Feedback derived from 3D Accelerometers used for Autonomous Correction of Chest Compression Movement in Cardiopulmonary Resuscitation Training

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ABSTRACT
This paper reports on an exploration whether feedback, derived from the comparison of a programmed baseline and actual chest compressions during cardiopulmonary resuscitation (CPR), will help trainees to improve their chest compression movement without the need for personal training by a coach.

A prototype is constructed that is used to investigate if it is possible to reliably detect chest compression movement and derive feedback from the comparison of that movement to a programmed baseline. Several methods to present the resulting feedback are implemented as well. An experiment is set up to test these feedback methods and to see how well the derived feedback allows the trainees to improve their skills.

The results show that reliable feedback can be derived from the 3D accelerometer of a SunSPOT device attached to the back of the hand of the person performing chest compressions. It is also shown that trainees markedly improve their chest compression skills after the feedback is presented to them. The method of feedback that uses audio is preferred by trainees, but measurements show a combination of audio, text and LED-based feedback leads to the greatest improvement of chest compression skills.

Keywords
Cardiopulmonary resuscitation, CPR, chest compressions, movement detection, feedback derivation, feedback presentation, movement correction, 3D accelerometer, sensor node, sensor nodes, SunSPOT

1. INTRODUCTION
To save lives by performing Cardiopulmonary Resuscitation (CPR), the correctness of movement is very important. Learning to correctly execute these movements requires several personal trainings from a coach and repetition of this training every few years. As sensor nodes become more prevalent every day, perhaps they might assist a coach in managing larger groups of trainees. This could be achieved by providing feedback, derived from such a sensor node, to the trainees. This way, trainees would not require constant supervision by the coach, but can instead correct their movement themselves. Another possible advantage is that feedback derived from the measurements of sensor nodes would allow trainees to improve their skills in their own time, so they can practice even when their coach is absent.

Chest compressions are a vital component of CPR and therefore in saving someone’s life. It is essential that these chest compressions are executed in the correct rhythm and with a solely downwards motion.

A lot of research has been done in the field of movement detection and comparison between movements, but little is known about presenting feedback derived from this comparison to the trainees, allowing them to improve their movement themselves.

For instance, technology using 3D accelerometers to accurately detect movements and match these onto an activity has already been investigated previously [3]. The resulting conclusion that movements can be accurately detected and classified, paves the way for the derivation of meaningful feedback from this. The technology to compare the movements of a coach to those of his trainees has also been investigated [4]. That research has shown it is possible to discriminate between spatial and temporal differences and derive feedback from those differences. Technology to match activities to an offline stored baseline has also been investigated before [4] [7].

Much is known about the way chest compressions should be performed. For instance, the chest compression depth and rhythm relate closely to the amount of oxygenated blood perfusion to the organs. Currently, reviewing whether trainees are correctly performing the necessary movements is done using manikins that resemble human torsos [2] [5].

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Figure 1: CPR Manikin
These manikins (Figure 1) can contain sensors that measure compression depth, compression rhythm and hand position. However, due to all these integrated sensors, the cost of these
manikins is at least three times as high as the cost of a manikin without sensors.

Research into the use of accelerometers to measure compression depth during CPR has shown that it can be reliably detected within an acceptable margin of error [1].

Once the chest compression movement is successfully detected and a comparison is made with a baseline, the resulting feedback must be provided to the trainee. This can be done in several ways. The real time acceleration data will be used to generate the feedback and that will be transmitted to a computer, which will then display it on its screen or play audio feedback on its speakers. If the device itself is also capable of presenting feedback, that may be another option to explore. User experiments will have to determine which method of feedback or which combination thereof is most successful in improving the participants’ chest compression movement.

1.1 Research questions

This study will focus on whether or not the feedback derived from the comparison of measurements from sensor nodes and a stored baseline can help CPR trainees improve their chest compression skills. Also researched is whether they feel they have improved just as much without involvement of a coach as they would have if a coach was present.

This research answers the following question:

How well can useful, real time feedback be derived from the comparison of a trainee’s movement and a stored baseline and how well can it be used to improve the trainee’s movement?

To completely answer this question, the following questions should be answered as well.

How reliable is the feedback derived from the real time comparison between a programmed baseline and a trainee’s movement?

How useful is the derived feedback in the process of improving movement?

2. HARDWARE

Since human movement is performed in all directions and detecting and correctly classifying this movement is necessary for this research, it requires the use of one or multiple 3D accelerometers. Present day smartphones are capable of detecting movement using 3D accelerometers and performing complex calculations, but are not well suited to be attached to body parts due to their size and weight.

