Application of Robot Manipulator for Cardiopulmonary Resuscitation

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Abstract. This paper presents an application of a robot manipulator to perform Cardiopulmonary resuscitation(CPR) in emergency situations. CPR is one of the most important treatments which serves to save patients in cardiac arrest. The proposed robot CPR system attempts to overcome the limitations of current CPR methods in two aspects. First, it can provide much more consistent CPR than humans in terms of strength and timing. Second, biological data of a patient can be used to determine the best compression point during CPR. The feasibility of the proposed system is demonstrated through experiments: one simulation on a mannequin and two animal tests. It is also expected that this robotic CPR system can be a good platform to investigate many aspects of CPR methods and guidelines with accurate measurements and actions.

Keywords: Cardiopulmonary resuscitation, robot manipulation, medical robot

1 Introduction

In the field of emergency medicine, cardiopulmonary resuscitation is an important treatment which is used to save the lives of people in cardiac arrest [1]. Hence, there are international guidelines for CPR to improve the quality of this treatment. The quality of CPR is evaluated in terms of the depth, the rate, and the continuity of compression [2]. Guidelines suggest that those performing CPR compress a patient's chest by 5 cm at a rate of 100∼120/min for at least two minutes [2][3]. Despite these guidelines, proper CPR is not performed consistently due to insufficient human stamina levels. The required guidelines are difficult to meet for nonprofessionals and even for professional medical personnel. Furthermore, improper CPR can even cause the death of a patient in cardiac arrest. Therefore, several people must alternate when performing CPR, which causes a blank period during switching.

Automatic CPR devices are developed to provide CPR in emergency situations [4] [5] [6]. However, these automatic devices cannot deal with various cases on different people, because they compress only one fixed point and have a limited size. Also, these devices bind the chest for compression and they must be unbound from patients to move their compression point, and this unbinding also causes blank periods. Moreover, the performance of these devices is insufficient to satisfy international CPR guidelines. X-CPR, for example, a 1DOF pneumatic type of device, lacks the power to compress to 5 cm.

In this paper, a robot CPR method is suggested to overcome the problems associated with conventional CPR method. The robot manipulator can deal with a greater variety of patients, as it can change its compression point without stopping CPR and has a larger workspace than conventional automatic CPR devices. It can also change its compression point if there is better position to compress. Furthermore, it is powerful enough to compress 5cm and it can repeat compression regularly for a long period of time without blank periods.

This paper is organized as follows. Section 2 presents an overview of the robot CPR system and details its manner of compression. In section 3, the experimental set-up, the process of the experiments, and the results will be presented. The paper is concluded in section 4.

2 Technical Approach

2.1 System Overview

The entire system is organized as shown in Fig. 1. The proposed CPR system is composed of three main components: a robot manipulator, an integrated user interface, and the monitoring devices. The first element is a robot manipulator which performs CPR. The VM-6083G model (DENSO, CO., LTD, Japan) [7] was selected as the robot manipulator because it has enough power to perform CPR. The robot manipulator can also move the compression point and can, therefore, solve a problem of conventional automatic CPR devices, which can only compress one fixed point. The second element is an integrated user interface.

