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Cardio Compression Control Device

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Abstract - **Cardio Compression Control Device is an autonomous system for automatic control the quality of the cardiac compressions (CC) during cardiopulmonary resuscitation (CPR). The prototype embeds hardware and software solutions that accurately measure the CC depth, rate and chest recoil. As the system provides a feedback about the efficiency of the cardiac massage, it is applicable as a training device for basic education in CPR or as a consulting system for life-savers at the scene of the cardiac incident.**

Keywords – **cardiac compressions quality monitoring, CPR training device, accelerometer.**

I. INTRODUCTION

Cardiac compressions (CC) are part of the cardio-pulmonary resuscitation (CPR), which is a life-saving first aid given in case of sudden cardiac death. One cardiac compression has two phases: (i) an active phase, when the force is applied downwards on the chest, and (ii) a passive phase, when the pressure is released and the chest is allowed to recoil to its initial shape. During the active phase, the heart is squeezed between the sternum and the spine, compressing the ventricles and causing blood to be pumped out to the lungs and the body. Venous blood returns to the heart during the passive phase, flowing through the atria and into the ventricles. During the passive phase, venous blood will return to the heart only if the intra-thoracic pressure is lower than the intra-abdominal pressure. Therefore, the recoil of the chest is critical to the effectiveness of CPR.

Performing qualitative CPR in the treatment of cardiac arrest may increase the patient's chance of survival and may improve the outcome for a complete neurological recovery [1]. The American Heart Association 2005 Guidelines for CPR [2] state that methods should be developed to improve the quality of CPR delivered at the scene of cardiac arrest by healthcare providers and lay rescuers. The Guidelines define the requirements supporting the optimal metabolic environment for the heart so that the defibrillation to result in a return of spontaneous circulation. In the view of chest compression quality, there are three key components that should be considered:

- Optimal compression rate is 100 compressions per minute (cpm), regardless of the number of rescuers or whether or not an advanced airway is in place.
- Optimal compression depth is 4 -5 cm.
- It is vital to relieve all pressure off the chest and allow it to completely recoil during the passive phase.

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Many studies on manikins report inadequate CPR performance and a need for improvement of the basic CPR skills of professional rescuers from the emergency medical services, paramedics and lay persons when a real-time audiovisual feedback system (e.g. Automated Voice Advisory Manikin System) is provided [3, 4, 5].

The present work is aimed at designing a system for monitoring the main CC quantities, and feeding back an indication about the efficiency of CPR. This system can be used for basic education in CPR, as well as on humans in cardiac arrest.

II. HARDWARE SOLUTION

The block diagram of the Cardio Compression Control device is presented in Figure 1. It includes a POD with compression sensors, a Display Unit, and a cable connecting the POD with the Display Unit.

The POD is equipped with a 3-axis accelerometer (ADXL330, Analog Devices) mounted on a printed circuit board parallel to the surface of the POD. Thus the whole assembly is designed to produce an acceleration signal on the accelerometer Z-axis output during the up-and-down movements related to the cardiac massage. Any parasitic horizontal movements could be detected by measurements along the accelerometer's X and Y axes and the lifesaver could be warned in a feedback. The POD is equipped also with a force activated switch, mounted just beneath its flexible upper surface. The idea is that any applied vertical force is activating the switch, thus the lack of switch activation is a reliable feedback about the complete recoil of the chest.

A cable connection is used to interface the POD (its accelerometer and switch outputs, power supply) to the main processing blocks in the Display Unit.

The Display Unit embeds electronic circuits designed to provide the acquisition, signal processing and indications concerning continuous monitoring of the cardiac compressions quality. The autonomous operation of the Display Unit is controlled by PIC24HJ256GP206 microcontroller, which handles all operations related to data sampling and signal processing. All results are presented by a simple indication output, designed for easy apprehension by the human eye. Sets of light-emitting diodes (LEDs) are used to display independently the compression depth, rate and chest recoil. Green LEDs in each set indicate the normal ranges of depth, rate and the recoil. Such indications facilitate the lifesavers who have to keep only green lights blinking to be sure that the massage is performed correctly. The lighting of red LEDs is an instant visual warning for disturbance of the compression quality and the position of the red LED (weak depth, extreme depth, low rate, high rate, incomplete recoil) is just a simple feedback for the CC correction needed.

