

# Biofeedback in the Wild - A SmartWatch Approach

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**Abstract**—The human body is one of the most complex biological organisms on our planet. A multitude of parallel, interleaving and sometimes opposing physiological and psychological processes can happen without, as a human being, be conscious about them. Biofeedback is a well-established method in clinical treatment providing humans awareness of the hidden signals their body is emitting and control over these signals under a variety of differently perceived situations. The epoch of smart wearables enables people to wear the necessary sensors and to view the abstracted visualizations on their wrist. In putting the formally stationary and clinical approach into everyday life, we see the possibility of a more effective treatment during the daily routines of people and therefore a shorter and more effective therapy phase. This work presents the design and implementation of a fully mobile biofeedback system utilizing a smartwatch enabling people to do personalized bio feedback training while being in their natural living habits with the possibility of being remotely monitored and guided by a professional trainer.

**Keywords**—SmartWatches; Biofeedback; Wearable Computing; Health Monitoring; Realtime; Bio Sensing System;

## I. INTRODUCTION

Biofeedback, basically the hidden feedback of the human psychology including heart rate and heart rate variability, can be a very useful indicator for doctors and therapists when treating patients suffering from stress symptoms or mental illnesses (e.g. panic attacks) [1]. The national institute of health (NIMH) defines Biofeedback as "a treatment technique in which people are trained to improve their health by using signals from their own bodies". The word "Biofeedback" was coined in the 1960s when researchers were examining the possibility of individuals altering their own involuntary bodily functions [2]. In simple words, "Feedback" is how the mind learns and processes information over time to enhance itself utilizing the bodily signals better. For example, when the body triggers a signal like pain or hunger, the mind senses this signal and responds according to the information within the signal. This process is repeated over and over again giving the mind the ability to learn the responses and to be able to produce them automatically or voluntarily [3].

Biofeedback at its simplest is a process that utilizes one or more sensing devices or instruments to provide the user with detailed information about their body that otherwise would not have been perceivable by the user. Not being able to perceive the body signals correctly can be traced back to a distortion in the highly complex mind-body relationship [4]. In most cases, bio signals are visualized for the user during a biofeedback training session and collected for later analysis [5].

Nowadays, state of the art training devices and methods help the patients to have reliable results when doing biofeedback training [6]. To achieve this, a combination of (i) measurement devices and interfaces for the user interaction and (2) visualization for feedback is needed. A lot of different sensors are used to collect bio signals like heart rate, heart rate variability, electroencephalography (EEG), respiration rate and more as exemplary presented in Fig. 1 during a reference biofeedback training session at a hospital. Often, disposable electrodes are attached to the chest, hands and other body parts of the user. The data is then transmitted to a computer with the biofeedback training software installed where the data is then visualized and stored for later analysis. This system in conjunction with trained professionals provide great results for the patients and users and can be a viable alternative for treating a variety of medical issues like high blood pressure, severe headache, panic attacks and heart problems.

During biofeedback training, the subject is exposed to variable levels of stress while data is being recorded. The collected bio signals are later analyzed by the therapist, providing valuable information about the subject's health status. This data can be a useful addition to traditional treatment methods like prescription medicines. Additionally, the data can be visualized live and used during the training session itself. This allows the subjects to sense, or to get a feeling about their biological signals which would, otherwise, not have been perceivable. As previously mentioned, this is the most common form of biofeedback. Typical use cases see the user taking control over certain body functions e.g., by changing the rate in which they breath resulting in a lower heart rate. Without proper health data and visual feedback, doing biofeedback training is not possible and is therefore mostly limited to mediated sessions at a hospital.

The current state of the art technology in this field is considered accurate enough for medical diagnostics. These systems are specifically designed for biofeedback training and have reached a very sophisticated level, but due to their high costs, complicated operating procedure and the overall bulky form factor, are not suitable to be used at home or alone on the go. When doing biofeedback training or a therapy, regular appointments are needed for the training to be effective. It is also very common for the users to do certain exercises in-between sessions. These exercises do not provide the same results as the ones in therapy since the biofeedback part is missing leaving even the doctors uninformed (i) if the

exercises were performed at all or (ii) their results in terms of measured body signals. Biofeedback training at home is supposed to be highly beneficial for the user's medical state. Recent progress in consumer-grade health monitoring devices and wearables enables the design and implementation of a more modern, practically usable and cheaper solution. Off the shelf consumer-grade health monitoring devices and wearables enable the design and implementation of an open, cheaper, daily usable, wearable system solutions that can even be embedded into technology users already have at home (e.g., smartwatches [7]).