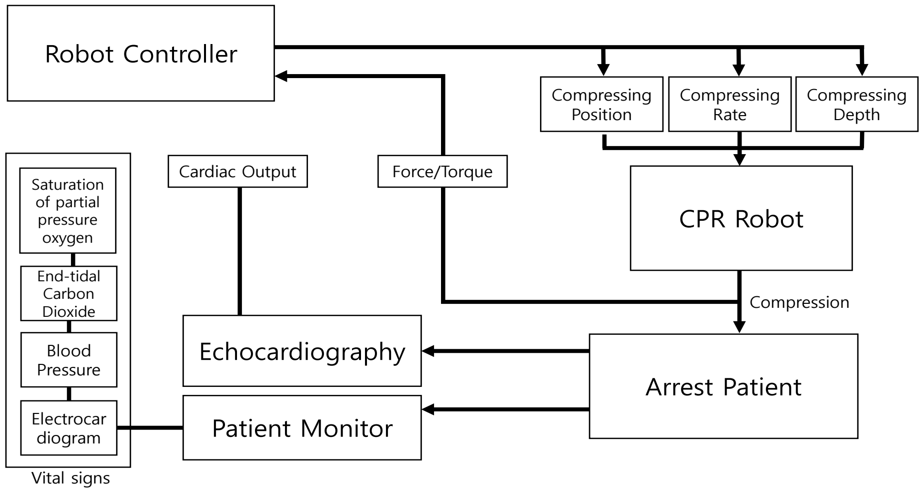


Fig. 1. Block diagram for the entire Robot CPR system. Biological data are acquired from a patient in cardiac arrest, and the robot controller controls the position, rate, and depth of compression.

The integrated user interface offers two functions for control of the robot. One is the remote control of the robot manipulator with a 3D mouse [8]. Given that the robot manipulator needs to be guided to a compression point by a human in the initial state of the CPR process, each position and orientation of the end-effector are mapped to a 3D mouse to move the robot. The second function is a Graphical User Interface (GUI) that enables human intervention and shows the state of the robot while CPR is in progress. The last element consists of monitoring devices that provide the operator with the current state of the patient.

2.2 Compression Methods

For the robot CPR system to perform efficiently, compression needs to be performed at the point where the largest cardiac output can be generated. In addition, the robot needs to perform the compression at the surface of the patient, and it should not inflict too much force. For these reasons, there are several types of feedback in the system, as shown in Fig. 1. First, monitoring devices to check the patient's state and the influence of CPR are added. The vital signs and echocardiography image are displayed on monitoring devices. The output image of an echocardiography device is used to compute the cardiac output caused by CPR with a Gabor filter [9]. An operator can control the robot manipulator based on these data to find the point where better vital signs are shown. Second, a Force/Torque sensor is used to guarantee that the top dead point of compression is always at the surface of the patient. The height of the chest is uneven, and compressing the patient with a heavy load would cause deformation of the chest. Therefore, force feedback is used to detect the change of the height

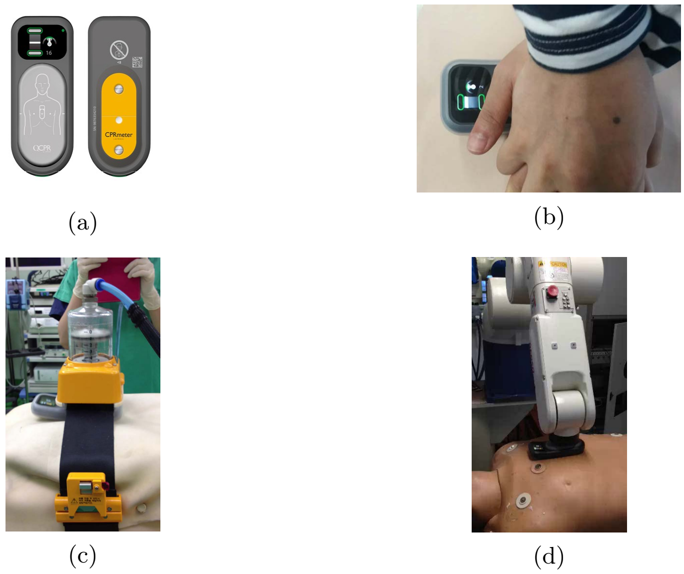


Fig. 2. CPR simulation using a mannequin and Q-CPR: (a) Q-CPR [10], (b) Manual CPR, (c) X-CPR, and (d) Robot CPR

of the compression surface and modify the top dead point of compression. This ensures that the robot operates at an appropriate height so that it does not either over-compress or under-compress a human chest.