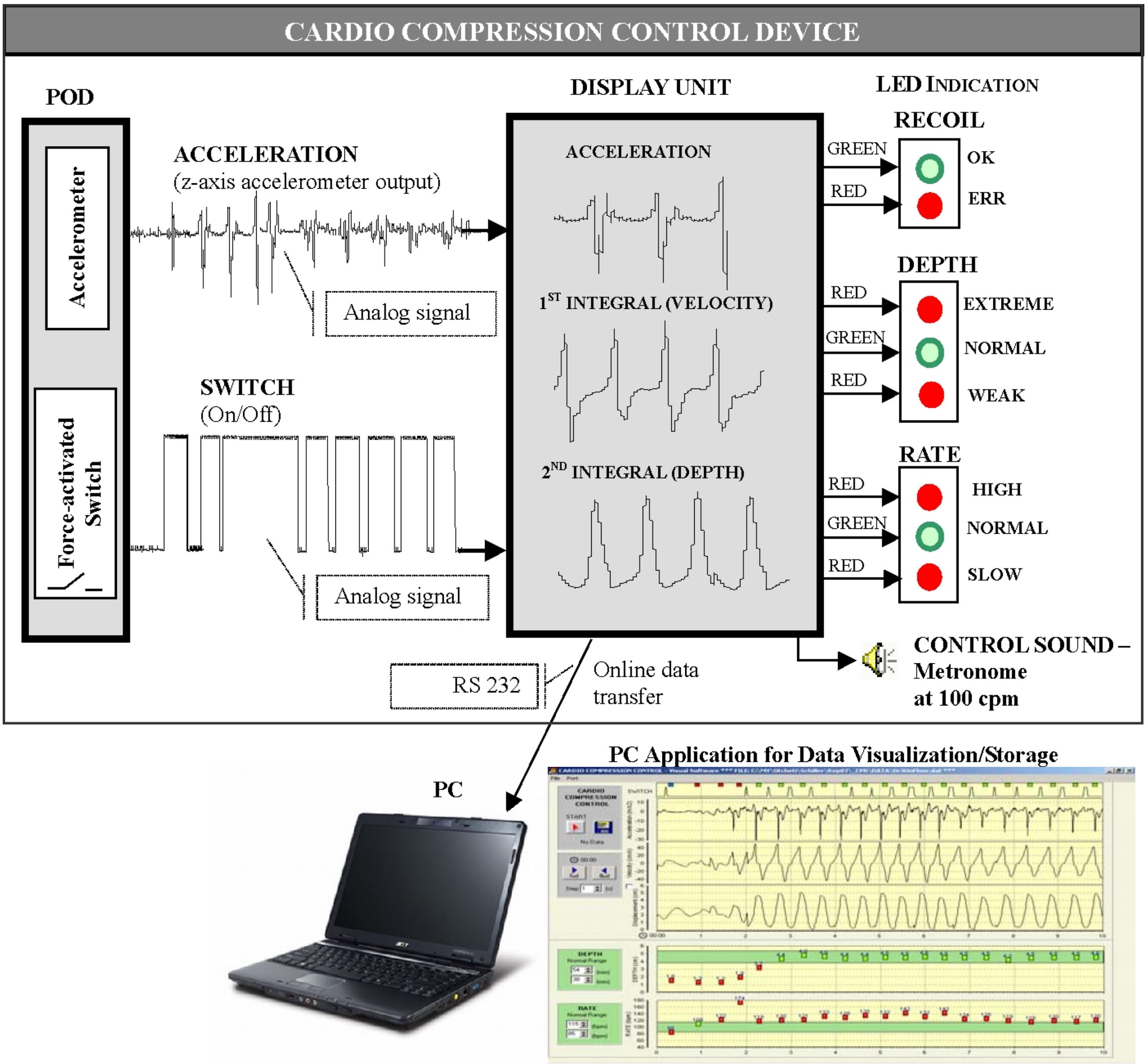

FIGURE 1. BLOCK DIAGRAM OF THE CARDIO COMPRESSION CONTROL DEVICE (CC DEVICE): THE SIGNALS GENERATED BY THE POD'S COMPRESSION SENSORS (ACCELEROMETER AND FORCE-ACTIVATED SWITCH) ARE PROCESSED IN THE DISPLAY UNIT TO PRODUCE ADEQUATE LED INDICATION ABOUT THE CHEST RECOIL, COMPRESSION DEPTH AND RATE. ONLINE DATA TRANSFER IS PROVIDED FOR TESTING PURPOSES INCLUDING SIGNALS VISUALIZATION AND STORAGE.

