Heart rate prediction for coronary artery disease patients (CAD): Results of a clinical pilot study

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Abstract. This paper describes the results of a pilot study with cardiac patients based on information that can be derived from a smartphone. The idea behind the study is to design a model for estimating the heart rate of a patient before an outdoor walking session for track planning, as well as using the model for guidance during an outdoor session. The model allows estimation of the heart rate several minutes in advance to guide the patient and avoid overstrain before its occurrence. This paper describes the first results of the clinical pilot study with cardiac patients taking β-blockers. 9 patients have been tested on a treadmill and during three outdoor sessions each. The results have been derived and three levels of improvement have been tested by cross validation. The overall result is an average Median Absolute Deviation (MAD) of 4.26 BPM between measured heart rate and smartphone sensor based model estimation.

Keywords. Coronary Artery Diseases, rehabilitation, heart rate, Cardiovascular Model, Decision Support Systems

Introduction

It is well known from literature that Cardiovascular Diseases are the number one causes of death by 48% worldwide [1]. In addition, one of the main prevention drivers is physical activity, which is also clearly stated in the guidelines for cardiac rehabilitation [2]. Also mentioned is that the physical activity must not stop with discharge, but should be extended for life time [3]. Therefore medical monitoring, guidance and alerting are essential. To support healthy people, sports tracker apps are already available at the marked, but those apps are not designed for cardiac patients taking β-blocker or other heart rate limiting drugs [4].

To support individual exercise planning, guidance and alerting for unexpected heart rates, a model was developed to estimate and predict the individual heart rate of a patient during outdoor walks, based on physical load and the patient’s stress test results. The physical load is estimated by using barometric pressure sensor, GPS and accelerometer available in today’s smartphones.

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1. Methods

The model can be used in a predictive way to estimate the heart rate on a given track for planning, but also while training to advise the patient to change track or movement speed to avoid possible overstrain [5]. Large differences between estimation and measured heart rate might also indicate an unhealthy state. The method is load based which implies that the model is fitted to the reaction of the heart rate due to load changes for every patient individually. The load is calculated by the model of Baruch/Givoni [6], which is defined as follows:

\[
M = n(W + L)(2.3 + 0.32(V - 2.5)^2 + G(0.2 + 0.07V - 2.5))
\]

where: 
- \(M\) = total energy cost in [kcal/h];  
- \(n\) = terrain factor (depending on the surface, provided in the paper for several surfaces);  
- \(W\) = body weight in [kg];  
- \(L\) = extra weight in [kg];  
- \(V\) = speed in [km/h];  
- \(G\) = gradient in [%]

This formula is designed to be applied during outdoor walks, as well as on a treadmill. This was used to correlate a treadmill step test to outdoor walking. During outdoor exercises, speed and slope were derived from GPS, accelerometer and barometric pressure sensor. On top of this formula, a model was developed which estimates the heart rate in correlation to the physical load. As an example, Figure 1 (left) shows the results of a treadmill step test, which is performed during rehabilitation to estimate patients’ physical capabilities. The lower dotted line describes the physical load processed by Baruch/Givoni, the black line illustrates the measured heart rate and the upper dotted line shows the model based on the parameters derived from this step test. In general a PT2 control element [7] describes the relation between physical load and heart rate in addition to the delay time for a reaction on a load change [8]. In Figure 1 (left), two boxes can be found marked “1” for increasing load and “2” for decreasing load. The upper dotted line shows how the PT2 control element reacts on the load change. The error between the PT2 control element based curve and the real heart rate during initial measurement is processed and defined as offset [8]. As a result, the sum of the PT2 based curve and the fixed offset is the estimated heart rate (upper dotted line). The parameters derived during the step test for the PT2 control element and the offset are used during outdoor walking on top of the Baruch/Givoni [7] model (cf. Figure 1, right). This shows the real heart rate in black, an estimation based on the step test results marked as dotted line.

The goal of the pilot study was to measure the accuracy of the model for cardiac patients in terms of outdoor walking, based on parameters derived from a treadmill step test and also improving those parameters on already recorded outdoor sessions.

![Figure 1. Result of a treadmill step test (left); result of an outdoor walk including several models (right)](image-url)
The model was tested during a small pilot study against 9 cardiac patients between 39 and 64 years of age (54.8 years average), suffering from Coronary Artery Disease (CAD). The study was designed to fit to the individual rehabilitation therapies of the patients. Inclusion criteria were: suffering from CAD and taking β-blockers. Exclusion criteria were: physical disabilities regarding walking and expected overstrain estimated by the physician due to the study design. The patients had a Body Mass Index (BMI) of 24 to 37, on average 27.5. Seven males and two females participated, whereas 7 of those were suffering from hypertension. Each patient was asked to perform one treadmill step test and three outdoor walking sessions. Due to sensor issues and one patient leaving the hospital early, overall nine step tests and 24 sessions have been recorded successfully.