SunSPOT devices (Figure 2) house a 3D accelerometer and also have a more manageable size of 41 by 23 by 70mm, weighing 54 grams. This is thicker, but much smaller and lighter than conventional smart phones, so it can be more comfortably attached to body parts. SunSPOTs also have the ability to communicate with each other and with a base station connected with a computer. Real time communication with a computer is a requirement for this research since a computer will be used to present feedback to the user. Therefore SunSPOT technology qualifies well to measure the movement in the experiments.

It is expected that compression rhythm and deviation from a downward motion can be measured using the 3D accelerometers of SunSPOTs [1][3].

The SunSPOT devices are programmed using the software development kit (SDK) that is included with the devices. The SDK provides ready access to the 3D accelerometer by use of three functions, each returning the current acceleration in G-force along one of the three axes of movement.

3. METHODOLOGY

3.1 Measurement

The SunSPOT’s 3D accelerometers are continuously polled to determine what the current acceleration along the different axes is. If the downwards acceleration breaches a threshold (see section 3.6) that breach is considered the downward movement of a chest compression. During this time, any horizontal acceleration will be measured to see if there is any deviation from the downwards motion that can diminish the effectiveness of the chest compression. The downwards acceleration will remain being polled to see when it stops and an upwards acceleration is detected. Once this happens, the chest compression is considered finished.

The time it takes to complete five chest compressions is measured and is used to calculate the compression rhythm in beats per minute.

3.2 Baseline

A lot of research has been done as to the correct way to perform chest compressions [6]. As a result of this research and the resulting quantification of chest compressions, the baseline can be programmed. It will consist of a desired rhythm of 100 beats per minute (BPM) and the fact that only downwards pressure should be applied, any deviation is a waste of energy and can potentially decrease the effectiveness of the chest compressions.

3.3 Feedback derivation

The computations necessary for the comparisons can be performed on the SunSPOTs. An algorithm will be implemented that checks if the measurements described in section 3.1 are in line with the baseline. If this is not the case, it is determined whether the compression rhythm was wrong or there was sideways movement.

Checking these measurements against the baseline is done on the SunSPOT so all raw acceleration data does not have to be sent over the air to a base station. This would cause a delay in the measurements since the SunSPOT cannot send data as fast as it can poll its accelerometer.

The generated feedback can either be used by the SunSPOT itself or can be sent to a computer with a base station attached.

3.4 Feedback presentation

Every five compressions, when the feedback is ready to be presented to the user, there are several options to do so. One option uses the LED array on the SunSPOT to indicate the correctness of the compression rhythm. Another option is to send the derived feedback to a computer and have the computer display the feedback in text form to the trainee.

Figure 2: The SunSPOT device

SunSPOT devices (Figure 2) house a 3D accelerometer and also have a more manageable size of 41 by 23 by 70mm, weighing 54 grams. This is thicker, but much smaller and lighter than conventional smart phones, so it can be more comfortably attached to body parts. SunSPOTs also have the ability to communicate with each other and with a base station connected with a computer. Real time communication with a computer is a requirement for this research since a computer will be used to present feedback to the user. Therefore SunSPOT technology qualifies well to measure the movement in the experiments.

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The final option is to use audio as a means of feedback. The feedback is again sent to the computer which then will play a prerecorded message with the feedback.

### 3.5 Number of sensor nodes and location

The first experiment will be performed in order to study how many sensor nodes are necessary to reliably detect the chest compression movement. In conjunction with researching the optimal number of sensor nodes, the best location for them on the body is also studied. This experiment will use estimated guesses and trial and error to establish the results.

It is expected that one sensor node on the hand of the person performing the CPR will deliver good results, but perhaps using another one on the person’s arm will lead to better ones. Another possibility is that a sensor node on the chest of the person receiving the CPR may deliver more accurate results. Various combinations of both location and amount will be tested and the resulting acceleration data will be examined to see which combination allows for reliable feedback. Another factor in determining the number of sensor nodes needed is the desire to keep their number as low as possible to keep interference with the trainee to a minimum.

### 3.6 Corrective Feedback

Also derived from the acceleration data are the measured forces during a single chest compression. Once it is known what number of sensor nodes is needed, where they should be placed and which measurements constitute a single chest compression, the baseline can be implemented. All this can now be used to implement the feedback derivation algorithm. The compression rhythm is determined by measuring how long it takes to complete five chest compressions. Since the recommended rhythm is 100BPM [6], five compressions should take around $60/100BPM \times 5\text{ beats} = 3\text{ seconds}$. It is not to be expected that a human being can keep the rhythm at exactly 100BPM, so feedback will only be given if the BPM deviates more than 5 percent from the 100BPM.