An assistant for the lifesavers is the build-in Metronome Control Sound. It is beating the time of compressions with an optimal rate of 100 cpm according to the recommendations.

The application of the designed prototype on a manikin is presented in Figure 2. The POD should be placed on the chest, so its shape is designed with an ergonomic consideration to fit best at the lower third of the sternum.

III. SIGNAL PROCESSING

Step 1: Detection of the CC cycles with period $\boldsymbol{T}$ [s] used for calculation of the CC rate (Eq.1):

(1) $$CCrate = 60/T\ [cpm]$$

Step 2: Measurement of the compressions depth by fast algorithm for double integration over the acceleration samples $\boldsymbol{a}$ in one CC cycle $\boldsymbol{T}$.

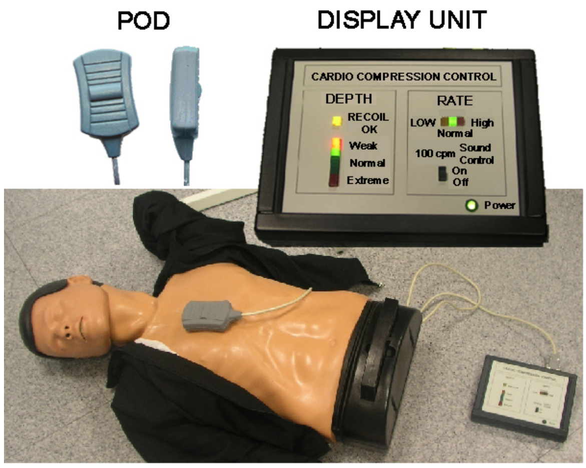

FIGURE 2. CARDIO COMPRESSION CONTROL DEVICE USED ON A MANIKIN. THE POD WITH COMPRESSION SENSORS IS DESIGNED TO FIT AT THE STERNUM. THE DISPLAY UNIT IS EQUIPPED WITH LEDS INDICATING THE QUALITY OF THE MASSAGE.

The first integration (Figure 3, 3rd trace) calculates the velocity ***v*** for each consecutive sample ***i***, according to Eq.2:

$$(2) \qquad v_i = \Delta t \sum_{1}^{i} (a_i) \Big|_{i=1}^{n}$$

where ***Δt*** is the sampling period; ***n=T/Δt*** is the number of the samples in one CC cycle ***T***.

The second integration (Figure 3, 4th trace) calculates the displacement ***s*** for each sample ***i***, according to Eq.3:

$$(3) \qquad s_i = \Delta t \sum_{1}^{i} (v_i) \Big|_{i=1}^{n}$$

The total depth of one full CC cycle is found by the peak-to-peak measure of ***s*** (Eq.4):

$$(4) \qquad \Delta s = [\max(s) - \min(s)]$$

Step 3: The signal from the force activated switch (Figure 3, 1st trace) is checked between each two consecutive CC cycles. If the switch does not turn off, incomplete recoil is detected.

IV. Results

Planned experiments

The correct work of the CC device was verified with a set of experiments on a manikin. The indications of the CC device were compared to the manikin's reference indications about rate and depth of the chest compressions. A real experiment in Figure 3 shows four simultaneous signals: switch output, acceleration, velocity and displacement, as recorded and calculated by the CC device.

