical Relevance*—This study reports a more intuitive means to display ECG and three-axis acceleration data from a novel subcutaneous sensor. The raw data is converted to cardiac displacement trajectories. The results show that the cardiac motion range reduced in heart failure patients that experienced congestion and heart failure related events.**

I. Introduction

The number of patients suffering from Heart failure (HF) is increasing globally, leading to frequent hospitalizations and reduced quality of life. Preventing acute congestive heart failure (CHF) events remains a significant challenge, as the onset of symptoms often occurs late in the progression toward decompensation. Traditional imaging modalities, such as echocardiography and cardiac MRI, provide valuable insights into cardiac function but are limited by cost, accessibility, and the inability to perform continuous daily monitoring. Wearable or implantable sensors offer an alternative approach to assess cardiac dynamics remotely and in real-time. In this context, deep implantable intravascular devices for long-term remote monitoring offer promising solutions for HF care. Implantable devices such as CardioMEMS (Abbott, Sylmar, CA, USA) and Cordella (Endotronix, Inc., Chicago, IL, USA) are currently among the most effective methods for remote monitoring of heart failure through pulmonary artery pressure (PAP) measurements [1, 2]. Evidence supports the safety, efficacy, and practicality of remote PAP monitoring. However, measuring PAP accurately using an absolute pressure sensor exposed to the tissue response inside a collapsible vessel such as the pulmonary artery remains challenging [3]. A recent development of a cross-sectional area measuring sensor inside the Inferior Vena Cava may overcome some of those challenges in the future [4]. Regardless, the invasiveness of such transcatheter-based procedures increases patient risk and imposes substantial healthcare costs. Subcutaneous insertable cardiac monitors, such as the Medtronic LINQ system, have been explored for HF risk assessment by integrating different physiological metrics like heart rate and impedance changes.

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Yet, their accuracy remains limited and could be improved by incorporating additional sensors to enhance patient monitoring and HF risk evaluation [5]. Subcutaneous acceleration measurements in three dimensions may add information that has not been explored to date. Prior studies have explored heart motion tracking using non-invasive sensors. Schmidt et al. demonstrated that a wearable accelerometer placed on the chest could capture cardiac trajectories in healthy individuals, suggesting that cardiac motion exhibits reproducible patterns in stable conditions [6]. Gymr et al. validated the concept of apex displacement as a marker of cardiac function in preclinical pig models using an open-heart setup [7]. Yet, the potential of subcutaneous 3D acceleration for HF monitoring remains unexplored to date. This study aims to assess the day-to-day repeatability and comparability of displacement trajectories in stable HF patients and to investigate their changes preceding a CHF event.

II. Methods

Future Cardia (Houston, TX, USA) has developed a minimally invasive subcutaneous device that combines a 3-axis piezoelectric accelerometer for monitoring mechanical cardiac activity and single-lead electrocardiography (ECG), designed to enhance the early detection of heart failure HF [8]. The ECG sensor records electrical activity, while the accelerometer captures cardiac motion along three spatial axes [X – (R)ight to (L)eft, Y – (H)ead to (T)oe, and Z – (A)nterior to (P)osterior]. The sensors were implanted subcutaneously in the left pectoral region, minimizing patient discomfort and maximizing long-term usability. An overview of the sensor placement and the synchronized raw data for one representative 40-second-long recording are shown in Figure 1. ECG and accelerometer signals were recorded continuously at a sampling rate of 100 Hz. The data was further processed in MATLAB (R2023b, The Mathworks, Inc. Natick, Massachusetts, USA).

A. Data Collection

Data was collected as part of the Future Cardia™ Insertable Cardiac Monitor in Subjects With Paroxysmal Atrial Fibrillation (First-in-Human Study), registered under NCT06167434 (ClinicalTrials.gov ID) and approved by the Institutional Review Boards of the Institutions involved. This initial work included data from five patients in two sites (Split University Hospital, Croatia and Na Homolce, Prague, Czech Republic): four patients (N=4) who experienced five heart failure related events and one patient (N=1) who served as a baseline, with no heart failure related event. Readings at night-time between 1am and 7am were considered for this analysis.