3 Experiments and Results

Three experiments are conducted to compare the proposed robot CPR with conventional CPR methods. The first experiment is a CPR simulation on a mannequin to compare the performance of the manual CPR, X-CPR, and robot CPR approaches. The second experiment is an animal experiment to infer the actual effect of the system on cardiac arrest patients. The third experiment is also an animal experiment conducted to find the optimal position to compress by compressing several points. In the animal experiments, the End-tidal Carbon dioxide ($ETCO_2$) amount and the cardiac output are the influential factors related to CPR on patients [11] [12]. As the CPR process more closely follows the guidelines, the influencing factors become more similar to those of typical people who are in spontaneous circulation.

3.1 CPR Simulation

CPR simulation was performed on a mannequin and reference data were measured by a Q-CPR device [10]. As noted in Introduction, CPR is evaluated by

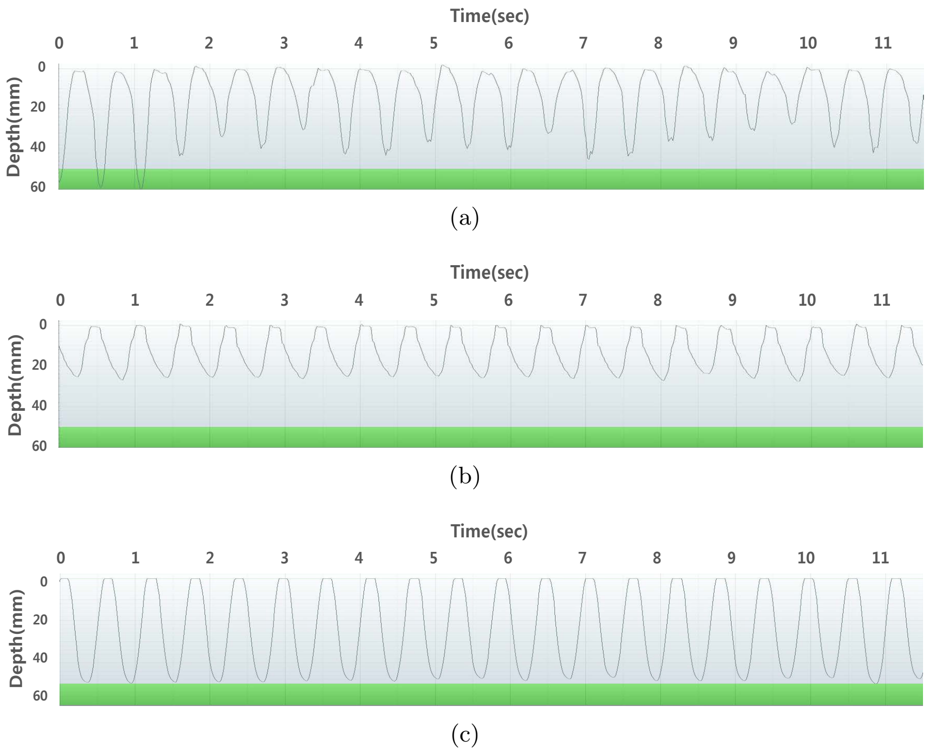
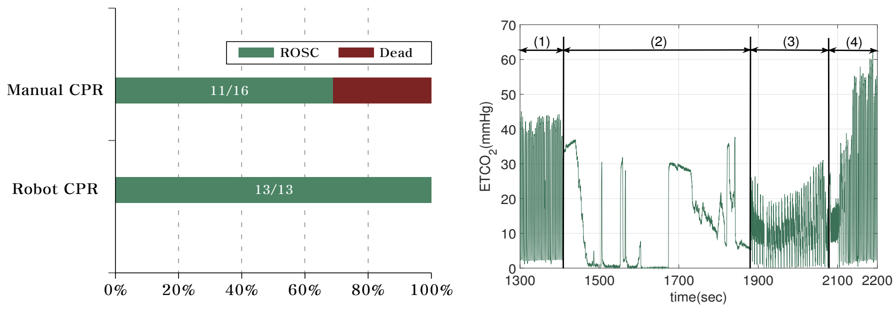


