Alternatives to Estimate the Compression Depth from the Acceleration Signal during Cardiopulmonary Resuscitation

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Abstract

Feedback devices improve the quality of chest compressions during cardiopulmonary resuscitation. Most devices use accelerometers to estimate the chest displacement using double integration and additional reference signals to ensure the stability of the process. We described and evaluated three novel methods for computing the compression depth using solely the acceleration signal.

The BPF method approximates the integration using a band-pass filter. The ZCV method computes the velocity and calculates the depth from the zero-crossing instants of each compression cycle. The SAA method computes the depth from the spectral analysis of the acceleration signal. We gathered twelve 10-min records in which chest compressions were provided on a manikin equipped with a displacement sensor. A tri-axial accelerometer was placed beneath the rescuer's hands.

The median (IQR) unsigned error in mm between the computed depth and the reference was 4.0 (2.1-6.2), 3.9 (2.0-6.2), and 1.2 (0.6-2.1) for each method, respectively.

Compression depth can be accurately estimated from chest acceleration. The spectral analysis method provided the best global performance. This alternative could be implemented for real time feedback during CPR.

1. Introduction

Early cardiopulmonary resuscitation (CPR) increases survival from cardiac arrest. CPR involves chest compressions to maintain a minimal blood flow to the vital organs. Compressions should be provided with a rate of at least 100 compressions per minute (cpm) and with a depth of at least 50 mm, minimizing interruptions and allowing full chest recoil between compressions [1]. In the clinical practice, even well-trained rescuers often provide poor quality chest compressions [2]. In recent years CPR feedback devices have been developed, [3] and they have shown to be effective in helping rescuers to adhere to CPR quality standards [4].

The most extended stand-alone feedback devices are based on accelerometers, and use double integration to compute chest displacement during compressions. Integration is unstable unless boundary conditions are applied for each compression cycle [5], for which additional reference signals are normally used [5,6]. This increases the complexity and cost of commercial devices.

In this study, we assess the accuracy of three methods to compute the chest compression depth using exclusively the acceleration signal. This could lead to simpler and widely available CPR feedback devices.

2. Materials and methods

2.1. Experimental setup

A resuscitation manikin (Resusci-Anne, Laerdal Medical, Norway) was equipped with an optic sensor (BOD 6K-RA01-C-02, Balluff, USA) to record the true chest displacement. The tri-axial accelerometer (ADXL330, Analog Devices, USA) was inbuilt in a metallic box, placed between the rescuer's hands and the manikin's chest.

We acquired twelve 10-min records during which two rescuers alternated every 2-min to provide CPR, consisting of series of 30 chest compressions with 5 s pauses in between. Compressions were applied with different target rates (80, 100, 120, and 140 cpm) and a target depth of 50 mm.

The signals were recorded with a sampling rate of 100 Hz and 16 bit-resolution.

2.2. Methods description

Two methods (BPF and ZCV) were developed in the time-domain, that is, based on processing the acceleration waveform. The third method (SAA) was developed in the frequency domain and analysed the spectral content of the acceleration.

2.2.1. Linear band-pass filtering (BPF)

The trapezoidal rule is one of the most common techniques to approximate the integration in the discrete domain. This rule can be implemented as a discrete filter [5] with the following transfer function:

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$$H_{TR}(z) = \frac{Ts}{2} \cdot \frac{z+1}{z-1},$$

where Ts is the sampling period. This filter presents a pole in z = 1, so the output tends to infinity when the input contains a DC component, and thus the filter is unstable. This results in a significant drift when computing displacement by doubly integrating the acceleration, which impedes the accurate estimation of compression depth, as illustrated in the second panel of Figure 1 (reference depth in blue, computed depth in red).

