Feasibility of Compression Depth Estimation from the Acceleration Signal during Cardiopulmonary Resuscitation in Long-Distance Trains

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Abstract

Early cardiopulmonary resuscitation (CPR) and early defibrillation improve survival from out-of-hospital cardiac arrest. Long distance trains are increasingly being equipped with defibrillators. CPR feedback devices help rescuers to deliver chest compressions with an adequate depth. Most of them are based on accelerometers placed beneath the rescuer's hands. However, in a moving train the measured acceleration is a combination of the acceleration of the chest and that of the train. We wanted to evaluate the accuracy of two accelerometer-based systems in this scenario.

Chest compressions were delivered on a resuscitation manikin during the Zaragoza-Bilbao (Spain) ALVIA train route. A tri-axial accelerometer was placed between the manikin's chest and the rescuer's hands. We acquired 3-min records between consecutive stations with compressions delivered at target depths of 35 and 50 mm. Records corresponding to intervals with different average train velocities were selected.

We applied a time-domain (TD) method and a frequency-domain method (FD) to the acceleration records for estimating the compression depth. We analysed the implications of using a single axis (a1) or composing the three axis (a3) of the acceleration.

The median (IQR) unsigned error in mm was 6.4 (3.7-10.1), 5.9 (2.9-10.1), 1.8 (0.8-3.1), and 2.0 (1.0-3.6), for TDa1, TDa3, FDa1, and FDa3, respectively.

Chest compression depth could be accurately estimated from the spectral analysis of the acceleration in a moving train. The accuracy of the time-domain method was severely compromised, with median errors above 10% of the target depth.

1. Introduction

Sudden cardiac arrest is defined as the sudden cessation of the mechanical activity of the heart, confirmed by the absence of signs of circulation. As time elapses the probability of a successful defibrillation decreases about 10% each minute the patient is unattended [1]. The International Liaison Committee on Resuscitation (ILCOR) establishes the actions that should be conducted to treat patients in cardiac arrest. These actions are represented by the chain of survival [2], which consists of four links: early recognition of the emergency, early bystander cardiopulmonary resuscitation (CPR), early defibrillation and early access to advanced care. CPR and defibrillation are the key elements of the chain. CPR involves chest compressions that maintain a small critical blood flow and increases the likelihood of a successful defibrillation. Survival of cardiac arrest can be doubled or triple by performing CPR [1,3]. Early defibrillation can be achieved by public access defibrillation programs. Minimally trained people can respond to a cardiac arrest using an automated external defibrillator (AED). Currently, AEDs are widespread in public places such as airports, sports facilities, shopping centres, schools and universities, and train and metro stations. Recently they have started being deployed also in long-distance trains, as the time between consecutive stations may require an immediate in-situ intervention.

Current resuscitation guidelines emphasize the importance of providing high quality chest compressions, with a rate of at least 100 compressions per minute (cpm) and a depth of at least 50 mm, allowing full chest recoil between compressions, and minimizing interruptions. However, studies showed that even trained rescuers often provided too slow and too shallow chest compressions both in hospital [4] and out of hospital [5]. To improve CPR quality the guidelines encourage the use of real-time feedback systems. These are typically based on processing the acceleration signal to obtain the chest displacement during compressions.

We recently developed two methods for calculating the compression depth exclusively from the acceleration signal [6]. The first one (TD) is based on applying a band-pass filter to the acceleration twice to obtain the chest displacement signal. The second method (FD) is based on the spectral analysis of the acceleration.

Accelerometer-based feedback systems working in a moving train record the sum of the chest acceleration during compressions and the train accelerations due to the train displacement. This study evaluated the accuracy of the TD and the FD methods when estimating the chest compression depth in a moving long-distance train.

2. Materials and methods

2.1. Experimental setup

A resuscitation manikin (Resusci-Anne, Laerdal Medical, Norway) was equipped with a linear resistive sensor (SP1-4 transducer, Celesco, USA) to register the reference compression depth (CD) signal. Chest compressions were delivered in the centre of the manikin's chest with a tri-axial accelerometer (ADXL330, Analog Devices, USA) placed beneath the rescuer's hands. The CD signal and the three axes of the acceleration were digitized using an acquisition card (USB NI-6211, National Instruments, USA) connected to a laptop computer, with a sampling frequency of 100 Hz and 16 bit-resolution.