2. Results

To derive the individual parameter set, every patient was recorded during a step test. The accuracy of the parameters fitted to the model can be seen in Figure 2 (left). For all patients the Median Absolute Deviation (MAD) between measured heart rate and the model estimation is, on average, 1.64 BPM. The error is 0 BPM per definition as during the fitting process the offset is defined as the average error. In the worst case the MAD is 3.07 BPM, in the best case 0.88 BPM. For this graph and all the following graphs three data sets are presented: The average error between heart rate and model (an unfilled box, in case of stress test 0 for all patients), the MAD between heart rate and model (filled box) and the MAD cleaned from the error (error indicator).

![Figure 2. Stress test results over all patients (left); outdoor session results based on stress test (right)](image)

The error indicator describes the MAD of the PT2 control element whereas the error shows the error of the offset and the MAD the overall deviation of the heart rate around the model. Therefore the overall MAD best describes the accuracy of the model. As the model has been fitted to the data sets in the left figure and the environment on the treadmill was very controlled, it is expected that these deviations cannot be reached during outdoor sessions.

In Figure 2 (right) the results of the outdoor sessions are presented. For better overview the session results are presented as average error of the MAD over all sessions per patient. Compared to the stress test results (left), it can be clearly seen that the average error for every patient is large, whereas the error indicators are only slightly larger compared to the stress test results. This shows that the PT2 control element is quite accurate compared to the offset, which caused the biggest part of the overall MAD. The maximum deviation over all patients is 11.92 BPM, 4.17 BPM at a minimum. The
average is 7.23 BPM. It can be clearly seen that the offset derived from the treadmill does not fit to the outdoor sessions. Therefore it was decided to test an improvement on the model. A new offset was derived from every outdoor session and the average of this offset and the step test offset has been generated and cross validated against the remaining outdoor sessions of the same patient. The results are shown in Figure 3 (left).

Figure 3. Results for three different levels of improving the offset derived from the step test.

It can be seen that the error indicators do not change in range compared to the outdoor session presented in Figure 2 (right). This meets the expectations as the PT2 control element was left unchanged. The average error for every patient decreased from -2.24 BPM to -1.21 BPM. The overall MAD decreased from 7.23 BPM to 5.94 BPM. Only for patient 8 the MAD increased. Due to sensor issues for this patient, only two training sessions are available, and the offset difference between those two sessions is very large compared to the other patients. The reason for this is unknown. However, as this improvement seemed to work well for all other patients, it was decided to test offset improvement based on two outdoor sessions and the step test for another cross validation against the remaining session of the same patient. As 24 sessions have been recorded successfully, only 7 patients did have 3 completed sessions available for cross validation. The results can be seen in Figure 3 (center). The error is in range of -3.50 BPM and 1.10 BPM, on average -1.80 BPM. Also the MAD for every patient decreases to between 5.88 BPM and 3.35 BPM, on average 4.26 BPM which is an acceptable result according to the physicians accompanying this study.

The last improvement step is taking daily conditions of a patient deeper into account and can therefore only be used as real time model. It processes the offset during an outdoor session for a continuous adaptation of the offset, starting on the parameter set of the second improvement level. This filters daily conditions and allows more accurate prediction for the next minutes during training. The error decreases to 0.35 BPM over all patients and the overall MAD decreases to 3.02 BPM.

3. Discussion

Even though that this was a first pilot study with only 9 patients, the results seem to be quite promising. The offset seems to be training modality depending, which was already observed in another study [8]. Figure 4 gives an overview of the results across all steps of improvement. It can be seen that in average the improvement steps decrease the error as well as the overall MADs. The maximum deviation was 14.63 BPM in the beginning and could be lowered to 11.34 BPM on the second improvement.
The real time model shows some improvements, especially for patients with a big offset error. The live model compensates this error very well and allows prediction of the heart rate several minutes in advance. This might allow detection of overstrain on a given track several minutes before its occurrence.

In summary, the pilot study shows that prediction of a cardiac patient’s heart rate by using smartphone sensors like barometric pressure sensor and GPS in addition to stress test results seems to be promising, but leave also space for further improvements. Following these results, the heart rate of a given patient can be predicted with the accuracy of around 5 BPM before starting to exercise, if speed and track is known. This can be improved to around 3 BPM during the training session. For future work this model needs to be checked against a larger datasets. However for the moment these results beat the expectations and are worth it to be investigated further.

References


