Monitoring cardiac function by accelerometer – detecting start systole from the acceleration signal makes additional ECG recordings for R-peak detection redundant

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***Abstract*— A miniaturized accelerometer attached to the heart has been used for monitoring functional parameters such as early systolic velocity and displacement. Currently, processing of the accelerometer signal for derival of these functional parameters depends on determining start systole by detecting the ECG R-peaks. This study proposes an alternative method using only the accelerometer signal to detect start systole, making additional ECG recordings for this purpose redundant. A signal processing method for automatic detection of start systole by accelerometer alone was developed and compared with detected R-peaks in 15 pigs during 5 different interventions showing a difference of 30 $\pm$ 17 ms. Furthermore, the derived early systolic velocity and displacement using only accelerometer measurements correlated well (r^2=0.91 and 0.82, respectively) with minor differences compared to the current method using ECG R-peaks as time reference. The results show that an accelerometer can be used to monitor cardiac function without the need to measure ECG which can simplify the monitoring system.**

I. INTRODUCTION

A miniaturized accelerometer attached to the heart may be used to monitor heart motion[1][2]. Such a sensor system can be used to detect abnormal myocardial motion which arises when complications, e.g. ischemia, occur during or following cardiac surgery. In a previous study, our group developed an automated method to detect abnormal myocardial motion based on accelerometer measurements[3]. The automatic analysis depended on additional ECG recordings to detect start systole defined as the time of the ECG R-peak. A filtering algorithm depending on this ECG heartbeat detection was subsequently run to remove gravity from the accelerometer signal as described below. Once start systole was defined, velocity and displacement during the heart cycle were calculated by integrating the filtered acceleration signal once and twice, respectively. Ischemia reduces the velocity and displacement during early systole[4][5], hence these two functional indices were extracted and used to automatically detect ischemic occurrences with high accuracy in the previous study[3].

The dependence of this method on ECG complicates the hardware of the system. Furthermore the analysis is also influenced by the quality of the ECG signal for automatic R-peak detection. Therefore, it is desirable to have an alternative for detection of start systole without ECG. The heart motion contains characteristic rapid movements and oscillations at the time of valve closure and opening during the different phases of the cardiac cycle. It may thus be possible to automatically detect the characteristic motion associated with start systole using just the accelerometer.

We developed and tested an algorithm for automatic detection of start systole using those characteristic motions in the accelerometer signal without using the ECG. We compared the time difference between our automatically detected event with the time of the ECG R-peak. Our automatically detected event was subsequently used as input to the algorithm for filtering and calculation of early systolic velocity and displacement. As the time of start systole detected by the two different methods may not be exactly the same, the subsequent filtering and values of the calculated indices may differ, which could affect clinical evaluation. Therefore, we also compared early systolic velocity and displacement calculated using the timing of start systole by these two different methods. It is of particular clinical importance that the values of the functional indices reflect changes in the myocardial function. Thus, we investigated whether quantitative and qualitative changes in the indices by the two different methods were the same during alterations of myocardial function induced by different interventions.

II. METHODOLOGY

In order to develop and test the concept, we used data from previous pig experiments performed at Oslo University Hospital[6][7]. This data included accelerometer measurements with simultaneous ECG recordings from 15 animals during 5 different interventions: baseline, infusion of adrenaline (epinephrine), ischemia induced by left anterior descending artery (LAD) occlusion, infusion of beta blocker (esmolol), and infusion of vasodilator (niprid).