During the five compressions, movement along the other axes of movement is also measured and the maximum value is saved. In case this value exceeds the value determined during the first round of experiments, the user will be apprised of this. Since it is more important that the user performs the compressions in the correct rhythm than not wasting energy while doing so, and avoid that the amount of feedback will overload the trainee, this type of feedback will only be presented if the compression rhythm is correct.

#### 3.6.1 SunSPOT LED array

Feedback using the SunSPOT LED array is encoded as follows. If the rhythm falls within the margin of error and only downward pressure is applied, the entire LED array will flash green. Should the rhythm fall below 95BPM, the array will flash from left to right indicating the need for a speed up. If the rhythm goes beyond 105BPM, the array flashes from right to left, indicating a needed slow down. The greater the deviation from the baseline of 100BPM, the quicker the lights will flash from side to side.

Feedback about accidental movement along the other axes of movement is displayed by flashing the entire array orange.

#### 3.6.2 Text Display

Feedback using text display on a computer will display the word ‘OK’ in green text if the rhythm is correct and there is only downward movement. If the rhythm is incorrect, red text will be displayed with instructions on how to correct it. Orange text is displayed to indicate not only downward pressure is applied.

#### 3.6.3 Audio

When audio feedback is used, all feedback messages are read aloud. There are four pre-recorded messages. One indicating that the trainee is performing the chest compressions correct, two indicating the need for a speed up or slow down and one indicating that only downward pressure should be applied.

### 4. USER EXPERIMENTS

Once all three methods of feedback have been implemented, one should test which method trainees prefer. These experiments will use people who have limited to no experience in CPR as they have more room for marked improvement of their skills than experienced CPR performers.

First, a new participant will be told what the experiment will be about and how the feedback of the SunSPOT LED array is encoded. They will then be shown the correct placement of their hands on the dummy or dummy equivalent and the SunSPOT device(s) will be attached to their body. A laptop with a SunSPOT base station connected to it will be placed nearby to capture and present transmitted feedback to the participant using text or audio.

After the set up is completed, the participant will be told to perform chest compressions at 100BPM and follow the instructions provided by the feedback. One minute only the SunSPOT LED array is used as feedback. Next minute, only text feedback on the computer display is used. Yet another minute, the audio feedback is used. Finally, the fourth minute, all three methods are combined. The first three minutes will take place in a different order for every participant to minimize the influence of participants learning the correct rhythm as the experiment progresses in the aggregated end results. After each minute, a small pause is given to the participants to rest and to instruct them which method of feedback will be used next.

Every time corrective feedback is presented to the participant this is accounted and this should give an indication whether the amount of corrective feedback diminishes as the training progresses.

Since it is likely the user will have his attention on the dummy receiving the CPR, it is expected the SunSPOT LED array will prove to be the best method of feedback, if the SunSPOT is attached somewhere in the user’s sight.

During the experiments the user will be observed to see where he is looking and whether or not a positive change occurs after corrective feedback is presented. The amount of corrective feedback given as the experiment progresses is an indication of whether it has helped the trainees in correcting their movement: if less corrective feedback is given over time, then apparently the trainee has independently corrected his or her movement.

After the experiments, participants will be asked to fill out a questionnaire, answering the following items:

- Which method of feedback do you prefer? Why?
- Which method of feedback do you like least? Why?
- Do you feel the feedback helped you improve your chest compression skills?
- Would you prefer training using feedback from a device or do you prefer a coach being nearby? Why?
- Do you have any other comments?

The results from this survey, combined with the observations made during the experiment will lead to the results.
5. RESULTS
After the trial and error experiments that varied the number and location of the SunSPOT devices, it was found that chest compressions can reliably detected using a single SunSPOT attached to the back of the hand of the trainee. This means there is no need to synchronize or combine the output of several SunSPOT devices during the derivation of feedback.

A total of 11 people participated in the user experiments. The results from these experiments are measured by looking at the amount of corrective feedback over time for each method of feedback and their responses to the survey. First the amount of corrective feedback over time for each method of feedback is shown. The lesser corrective feedback is presented, the better the exercise is being performed. After these measurements, the answers to the survey are listed.

5.1 Measurements
Every five compressions, feedback is presented to the participants. Since each exercise takes one minute and the BPM should be around 100, this means there are 20 moments where feedback is presented. The following graphs show the total amount of corrective feedback for all participants, given at each of those 20 feedback moments.

Also calculated for every method of feedback is the average amount of feedback given at each of the 20 feedback moments. This is the total of times feedback was given divided by the amount of participants. The lower this value, the better that method is at reducing the amount of feedback, because less feedback means better chest compressions.