B. Posture estimation

Posture was analyzed using the absolute acceleration measurement which was exposed to gravitation on earth. As the sensor is exposed to the gravitational force of 9.81m/s^2 each of the three acceleration directions record a fraction of that gravitational force. Hence, positioning of the sensor relative to the gravitational axis can be derived from this information. This is a common method applied using acceleration sensors and has been described elsewhere [9]. The data shown here included patient data captured for patients in supine position.

C. ECG Signal pre-processing

ECG signals are filtered to remove noise and artifacts using a bandpass filter (0.5 to 50 Hz). R-peaks are detected using a modified Pan-Tompkins algorithm to determine the cardiac cycle phases during the 40 second recordings. High-frequency noise was removed using a fourth-order Butterworth low-pass filter with a cutoff frequency of 50 Hz. To address baseline drift a high-pass filter with a cutoff frequency of 2 Hz was utilized. The R-peak location for every detected cardiac cycle was used to compute one event related ECG average of the cardiac cycle per 40-second-long acquisition.

D. Accelerometer Signal pre-processing

A low-pass filter was applied to remove high-frequency noise. The accelerometer detected cardiac micro-movements by measuring displacement and velocity variations synchronized with the ECG signal. A high pass filter was applied to remove respiration related noise and low frequency drift. The R-peak locations in each cardiac cycle were used to compute one event related acceleration average of the cardiac cycle per 40-second-long acquisition. The noise of the accelerometer was approximately ±8mg which reduced to ±1.5mg after event related averaging across ~40 cardiac cycles depending on the number of recorded cycles per trace.

E. Trajectory calculation and systolic phase area estimation

The motion trajectory of the heart was reconstructed by integrating accelerometer signals over time and aligning them with ECG-derived cardiac cycle phases. The displacement of the heart is calculated using double integration of acceleration as a function of time as shown here for the example of the x-dimension:

$$x(t) = \iint a_x(t)\, d^2t \qquad (1),$$

where a(t) is the measured acceleration along the x axis. Preprocessing correction as described above was applied to mitigate drift – a major confounding factor when using the proposed integration process. The final reconstructed heart trajectory is visualized in three dimensions, showing the characteristic movement patterns of the heart during systole and diastole. Filtered acceleration signals were integrated twice using the trapezoidal rule to derive velocity and displacement along each axis. Initial velocity and displacement were assumed to be zero, and velocity signals were detrended using a fourth-order Butterworth high-pass filter with a cutoff frequency of 2 Hz (Figure 2) – this was to remove any remaining low-frequency trends that may have been unrelated to cardiac motion. The displacement signals were then used to reconstruct a 3D trajectory of chest motion during the cardiac cycle. Systolic and diastolic phases were identified using ECG data collected by the sensor, manually marking the Q-start, S-end, and T-end. Planar fits to systolic phase trajectories (from S-end to T-end) were generated using the least squares method. The planes were constrained to the regions defined by the minimum and maximum x, y, and corresponding z values. The surface area of these bounded planes was calculated by dividing the projected area on the xy-plane by the cosine of the angle between the plane and the xy-plane (Figure 3).

III. Results

A. day-to day variation

In a patient without clinical events, heart motion trajectories were comparable over eight different days, demonstrating the stability of our method in the absence of disease progression (Figure 4). The motion was small downward after the end of the S-wave likely corresponding to the isovolumetric contraction phase. The ejection phase showed a significant motion towards the back and head.

B. Congestive Heart Failure related changes

In four patients who experienced five HF-related events in total (e.g., worsening symptoms, hospitalization), the heart motion trajectory described a smaller systolic plane in the days leading up to the event compared to baseline (Figure 5). A quantitative summary of the results can be found in Table I. The systolic area covered reduced significantly before CHF events while the area recovered after the event, although insignificantly.