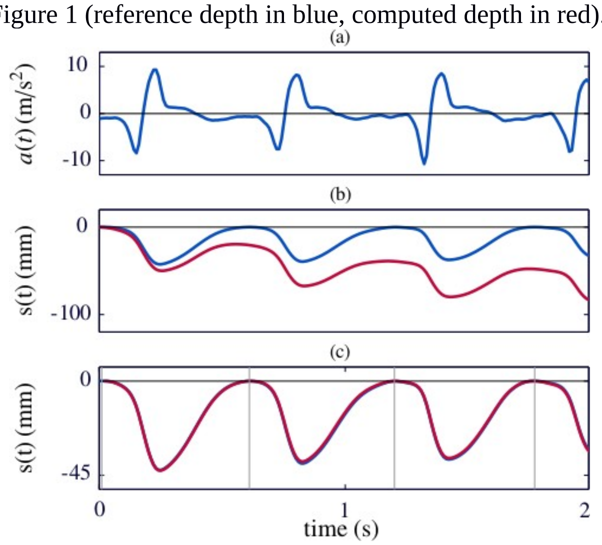

Figure 1. Example of the drift effect in the displacement (b) after double integration of the acceleration (a), which is canceled if proper boundary conditions are fixed (c).

In order to reduce the accumulation errors, the integration could be performed for each compression cycle after identifying the onset and the offset of each chest compression. The third panel in Figure 1 shows the result of applying boundary conditions to the integration, i.e., null velocity and null displacement at the start and end points of the compression cycle. For fixing these boundary conditions, commercial solutions generally use reference signals such as compression force.

Our first alternative to this procedure was the design of a stable band-pass filter that approximates the trapezoidal rule. It was designed as the serial connection of a high-pass filter and the trapezoidal rule system.

The transfer function for the polinomial approximation of a high-pass filter of order *k* with a gain factor *G* is given by:

$$H_{HP}(z) = G \frac{(z-1)^k}{\prod_{i=1}^{k}(z-z_{pi})},$$

where z_{pi} are the poles of the filter. The serial combination of the high-pass filter and the trapezoidal rule system has the following transfer function:

$$H(z) = H_{HP}(z) \cdot H_{TR}(z) = G \cdot \frac{Ts}{2} \cdot \frac{(z-1)^{k-1}(z+1)}{\prod_{i=1}^{k}(z-z_{pi})}$$

The equivalent filter compensates the instability of integration at low frequencies, as the high pass filter cancels the pole in z = 1 of the trapezoidal rule system.

The magnitude of the frequency response of the band-pass filter is depicted in Figure 2. It matches the ideal response of the trapezoidal rule for frequencies above approximately 0.6 Hz.

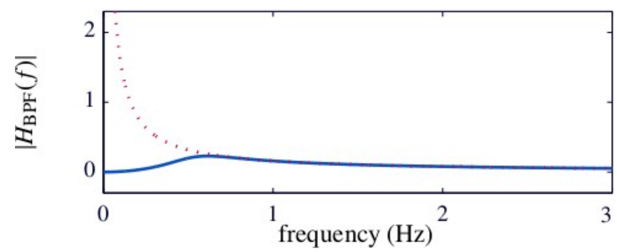

Figure 2. Magnitude of the frequency response of the band-pass filter (solid blue line) compared to the ideal response of the trapezoidal rule (dotted red line).

The filter was applied twice to the acceleration signal to compute the chest displacement signal (Figure 3). A peak detector was applied to this signal to identify each compression and the corresponding depth was calculated as the peak-to-peak amplitude of each fluctuation.

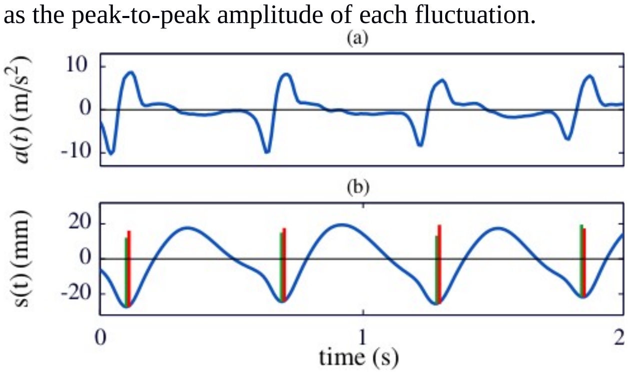

Figure 3. Example of the BPF method. Once the displacement is computed, the depth of each compression is estimated (red lines) and compared with the reference depth (green lines).

2.2.2. Velocity zero-crossing (ZCV)

The second alternative estimates the depth of each compression by processing the velocity signal; the computation of the chest displacement signal is not required in this case. The acceleration signal is filtered once with the linear band-pass system described in the previous section to obtain the velocity signal (Figure 4).