A. Algorithm for Detection of Start Systole

Motion signals were acquired from a tri-axial accelerometer attached to the epicardium of the heart. Figure 1 shows an overview of the algorithm to detect start systole, described as follows: Three dimensional data from all axes (x-,y- and z-axis) (Figure 1a) were pre-processed by a 3-point moving average filter to smooth out any unwanted spikes and

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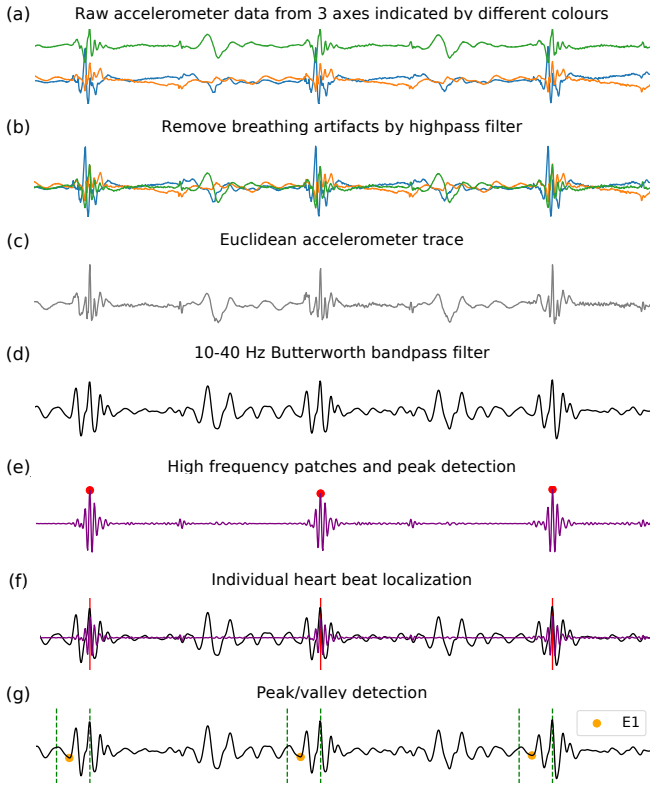

Fig. 1. Different steps in our algorithm to determine detected systole using accelerometer data. Red vertical lines in (f) represent individual heart beats. Dashed lines in (g) show the region of interest for valley detection algorithm. Orange circles mark the detected time points for start systole, denoted "E1".

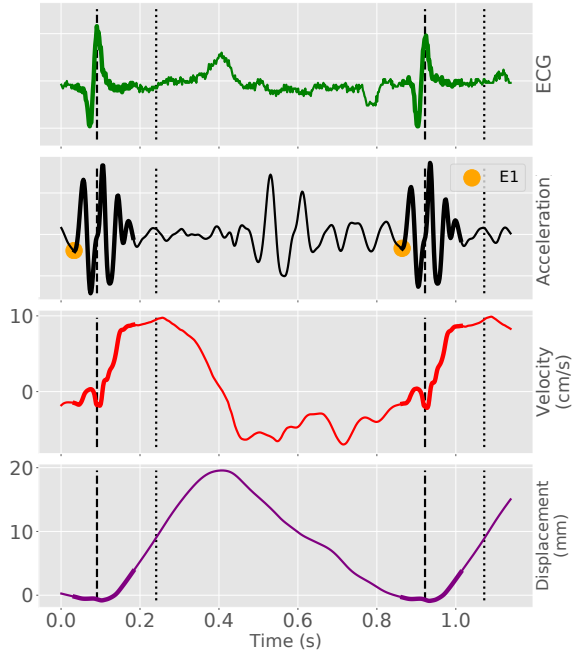

Fig. 2. Representative recording from one animal. Orange circle (E1) represents start systole defined by our algorithm. Bold traces indicate 150 ms period after event E1 when early systolic velocity and displacement are assessed. Dashed lines represent ECG R-peaks. Dotted lines represent 150 ms interval from R-peaks. Note the delayed R-peak and associated 150 ms interval resulting in higher early systolic velocity and displacement compared to the interval marked with bold trace.

fluctuations. All three axes readings from the accelerometer were also subjected to a high pass filter to remove respiratory motion artifacts (Figure 1b). In this case we used a Butterworth high pass filter of 1 Hz as the respiration rate in pigs was set to 15-20 breaths per minute while the heart rate was 90-100 bpm at baseline. The accelerometer senses in three directions, thereby producing three motion signals which are dependent on the orientation of the sensor. In order to remove this dependency, and to simplify the calculation, we assessed the Euclidean acceleration trace, shown in Figure 1c, calculated as a_{euclid} with a_x, a_y and a_z being the acceleration in x, y and z-axis respectively:

$$a_{euclid} = \sqrt{a_x^2 + a_y^2 + a_z^2}$$

A 4th order Butterworth filter with pass band 10-40 Hz was applied to the Euclidean acceleration trace (Figure 1d). This was done to enhance the frequencies between 10 to 40 Hz as the point of interest was observed to be present in this frequency range.