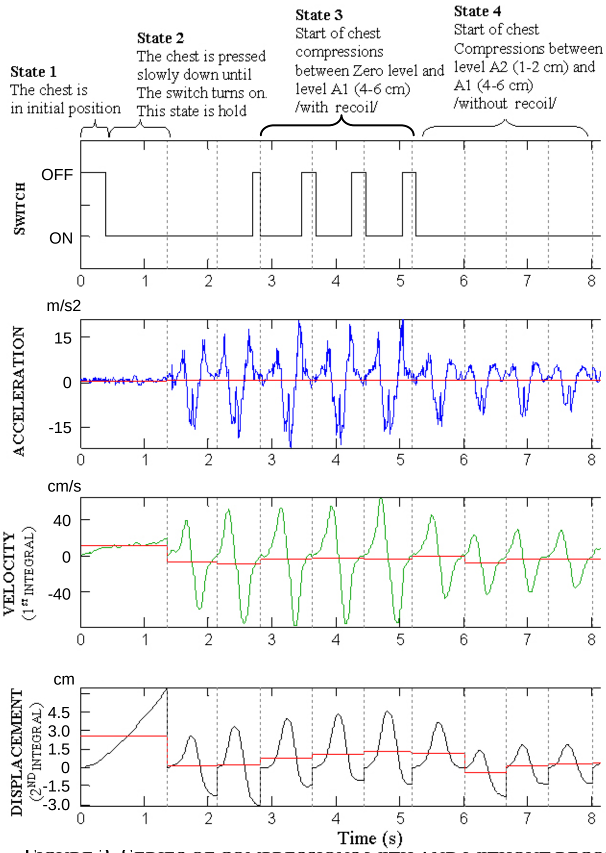

FIGURE 3. SERIES OF COMPRESSIONS WITH AND WITHOUT RECOIL PERFORMED BY KEEPING RELATIVELY EQUAL BOTTOM DEPTH POSITION A1 (4-6 CM). THE MEASURED AMPLITUDE OF THE COMPRESSIONS WITH AND WITHOUT RECOIL IS DIFFERENT.

State 1: the chest is in its initial position (named also Top Dead Center or Zero level) – the switch is OFF, the acceleration is zero.

State 2: the chest is pressed slowly down until the switch turns ON; the acceleration still remains at about zero.

State 3: a series of three chest compressions with recoil between Zero level and level A1 (about 4-6 cm in depth). The peak-to-peak amplitude of the calculated displacement corresponds to this depth. The switch was also activated three times as the number of compressions. The switch activation phases are described in figure 4.

State 4: a series of four chest compressions without recoil between level A2 (1-2 cm in depth) and level A1 (4-6 cm in depth). The peak-to-peak amplitude of the displacement is reduced compared to State 3, correctly measured to be about 4 cm. The switch is permanently turned ON, which is the indication for incomplete recoil.

Figure 4 presents the switch signal superimposed with both the acceleration and the calculated displacement. This illustration confirms the correct operation of the switch:

(1) the switch turns from OFF to ON state just after the beginning of the up-down movement, identified from the first fast rising front of the acceleration and the displacement near to its minimum;

(2) the switch keeps its ON state during the active phase, identified by the rapid change of the acceleration during the up-down and the down-up movement. This concurs with the rising and the falling phase of the displacement, corresponding to the gradual chest concavity and the gradual chest release during the compression;

(3) the switch turns from ON to OFF state just after the chest is almost fully released during the final phase of the down-up movement, identified from the slowing down front of the acceleration, and from the displacement near to its minimum.

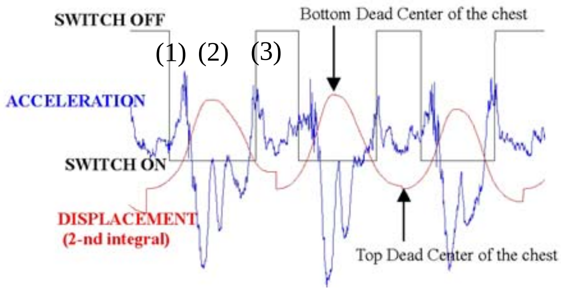

FIGURE 4. SWITCH OUTPUT, ACCELERATION AND DISPLACEMENT.

Experiments with a medical team

Initial in-hospital testing of the CC device was done in the Coronary Care Unit of the National Heart Hospital, Sofia, Bulgaria. Twelve members of the medical team, working in the unit but not trained in basic CPR skills, were asked to perform CC on a manikin by using the prototype of the CC device. The prototype was applied in the same way as it should be used for training of first responders. The manikin was placed on the floor. The POD was put on the chest of the manikin, and the Display Unit provided: (i) LED indication as a feedback of the compressions depth, rate and recoil; (ii) metronome sound to pace the compression rhythm. The operation of the CC device was observed in real-time on PC supported by in-house developed software for data transfer, visualization and data storage (Figure 1).