Then the zero-crossing instants of the velocity are automatically detected (Figure 4, second panel). The positive to negative zero-crossing points correspond to the onset of the compression cycle, whereas the negative to positive points correspond to the maximum displacement point. The depth of each chest compression is the area of the velocity signal between the onset and the maximum displacement.

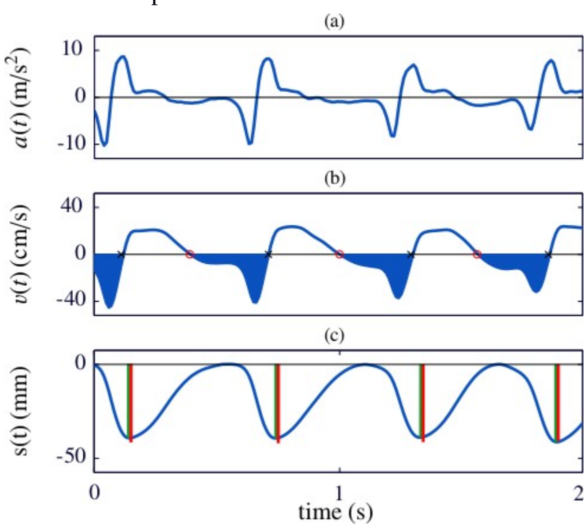

Figure 4. Example of the ZCV method. Once the velocity is computed, the depth of each compression is estimated and compared with the reference depth.

2.2.3. Spectral analysis of acceleration (SAA)

During short intervals of chest compressions, the acceleration and the displacement can be considered quasi-periodic. For an analysis interval of duration Tw seconds, both signals can be modelled using the first N harmonics of their Fourier series (without DC component). Since the acceleration is the second derivative of the displacement, the corresponding amplitudes and phases of the harmonics of the displacement can be obtained as:

$$S_k = \frac{A_k}{(2\pi k f_0)^2} \cdot 1000 \text{ (mm)}$$

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

where f_0 (Hz) is the fundamental frequency of the acceleration, and A_k (m/s^2) and θ_k (rad) the amplitude and phase of the *k*-th harmonic, respectively.

The mean chest displacement in the analysis interval can be estimated from its Fourier series, with its coefficients computed using the equation above, as:

$$s[n] = \sum_{k=1}^{N} S_k \cos(2\pi k f_0 n T_s + \varphi_k)$$

The mean compression depth is then estimated as the difference between the maximum and the minimum value of s[n].

We fixed the analysis interval to Tw = 2 s. A Hamming window was applied to the acceleration signal, and its 2048-point Fast Fourier Transform was computed. Then, the first three harmonics of the acceleration were calculated from the magnitude of the spectrum. An example of the SAA method is shown in Figure 5.

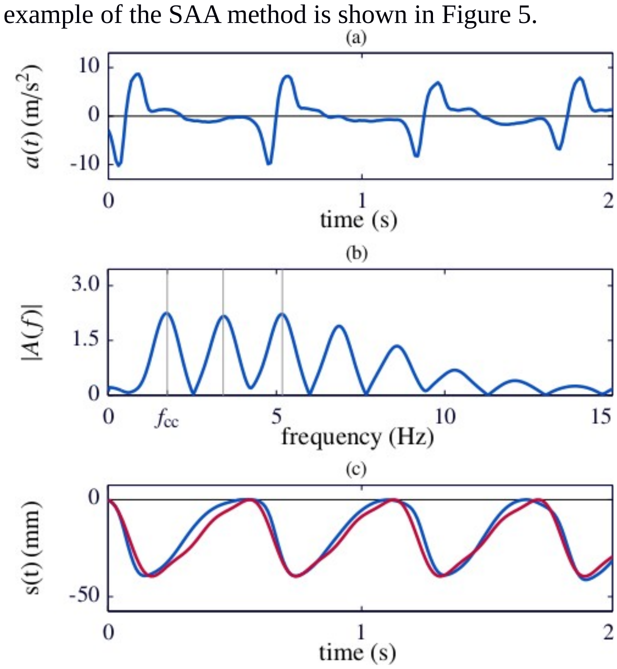

Figure 5. Example of the SAA method. The computed mean compression depth in the 2-s interval was 40.6 mm, and the mean reference depth was 40.1 mm.