Discussion

Our findings suggest that continuous monitoring of heart motion via a subcutaneous ECG and accelerometer can provide critical insights into HF progression. The consistency of heart motion in a stable patient indicates that the proposed method is reliable for long-term monitoring, in agreement with findings in healthy volunteers using a non-invasive chest sensor [6]. Schmidt et al. reported displacement in five healthy volunteers (age 27 to 44 years old) lying in left lateral decubitus position. The peak-to-peak displacements ranged from 0.39±0.35 mm to 0.28±0.15 mm (mean±std) for three perpendicular planes investigated. The displacement in this study was slightly below 0.2mm and varied between patients of different age and health status. We hypothesize that those differences may be related to age and cardiac dysfunction warranting future exploration. The subcutaneous implantation may have also restricted sensor motion more than for chest strapped sensors. An acceleration sensor on the chest may indeed underly slightly more displacement due to the less restricted environment it is positioned in. Radar based systems measured comparable results in Anterior-Posterior direction for 20 healthy adult volunteers with displacement being in the range of -0.2 to 0.2mm [10]. It remains unclear how precisely one and the same point on the surface is captured using such solution. The small-scale dimension of the chest wall motion poses a challenge to validation of the measurements as non-invasive imaging methods struggle to resolve such small sub-millimeter motion. Differences in measurement location between studies may also be considered as confounders for comparison. Future work will explore the algorithmic robustness of the proposed algorithm by evaluating the impact of drift methods and initial-condition assumptions on double integration. It can be expected that age and cardiac health status are significant factors influencing displacement magnitude of the chest. Hence, reduced displacement was expected near the CHF event. Although the post-event data was not significantly increased, we hypothesize that not all patients recovered completely after their events and hence displacement was expected to return only partially to normal for all patients that experienced an event. Grymyr et al. recorded apex displacement on the heart directly during in vivo open-heart surgery reporting a range of 50mm motion during the heartbeat – expectedly the displacement of the heart is least restricted when the chest is open, and sensors are directly placed on the heart itself. They showed how pathological cardiac conditions impact on the heart's ability to move – ultimately reducing displacement. The observed reduction in systolic plane size before HF-related events suggests that cardiac motion abnormalities may precede clinical deterioration. By tracking individual patient trajectories, this method could guide therapy adjustments, particularly in patients with implantable cardiac devices. Integrating this technology with mobile health platforms could facilitate at-home monitoring, reducing the burden of frequent hospital visits. The advantages of subcutaneous monitoring over non-invasive approaches for chronic long-term monitoring on the scale of weeks and months are patient compliance, day-to-day measurement reproducibility.

Conclusion

This paper presents a novel method for visualizing heart motion using subcutaneous ECG and a three-axis accelerometer. Our results demonstrate that heart trajectories remain stable in event-free patients but show a reduced systolic motion range before clinical deterioration. These findings extend prior research on heart motion tracking and highlight the potential of continuous heart monitoring for early HF detection and personalized management. Future research will focus on refining predictive models and expanding clinical validation.

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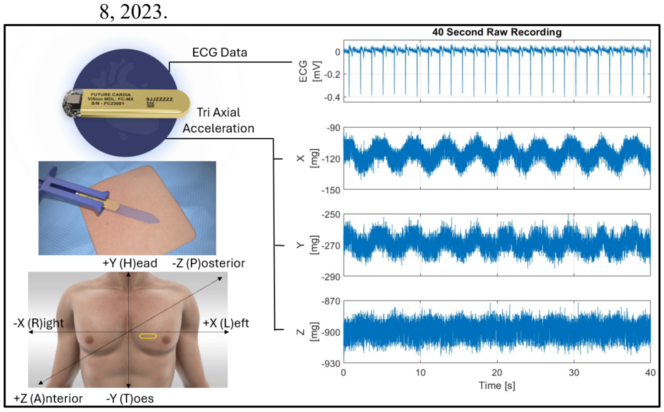

Figure 1: Implantable sensor, deployment, positioning, and sensor raw data for standard 40 second capture in one patient.