From the start of the ECG QRS-complex, characteristic oscillations in the accelerometer trace, associated with onset of myocardial contraction and the closing motion of the mitral valve leaflets[8] were present. High pass filtering emphasized and made these oscillations more prominent (Figure 1e), allowing a generic peak detection algorithm to split the trace into heart beats (Figure 1f). Finally, once the individual heart beats were located, a peak/valley algorithm was used to detect the start of high frequency oscillations on the Butterworth filtered signal in each heart beat. This was done using a search window with a duration of 15% of the heart cycle and starting prior to the peak found in Figure 1f. The detected point (Figure 1g) was defined as start systole and denoted E1, the first event of the cycle.

B. Early Systolic Velocity and Displacement

Accelerometers cannot differentiate between gravity and acceleration caused by motion. Thus, each axis of the accelerometer will include a component of gravity depending on its vertical direction component. As the heart moves in a cyclic motion, a point on the myocardial surface will start and end in approximately the same position in space during each heart cycle. This implies that the mean acceleration over each heart cycle is zero. This assumption was used to remove the gravity component by subtracting the mean acceleration of each cycle, where timing of each cycle was found using the detection algorithm for start systole.

The accelerometer was attached in the apical, anterior region of the left ventricle. Rotational motion, i.e. circumferential velocities and displacement, dominates in this region. The accelerometer y-axis was aligned in the circumferential direction. After subtraction of mean acceleration, integration and double integration to velocity and displacement, respectively, were performed along the y-axis for each heart cycle. Motion abnormalities are typically prominent during early

TABLE I

DIFFERENCE IN MILLISECONDS (MEAN±SD) BETWEEN ECG R-PEAK AND E1. POSITIVE VALUE MEANS E1 OCCURS FIRST.

Total	Baseline	Adrenaline	LAD Occlusion	Esmolol	Niprid
30 ± 17	30 ± 17	35 ± 19	30 ± 15	24 ± 17	34 ± 17