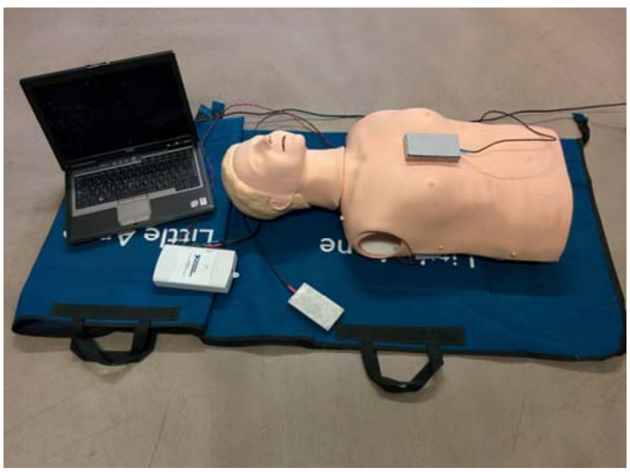

Figure 1. Experimental set-up

Grouped in two couples, we delivered chest compressions on the manikin during the Bilbao-Zaragoza-Bilbao (Spain) ALVIA train route. The manikin was placed on the floor of the train car. We acquired 3-min records between consecutive stations with a target compression rate of 100 cpm and two target depths, 35 and 50 mm. The records comprised a first minute of continuous chest compressions, and alternated series of 30 compressions with 5-s pauses in between for two minutes. Six records corresponding to three intervals with different average velocities were selected.

2.2. Methods description

2.2.1. Time-domain (TD) method

The acceleration signal can be integrated once to obtain velocity, and again to obtain displacement. From the different discrete integration algorithms available, the most used one is the trapezoidal rule because of its simplicity and high accuracy. This rule can be implemented as a discrete linear filter, but this filter presents a pole in the unit circle for z=1, and thus it is unstable. We designed a band-pass filter combining the trapezoidal rule with a high-pass filter that cancels the pole in z=1 of the trapezoidal rule, so the equivalent band-pass filter becomes stable. A detailed description of the method is presented by Ruiz de Gauna et al. in Cinc 2015 [6]. The band-pass filter is applied twice to the acceleration signal to obtain the chest displacement signal.

Figure 2 shows an example of the aplication of the method. A segment of the acceleration signal is represented in panel a, and the computed compression depth signal in panel b. The compression depth of each compression (peak-to-peak amplitude) is represented with a red line, and compared to the gold-standard value (green line).

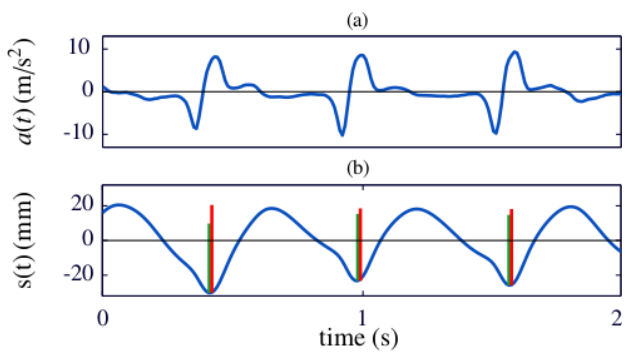

Figure 2. Illustration of the time-domain method

2.2.2. Frequency-domain (FD) method

In order to provide feedback to the rescuer it is not necessary to compute the depth of each chest compression; an average value every certain period of time could be computed. In this second method, the chest compression depth is computed every 2 seconds by applying spectral analysis to the acceleration signal. During short time intervals with continuous chest compressions, the acceleration and the displacement are almost periodic signals, so they can be approximated by their Fourier series decomposition. The amplitudes A_k (m/s^2) and phases θ_k (rad) of the principal harmonics of the acceleration signal can be obtained from the spectral analysis, as shown in Figure 3, panel b. Then, the amplitudes S_k and phases φ_k of the displacement signal can be computed as:

$$S_k = \frac{A_k}{(2\pi k \cdot f_{cc})^2} \cdot 1000\,(\mathrm{mm})$$

$$\varphi_k = \theta_k + \pi\,(\mathrm{rad}),\ \text{with } k = 1 \ldots N$$

where f_{cc} represents the fundamental frequency of the acceleration, that is, the compression frequency in Hz. The average displacement signal in the analysed 2-s window can be reconstructed from S_k and φ_k. Figure 3c shows the reference compression depth (blue) and the reconstructed compression depth, periodic for the 2-s interval (red). The mean chest compression depth in that interval is then computed as the peak-to-peak value of the average displacement signal. For more details about the implementation, refer to Ruiz de Gauna et al. (2015) [6].