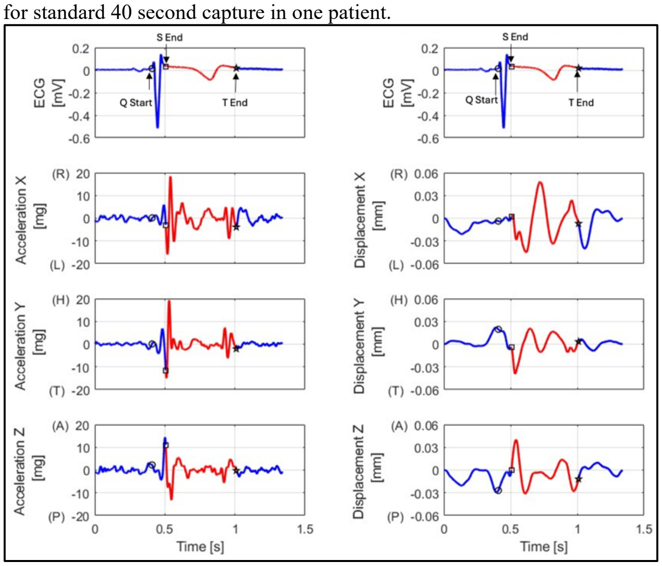

Figure 2: post-processed ECG and acceleration data on scale of the average cardiac cycle (left) and displacement time series data (right column) for one representative patient dataset.

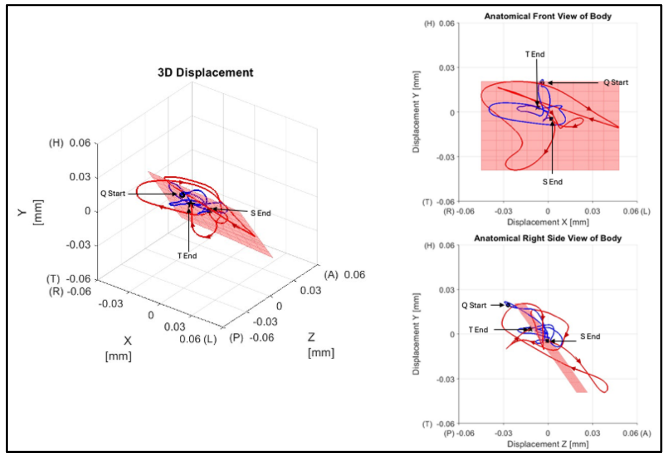

Figure 3: Displacement trajectory in 3D and in two-dimensional view used for consecutive figures.

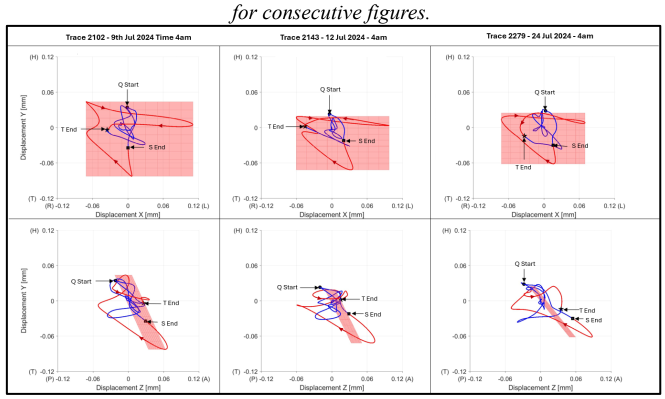

Figure 4: Day-to-Day variability of representative trajectories for one patient showing similar characteristics.

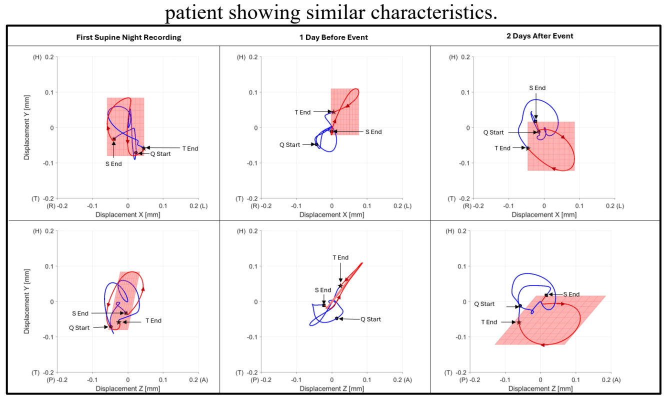

Figure 5: event related changes of trajectories for one patient that experienced a congestive heart failure hospitalization.

TABLE I: QUANTITATIVE RESULTS

Observation	area covered during systole [mm^2].		
	Mean+- Std	*Significance (p<0.05)*	*Compared to*
Normal (8 different days)	0.0140 ± 0.054	n.a.	n.a.
Baseline	0.0158 ± 0.0096	**0.037***	event
Event	0.0061 ± 0.0044	0.1677	post event
Post Event	0.0129 ± 0.0141	0.642	baseline