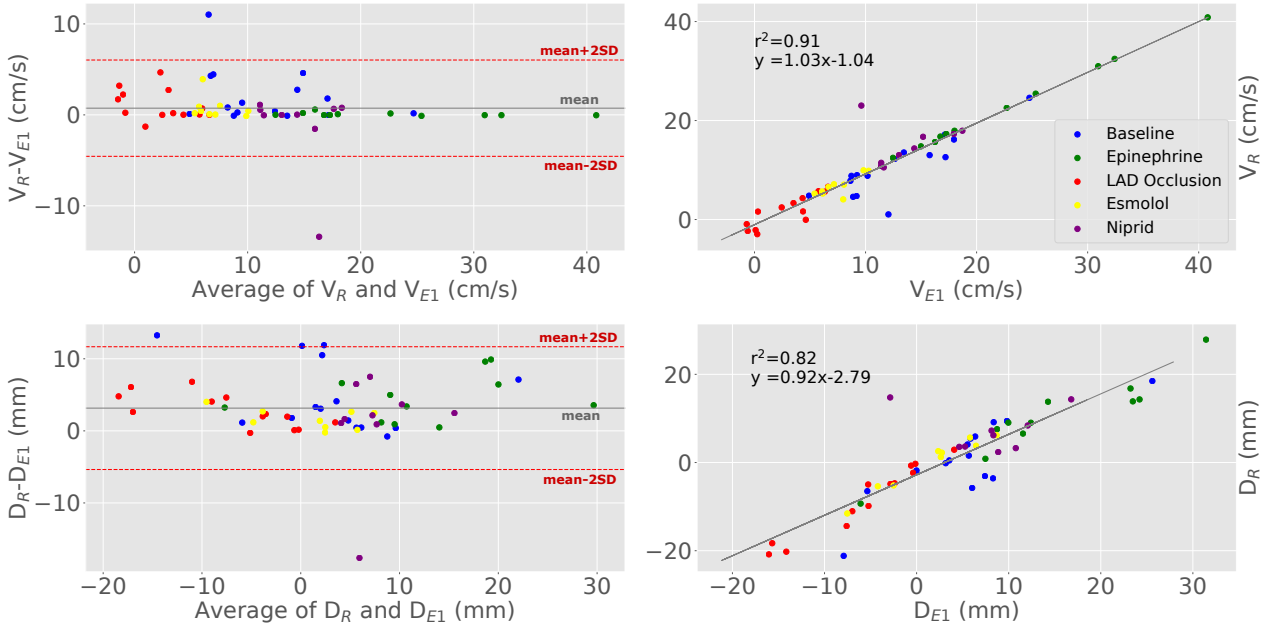

Fig. 3. Bland-Altman (BA) and correlation plots between early systolic velocity and displacement obtained by defining start systole as ECG R-peak (V_R and D_R, respectively) and by our proposed time point E1 (V_{E1} and D_{E1}, respectively).

systole[4]. As in the previous study[3], peak early systolic velocity was extracted, defined as maximum velocity during the first 150 ms from start systole. Furthermore, early systolic displacement, defined as the displacement during this 150 ms interval, was extracted (Figure 2).

C. Comparison with ECG R-peak as Reference

The calculations were performed on the previously acquired data[6][7]. For that study, recordings spanning approximately 10 seconds from the 5 interventions had been analyzed, providing a dataset of 1036 heart beats with detected ECG R-peaks. The ECG R-peaks in that study had been automatically detected and manually verified, providing us with an ECG R-peak reference.

We first tested the feasibility to detect start systole with our E1-detection algorithm and investigated the time difference between the time-point of E1 with the previously detected ECG R-peak time-point. We then compared the calculated early systolic velocity and displacement derived using E1 as time reference for start systole with the calculated early systolic velocity and displacement derived using the ECG R-peak as time reference for start systole.

III. RESULTS

A. Event Detection

Out of the 1036 analyzed beats, the algorithm detected start systole in 1001 beats. In 35 beats (3.3%) the algorithm could not locate E1.

On average, start systole was detected ∼30 ms before the ECG R-peak with a standard deviation of ∼17 ms as shown in Table 1. 30 ms accounts for approximately 10% of systole at baseline heart rate. The earlier occurrence of E1 is consistent with onset activation occurring prior to the ECG R-peak, which occurs at Q in the ECG QRS-complex. Thus, rapid accelerations and systolic contractions start prior to the later occurring R-peak (Figure 2) at a time when ventricular pressure, and thus opposing force to motion is low.

B. Early Systolic Velocity and Displacement

In total for all interventions, early systolic velocity was 0.7±2.7 cm/s lower on average by using E1 compared to using ECG R-peak. Early systolic displacement was 3.1±4.3 mm lower. Figure 3 shows the resulting Bland-Altman and correlation plots. The somewhat lower value of the indices, resulted mainly from the earlier time-point of start systole as velocity in many cases was still on the rise after the 150 ms interval. In such cases, a later start would also result in a higher maximum velocity as can be seen by the bold 150 ms line of the velocity trace in Figure 2. Similarly, circumferential displacement tends to be directed in the negative direction at the start of systole as a result of the complex interaction between the transmural activation sequence and the different orientation of endocardial and epicardial fibers[9]. Therefore, an earlier time of start systole