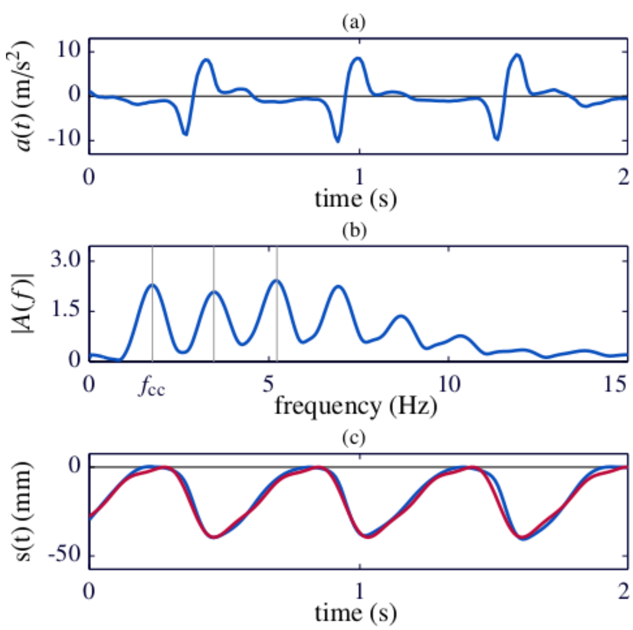

Figure 3. Illustration of the frequency-domain method

2.3. Performance evaluation

To evaluate the performance of each method, we evaluated the error as the difference between the estimated depth and the gold standard (GS) obtained from the reference displacement signal. We applied an automatic peak detector to the reference signal to identify chest compressions. The depth of each compression was computed as the peak-to-peak amplitude of the displacement. This was the GS for the TD method. For the FD method, the GS was the mean value of the depth of the compressions within each 2-s analysis interval. We evaluated the accuracy of both methods when using a single axis of the acceleration (a1, z-axis) and when composing the three-axis signals (a3).

The distribution of the errors was analysed using boxplots for the TD and the FD methods, when using one single axis (TDa1 and FDa1), and when composing the three axis (TDa3 and FDa3). Unsigned errors were also computed, and are presented as median (IQR) of the absolute and relative values. Wilcoxon rank sum test was used to perform between-groups comparisons, and p-values <0.05 were considered significant.

3. Results

The distribution of the errors is shown in Figure 4. Table 1 shows the median (IQR) absolute and relative unsigned errors. There were statistically significant differences between TD and FD methods both when composing the acceleration and when using a single axis ($p<0.001$). For each method, there were differences in the errors when using one axes (a1) or three axis of the acceleration ($p=0.007$ and $p=0.03$ for TD and FD, respectively).

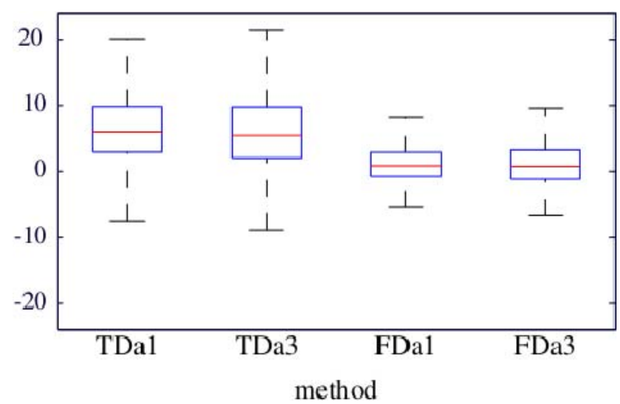

Figure 4. Distribution of the errors for each method

Table 1. Median (IQR) absolute and relative unsigned errors of the methods in a moving train

Method	Abs. error (mm)	Rel. error (%)
TDa1	6.4 (3.7-10.1)	16.0 (8.4-25.8)
TDa3	5.9 (2.9-10.1)	14.7 (6.9-25.2)
FDa1	1.8 (0.8-3.1)	4.4 (2.0-7.4.0)
FDa3	2.0 (1.0-3.6)	5.0 (2.4-9.2)

4. Discussion

The movement of a long-distance train involves different accelerations, affecting the three axis of a Cartesian coordinate system. The main accelerations measured in the longitudinal axis (in the direction of travel) are caused by accelerations and decelerations of the train. In the transversal axes, the most significant components are the centrifugal accelerations during the curves. Finally, the axis perpendicular to the floor shows high frequency vibrations and acceleration components caused by the damping system. Accelerations generated during chest compressions are in the range of 1-10 Hz. We have studied how the train accelerations could affect the accuracy of the estimation of chest compression depth when a time-domain and a frequency-domain method are used.

Table 2 shows the results of the methods in static, that is, when the measurements are performed in the laboratory instead of in a moving train [6].

Table 2. Median (IQR) absolute and relative unsigned errors of the methods in static conditions when composing the three axis [6]

Method	Abs. error (mm)	Rel. error (%)
TDa3	4.0 (2.1-6.2)	7.7 (3.9-11.9)
FDa3	1.2(0.6-2.1)	2.4 (1.1-4.0)

When chest compression depth is estimated in a moving train, the accuracy of the methods decreases, as expected. In the TD method, the error is slightly lower when composing the three axis (p=0.015). This tendency is reversed for the FD method, although differences were not statistically significant (p=0.49).

The accelerations due to the movement of the train negatively affect the performance of both methods, but the frequency-domain method is more robust (p<0.001), and the error increases less when compared with a static setting. When composing the three axis, the median unsigned error in the train is 2.0 (1.0-3.6) mm, compared to 1.2 (0.6-2.1) mm in the laboratory. The simplicity of this method make it suitable for its implementation to provide real-time feedback to rescuers.

5. Conclusions

Chest compression depth could be accurately estimated from the spectral analysis of the acceleration in a moving train. In the 95% of the cases the error in the depth estimation was below 9 mm. However, the accuracy of the time-domain method was severely compromised, with a median error above 10% of the target depth, and above 10 mm in 25% of the chest compressions.

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