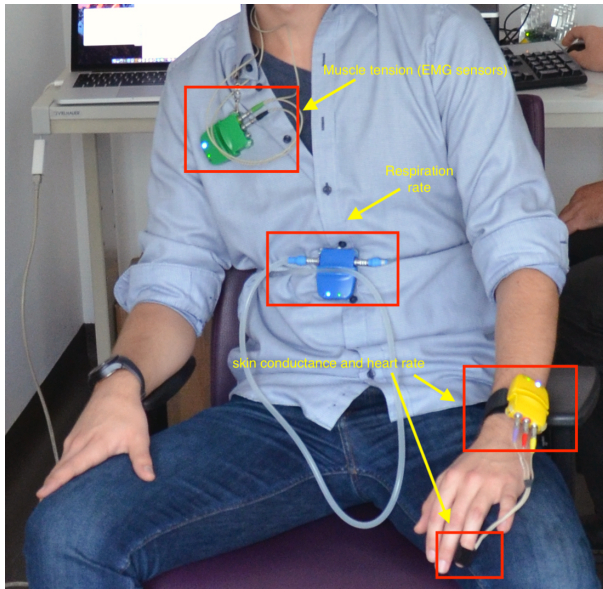


Fig. 1. Bulky sensors and modules attached to a user during a traditional biofeedback session renders the system stationary and not mobile. The user is put into an unnatural situation that biases the results of the training.

## II. SYSTEM DESIGN

The ability to do proper biofeedback training at home, in addition to the clinical treatment, would be beneficial for the patients and is supposed to improve their state of health drastically in a more controlled way [8]. To achieve this, a more usable, practical, and portable solution could lead to great improvements in the context of biofeedback training. An easy to use, cost-effective system allows the patients to do biofeedback training at home without the need to go to a specially trained therapist. BF training programs should be available on the system itself to allow users to conduct biofeedback sessions complementary to the ones in the therapist's office at home. With a carefully designed system that is easy to use even for elderly people, trained operators are no longer needed to moderate the sessions. This leads to far more cost-effective sessions which can be done on a more regular basis, even multiple times per day.

Today, the therapists do not have accurate health data of the patient doing everyday activities. This information could be useful in the context of analyzing the user's stress level in certain situations. The inclusion of bio signal data collection

during the day could help the therapist when coming to conclusions about the patient's condition and when planning out the next steps of the patient's medical treatment. In order for the system to be useful and practical, certain design criteria can be specified. These can be divided into four categories: (i) the hardware consisting of the mobile system responsible for collecting the biological signals in conjunction with (ii) a backbone server to archive the health data and training programs; (iii) to use the hardware, a sufficient software system is needed, including a realtime interface for the therapist to visualize the data and plan remote training sessions; and (iv) training programs and usability completes the design of the portable solution.

### A. Design of a mobile solution

The following concept describes the idea of a mobile biofeedback monitoring and training system.

**Sensors and hardware:** For the system to be usable for biofeedback training, a variety of sensors needs to be available. Ideally, every sensor that is available on a conventional biofeedback training device should be compatible with the portable system. This includes heart rate and heart rate variability (HRV), EEG, respiration rate and many more [9]. Additional context information like performed activities or location/movement patterns can be easily included in utilizing a smartwatch as the interface for the user.

Besides the large variety of smart devices that can be used, the accuracy plays an important part in designing a useful biofeedback system. Inaccurate sensors can lead to a wrong diagnosis when analyzing archived data. During BF training sessions, they can also frustrate the users since their actions do not provide the wanted results even though they are doing everything correctly. During a session in private, accuracy and verity can be considered as the most important requirements. Since the system should be usable everywhere, social perception hinders the use of visible and obtrusive sensors. When dealing with people suffering from stress or even mental illness, visible sensors are not the way to go. The use of sensors that can easily be hidden under clothes is therefore preferable to avoid awkward situations in public. The use of hidden sensors also introduces the possibility to use the system to monitor the user's biological signals in everyday routines. This can be especially useful for stressed individuals or patients suffering from panic attacks since they are often happening in day-to-day life situations e.g. at work. The collected data can then be used by the therapist to adjust the treatment accordingly. Using the system for an extensive amount of time depends on the utilization of comfortable sensors. The whole system needs to be designed in a way that it is as comfortable and unobtrusive as possible. This includes the hardware responsible for collecting the data from the sensors, visualizing it for the user while establishing a bi-directional communication channel to the therapist. In addition, the utilized mobile interface must offer good battery life, connectivity to the sensors and provide visual feedback for the user while still being small and portable. Accompanying

the mobile biofeedback device, a stationary backbone server is needed. The main purpose of the server is to provide a secure archive for the collected biofeedback data for all the patients. It offers the needed interfaces to (i) transmit the collected data securely from the mobile system to the server and (ii) allows the therapist, if needed, to send notifications to specific users. The conceptual architecture is presented in Fig. 2.