Fig. 3. Results of the simulation: (a) Manual CPR, (b) X-CPR, and (c) Robot CPR

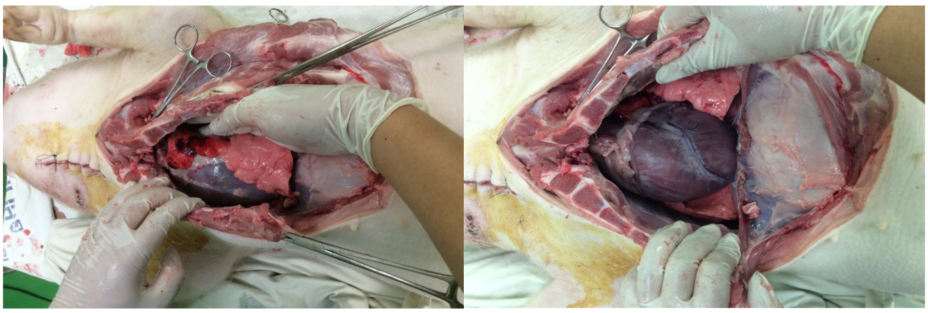
the rate of compression and the depth of compression which constitute the reference data acquired by the Q-CPR device. We can also observe the continuity of CPR with the acquired data. The measured depth from Q-CPR has errors in the millimeter range, because it uses an accelerometer to measure depth [10]. Thus, we used the measured data only for a relative comparison of the performance capabilities of the three types of CPR. Figure 2 shows the tested CPR types: the manual CPR, X-CPR, and robot CPR. The Q-CPR is placed on the chest of the mannequin and CPR is performed on the Q-CPR to measure the performance.

Figure 3 shows the result of this experiment. Figure 3(a) shows the depth and rate when CPR is performed by a human. Compression at the beginning of CPR fulfills the CPR guidelines. However, a decrease of the depth was observed over time. On the other hand, Fig. 3(b) and Fig. 3(c) show that the depth and rate are consistent when CPR is performed by the X-CPR and the robot manipulator respectively. Both methods adhere to the rate guideline, and the depth is held constant, but only the robot CPR meets the required depth from the guideline. In other words, X-CPR may not produce enough cardiac output, in contrast to robot CPR.



(a) (b)

Fig. 4. Results of the animal test: (a) Resuscitation rates for the Manual CPR and Robot CPR.(Return Of Spontaneous Circulation(ROSC)/Total Specimens), (b) $ETCO_2$ change during robot CPR: (1) Spontaneous Circulation, (2) Cardiac Arrest, (3) Robot CPR, and (4) ROSC



(a) (b)

Fig. 5. Anatomy after swine revival: (a) Lung state (b) Heart state

3.2 Resuscitation Test

A resuscitation test was conducted using a swine. With this animal test, the actual effect of robot CPR on actual arrest patients can be surmised. Twenty nine experiments were conducted. Sixteen swine were tested by manual CPR and thirteen were tested by the robot CPR. The swine were artificially placed in cardiac arrest and kept a no-flow condition for eight minutes, as neurological damage occurs at a rate of more than 50%, seven minutes after cardiac arrest [13]. After eight minutes, CPR was performed for three minutes and an electric shock was inflicted. In each case, if the swine did not revive, the process, i.e., performing CPR for three minutes and inflicting an electric shock, would be repeated several times. The detailed experiment protocol is explained in [14] and [15].

Fig. 6. Position numbering on the chest of a swine.