2.3. Performance evaluation

The error for each method was computed as the difference between the estimated and the gold standard depths, calculated from the reference chest displacement signal.

The distribution of the errors was analysed using histograms and boxplots. Median and quartiles of the unsigned error (absolute and relative values) were computed. The influence of the target rate and the rescuer couple was also studied by applying Kruskal-Wallis test (p-values < 0.05 were considered statistically significant).

3. Results

Figure 6 shows the distribution of the errors for the three methods. Median (IQR) values of unsigned absolute and relative errors are shown in Table 1.

Figure 7 shows the boxplots of the errors in depth per target rate. There were significant differences in errors for different rates and for different rescuer couples for the three methods.

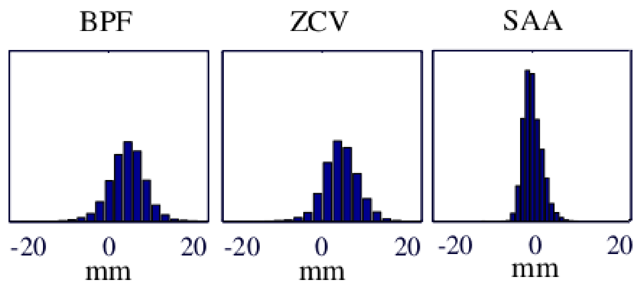

Figure 6. Normalised distribution of the error in the estimation of depth for the three methods

Table 1. Median (IQR) absolute and relative unsigned errors for the three methods.

Method	Abs. error (mm)	Rel. error (%)
BPF	4.0 (2.1-6.2)	7.7 (3.9-11.9)
ZCV	3.9 (2.0-6.2)	7.5 (3.9-12.0)
SAA	1.3 (0.6-2.1)	2.4 (1.1-4.0)

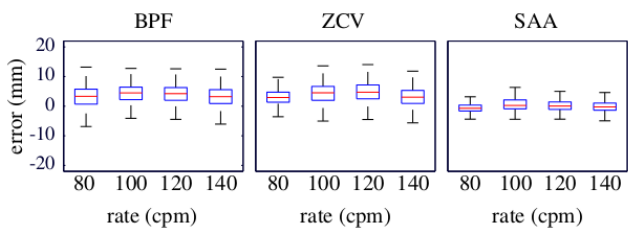

Figure 7. Errors in the estimation of depth per target rate

4. Discussion

This work assesses the accuracy of three strategies for estimating chest compression depth by processing exclusively the acceleration signal. For the time-domain methods (BPF and ZCV) errors were above 6 mm in 25% of the cases. The frequency-domain method (SAA) provided the best performance, with errors below 2.1 mm in 75% of the analysis windows. Accuracy of the three methods varied with target rate and with rescuer couples, but the SAA method performed better in all the conditions. This method directly estimates the mean compression depth without obtaining the instantaneous displacement signal. This avoids the need to integrate and deal with the drift problem.

Current technology relies on accelerometers and double integration to estimate depth. Two major companies in the market have developed drift compensations techniques based on either additional force or pressure sensors (CPRmeter stand-alone device by Philips/Laerdal), or on advanced filtering techniques, usually requiring reference signals (Real CPR Help technology by Zoll). TrueCPR device by PhysioControl based on tri-axial field technology is a recent alternative to accelerometers. All these solutions increase the complexity of the device.

The methods discussed in this paper are based solely on accelerometers, and could lead to simpler and cheaper devices, allowing their widespread use in the practice, especially for bystanders.

In this study we evaluated the accuracy of the method in a simulated cardiac arrest scenario. It would be interesting to validate these results with clinical data.

5. Conclusions

Accurate feedback on chest compression depth during CPR could be possible using only the acceleration signal. Among the alternatives discussed in this study, the method based on the spectral analysis of the acceleration provided the best performance. The method relies on the idea that the average compression depth in a short time interval can be estimated from the magnitudes and phases of the first harmonics of the acceleration. This could lead to simpler CPR feedback devices.

Acknowledgements

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