The results for feedback using the SunSPOT LED array are depicted in Figure 3.

Out of the 11 participants, an average of 6 people received feedback every feedback moment using audio. The results for audio feedback are shown in Figure 5.

The results for the feedback that combined all previous methods are as following: (Figure 6)

5.2 Questionnaire
The first question in the questionnaire asked which method of feedback the participants preferred. Out of the 11 participants, 5 (45%) indicated the audio feedback as preferred, 5 (45%) preferred the combined feedback and 1 (9%) preferred the text display. Participants that indicated the combination was best said it was mostly because the text feedback complemented the audio feedback. The LED array in the combination was only useful when it flashed green to indicate everything was OK.

The second question asked which method was liked least. Here, 6 of the 11 participants (55%) appointed the LED array; followed with 5 of the 11 participants (45%) saying the text display was liked least. Reasons for disliking the LED array was mostly that it was difficult to decode the feedback it was giving and that it was easily missed, since the hand was moving while the LEDs lit up. The reason for disliking the text display was unanimously that it was too passive; people forgot to look at it or overcorrected because the text changed only every 5 compressions.

The third question asked whether or not participants felt their chest compression skills improved as the experiment progressed. The answers were unanimous: Yes. Every participant felt their skills improved.
The fourth question asked if people were confident an autonomous learning experience such as this experiment resulted in the same skill level as training from a coach. Here, 6 of the 11 participants (55%) felt this was the case, while the other 5 (45%) felt it didn’t. The general sentiment among the participants who felt that training with a coach was more effective was that he could learn them other tips and tricks while they were exercising.

The fifth question was an open invitation for any other comment or feedback the participants might have had. One of the comments heard most was that the audio feedback became annoying once the exercise was performed correctly. The repeated reassurance that everything was going OK was experienced as irritating.

### 6. DISCUSSION
As can be seen from the graphics, the amount of corrective feedback over time diminishes for every method of feedback. This is a good indication that feedback derived from the measurements of the sensor node can be used to improve the chest compression skill of trainees.

Of the three individual methods of feedback, the audio feedback reduces the amount the quickest and keeps it at a low level for the duration of the exercise. Using audio feedback the amount of feedback is also lower than when using text or LED feedback.

Using text and LED feedback, a delay of several seconds is visible between the moment of feedback presentation and the moment people adapt their movement. The amount of feedback at the end of the exercise is also higher than with audio feedback.

The combination of all methods of feedback eventually resulted in the lowest amount of feedback. The reason the feedback started at a lower level was because the participants already practiced with the three methods individually beforehand.

The results from the survey seem to correspond to the measured effectiveness of every method. The survey showed that people preferred the audio feedback or the combined feedback. These methods were also most effective in improving their skill.

It was expected that the LED feedback would be most effective since that was in sight of the trainee and would not require him to divert his attention. But the LED array was deemed too difficult to read and easy to miss due to the movement of the SunSPOT. Instead, the audio feedback was preferred and worked best.

The reason that the feedback only reached zero once was not because one person was continually making mistakes, but that almost every participant who was doing the exercise all right every now and then made a mistake and then successfully corrected it.

### 7. CONCLUSIONS
The results show it is possible to derive feedback by comparing the movement of someone performing chest compressions to a programmed baseline. For this feedback to be reliably derived only an accelerometer attached to the hand of the person performing the CPR is sufficient.

Trainees presented with this feedback show a clear improvement of their chest compression skill. All of them also indicate that they experienced this improvement. More than half of them even think the autonomous training was as good as one with a coach.

Three ways to present the feedback were researched: using an LED array, using a text display and using audio. Trainees themselves preferred the combined feedback just as much as the audio feedback, but measurements showed presenting the derived feedback using a combination of the three was most effective in improving the skill of the trainees.

Comment from the participants shows that while audio feedback is a vital part of feedback presentation, providing too much feedback in this manner may annoy the trainees.

### 7.1 Future research
In this research, only the chest compression rhythm and accidental sideways motion were investigated. During chest compressions for CPR there are several other factors that are important, such as the compression depth and keeping the arms straight during compressions.

The compression depth can be measured using accelerometers [1] and would give trainees very useful feedback. Reaching the right compression depth will prevent potential injury to the person’s chest receiving the CPR and will increase the efficiency of the chest compressions [6].

Measuring whether the arms are kept straight might be possible using another accelerometer attached to the elbow of the trainee and providing feedback about that would allow a trainee to minimize the waste of energy.

### 8. REFERENCES