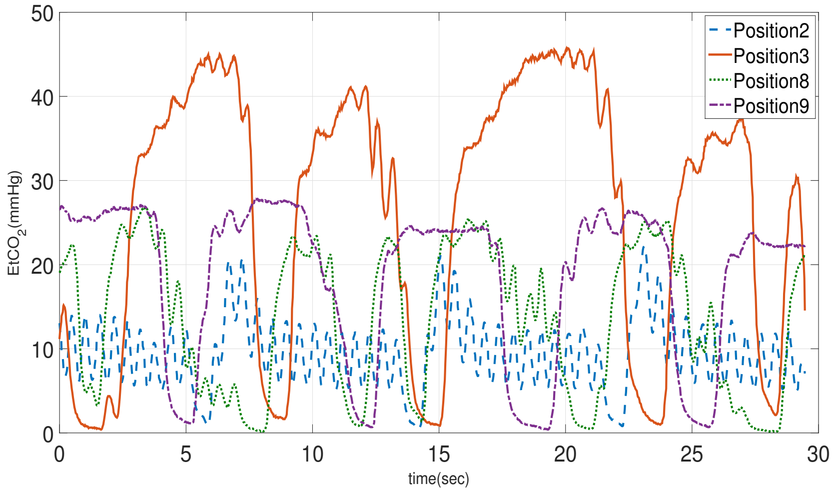


Fig. 7. $ETCO_2$ comparison according to the compression point during CPR

In this experiment, we acquired vital signs from a patient monitor and estimated cardiac output by the echocardiography image. The vital signs and the cardiac output data describe states of specimen, and $ETCO_2$ is mainly used to check the specimen's state during the resuscitation test. Figure 4(a) shows the resuscitation rate in the animal experiments. Robot CPR achieved a 100% resuscitation rate while the manual CPR showed a 69% resuscitation rate. The highest level of $ETCO_2$ during CPR needs to be at least 10∼20 mmHg ideally [15]. As shown in Fig. 4(b), the highest level of $ETCO_2$ during the robot CPR was over 20 mmHg, indicating that robot CPR was carried out successfully. Additionally, Fig. 5 shows that there was no harm in the important organs such as the lung and heart. Similarly, no bone fractures were observed.

3.3 Compression Point Comparison

The robot manipulator has the advantage of being able to move the compression point without stopping CPR, in contrast to conventional automatic CPR devices.

Moreover, the state monitoring feature allows for a comparison of the states when compressing several different points. Such a comparison can be used to find the best position to compress. Therefore, this experiment was conducted to verify the possibility of finding the optimal compression point. The test was also performed on a swine which was artificially arrested. The swine's chest was partitioned into several areas, as shown in Fig. 6 and the states of the swine were collected by the patient monitor.

Among the vital signs, $ETCO_2$ is used to check the specimen's state during the compression point comparison test, as the oxygen supply to the brain is important during cardiac arrest. Figure 7 shows the $ETCO_2$ readout of the swine while the robot compresses different points. Each position corresponds to the number shown in Fig. 6, and the distance between the positions is 3 cm. When the robot compresses position 3, the highest level of $ETCO_2$ exceeds 40 mmHg, while the values at other positions are lower than 30 mmHg. Considering that the $ETCO_2$ of normal breathing is 30$\sim$40 mmHg, compressing position 3 is much advantageous. From the result of the experiment, it is verified that the difference between compressing points induces the difference of nearly 30% in the supply of oxygen. Hence, it can be concluded that compressing position 3 will increase the probability of resuscitation.

4 Conclusion

In this paper, we proposed a robot CPR system that meets the international CPR guidelines and improve the quality of CPR. The main insight from each experiment is as follows. The first experimental result demonstrates that robot CPR outperforms conventional CPR methods. In the second experiment, a higher resuscitation rate was observed without special injuries to the subjects when CPR was performed with the robot manipulator. Hence, it can be inferred that people can also receive this type of CPR without injury. The last experiment demonstrated the possibility of finding the optimal position by comparing the effect of compressing different positions, indicating that the robot CPR system can much more effectively handle various patients and situations.

As noted in the results of the robot CPR assessment, the expected advantages include not only a high resuscitation rate in clinical practice but also a reduced cost in terms of manpower. Furthermore, if the process of finding the optimal position to compress can be automated, the effects of the robot CPR system will be enhanced even further. Also, the robot CPR can be used to investigate CPR more diversely in future experiments, as it acts and measures the data precisely.

5 Acknowledgements

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