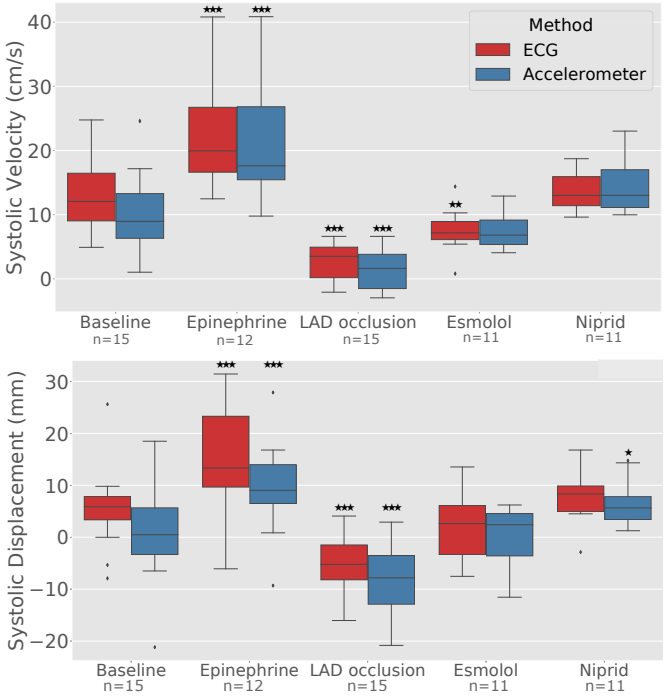

Fig. 4. Box plot of average early systolic velocity and displacement, derived using R-peak (red) or E1 (blue) as start systole. Some interventions were not performed in all animals as noted. To investigate difference between baseline and interventions, a mixed model analysis with subject as random intercept was used due to repeated measurements in each animal. $^{*}P<0.05$, $^{**}P<0.01$, $^{***}P<0.001$.

will include more of the negative displacement and less of the subsequent positive displacement in the early systolic interval.

Compared to baseline, early systolic velocity and displacement were increased by adrenaline, consistent with increased contractility. LAD occlusion substantially reduced the two indices. Early systolic velocity was also reduced for esmolol, consistent with reduced myocardial contractility during these two interventions. Niprid only had moderate effect on the indices. The major changes were seen both when the indices were calculated defining start systole as ECG R-peak and as E1. Figure 4 shows a box plot with the results for the 5 interventions.

IV. DISCUSSION AND CONCLUSION

The developed method for detection of start systole using only the accelerometer signal, had high feasibility and detected ∼97% of the beats. Compared to the ECG R-peak, start systole occurred consistently earlier which can be explained by the R-peak occurring after onset of mechanical activation of the ventricle. The earlier detection of start systole resulted in somewhat lower values of the subsequent derived early systolic velocity and displacement. The relatively small difference in the indices calculated by the two methods, may not be a problem as the reference velocity and displacement values for normal and abnormal function can easily be adjusted accordingly. More importantly, there were consistent changes in these indices with the different interventions, which is of most clinical interest as this demonstrated their ability to reflect changes in function and thus showed the potential for monitoring cardiac function.

In this study we used ECG R-peaks as reference which were manually corrected if the automatic R-peak detection did not locate each R-peak correctly. The reference therefore had unrealistic 100% detection feasibility and presumably accuracy as well. In practice there may also be limitations to ECG R-peak detection, particularly in cases with substantial noise or signal loss. In such instances it will be beneficial to use our method, or to use it in collaboration with the ECG to improve the robustness of early systolic velocity and systolic displacement calculations.

In conclusion, our derived method using only the accelerometer signal, without the ECG, showed high feasibility and accuracy in determining start systole and for calculation of early systolic velocity and displacement. This simplifies such a monitoring system as it removes the need for ECG recordings as input to the analysis, or it can improve the robustness of the system by providing an additional method for detection of start systole in cases of poor ECG signals.

V. CONFLICT OF INTEREST

OJE and PSH are patent holders of the accelerometer technology for assessment of cardiac function and together with MRK, OJG, and EWR share-holders in Cardiaccs A/S.

VI. SOURCES OF FUNDING

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