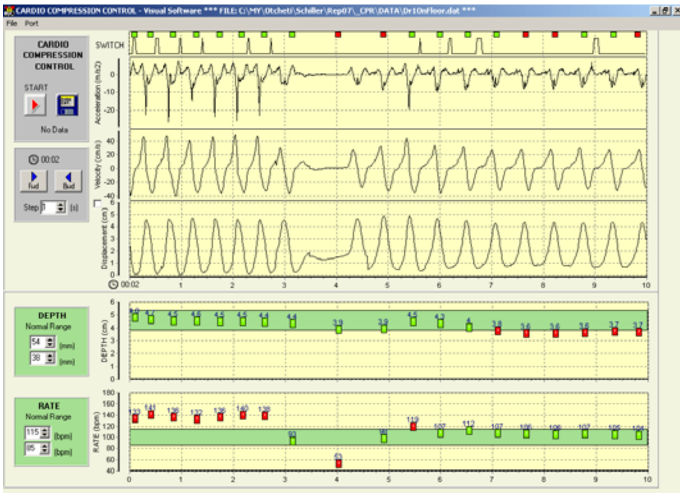

FIGURE 5a. RECORDED FIRST ATTEMPT OF A CARDIOLOGIST FOR CPR ON A MANIKIN: START WITH PROBLEMATIC HIGH CC RATE (~135 BPM); WHEN TRYING TO ADJUST THE CC RATE, THE CC DEPTH DECREASED BELOW THE LIMIT (<3.8 CM); PROBLEMS WITH THE RECOIL ARE ALSO OBSERVED.

FIGURE 5b. AFTER TRAINING, THE SAME CARDIOLOGIST SUCCEEDS TO PROVIDE CPR MASSAGE WITH STABLE MOVEMENTS, WHICH SATISFY THE REQUIREMENTS FOR CORRECT CC RATE, DEPTH AND RECOIL. HE WAS TRAINED TO CONTROL HIS STRENGTH AND RATE APPLIED DURING THE MASSAGE.

Figure 5a shows the signals and the indications recorded during the first attempt of a volunteer to perform CC on a manikin. This is a typical example of how the CC device works as a feedback guide for the compression corrections needed. The participant started with correct chest recoil and adequate compression depth but with too rapid rate. After a warning from the device, he slowed down the compression rate but at the same time he decreased the compressions depth, as well as some incomplete recoils occurred. After a training period of 35 seconds (Figure 5b), the same participant succeeded to maintain periodical chest compressions over time with a rate corresponding to that of the metronome, depth within the range of the 'green zone' and recoil 'OK' at the end of each CC. According to the protocol, the training process lasted maximum 3 minutes and if the participant succeed to maintain adequate chest compressions for at least 10 seconds he was asked to stop.

Table 1 shows the abilities of all participants in the experiment to perform CC massage on a manikin before and after training with the CC device. Only about 30 % of the participants begin with normal depth. After training to follow the feedback with green LED indications, 3 out of 7 cardiologists who started low depth CC, as well as the one who started with extreme depth CC, succeed to correct their chest compressions within the normal levels. Nevertheless, 4/7 participants, kept low depth CC along the test. It seemed that they did not have enough strength to maintain chest compressions with normal depth.

TABLE 1. CLASSIFICATION OF THE CC ATTEMPTS OF ALL 12 PARTICIPANTS ACCORDING TO THE ACHIEVED DEPTH (LOW, NORMAL, EXTREME), RATE (SLOW, NORMAL, RAPID) AND RECOIL (OK, ERR) MEASURED BEFORE AND AFTER TRAINING.

Parameter	Indication	First CPR attempt	CPR attempt after training
Depth	Low	58.3 % (7/12)	33.3 % (4/12)
	Normal	33.3 % (4/12)	66.7 % (8/12)
	Extreme	8.3 % (1/12)	0 % (0/12)
Rate	Slow	33.3 % (4/12)	0 % (0/12)
	Normal	33.3 % (4/12)	91.7 % (11/12)
	Rapid	33.3 % (4/12)	8.3 % (1/12)
Recoil	OK	75.0 % (9/12)	91.7 % (11/12)
	ERR	25.0 % (3/12)	8.3 % (1/12)

When the participants were trained to keep normal compressions rate, they observed the LED indications and simultaneously listened to the control sound of the metronome with a rate of 100 cpm. This technique proved to be effective since only 1 out of 12 persons did not succeed to correct his movements to follow the nominal rate of 100 cpm.

The indication for a recoil error helped 2 out of 3 participants to begin to release their hands from the chest.

V. CONCLUSIONS

In this study, we proved the capacity of the designed CC device to measure adequately the chest compression quantities. By real-time audiovisual feedback for the quality of CC, the abilities of the trained persons are improved to achieve and to maintain correct CPR massage.

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