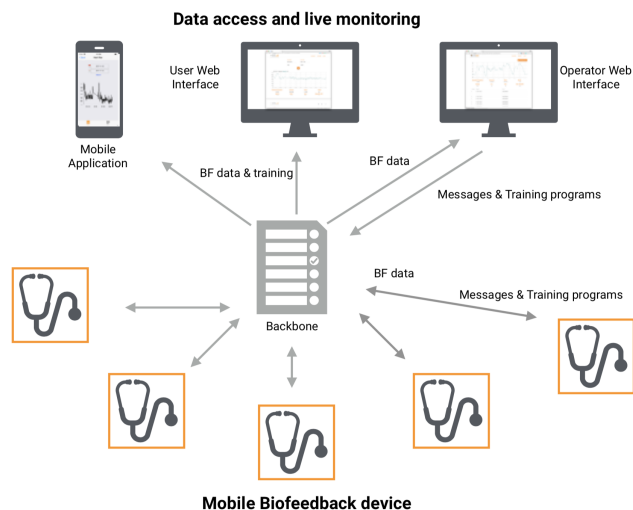


Fig. 2. Mobile biofeedback system with (i) real-time monitoring of the biofeedback data by the operators and the users, (ii) a communication channel from the trainers to the users for instant feedback and (iii) statistical tools for online and offline data analysis.

**Software system:** The presented software system can be divided into two main parts, one dedicated to the BF device and the other for the backbone server. Starting with the portable part, being as compact as possible, the screen size is the limiting factor (i.e. smartwatch). Next to numeric values (e.g. for the HR/HRV) alternative visualizations can be shown that fuse multiple sensor inputs (e.g., objects changes dependent on certain biological signals and states).

Additionally, to the pure information representation, public perception also has to be taken into consideration. Too prominent or identifiable representations are hindering the use of the system as they could be seen by other people. A more detailed visualization could be given using a companion (e.g., smartphone). Using a stable connection to the external sensors, the sensor samples are fetched at a constant rate and are transmitted to the backend server live over an internet connection, either via a WiFi or cellular network. This ensures that both the therapist and the patient can access and view the data during a biofeedback training session in pseudo real-time on a larger device Fig. 3.

Network connections can be fragile. To prevent data loss in case of a network failure, the data is cached on the device until a solid connection to the backend is established again. After the data is transferred, the system resumes with its normal operation. As previously discussed, the server's main purpose is the secure storage of the collected BF data. For the data

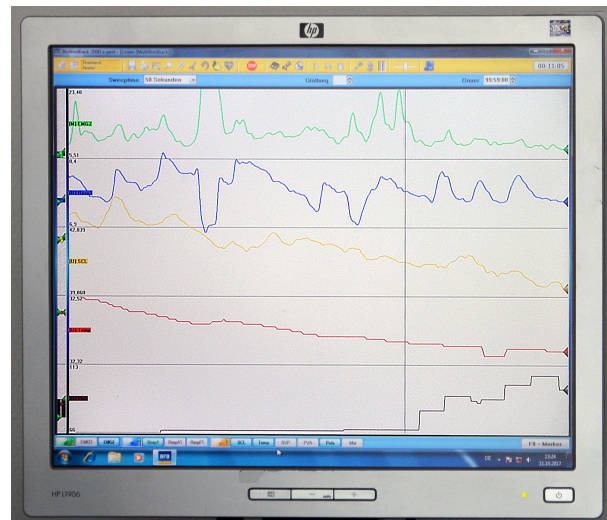


Fig. 3. Live data visualization of a traditional biofeedback system in a hardly understandable data representation for the not so well informed user.

transmission, a bi-directional socket connection is established between the mobile BF device and the backend. This socket connection is used mainly for the live data transmission but also to enable the messaging service between the user and the therapist. Additionally, the remote BF sessions are sent from the backend to the user's BF device. In addition to the socket connection, a REST API is provided for multiple reasons. First, it is used to receive the cached data in large junks for performance reasons and secondly, it is needed to offer an easy way to log into the application for the users and the therapists, additionally giving them the possibility to fetch archived data from the backend server for later analysis. The web application is the main hub for the operator to analyze the archived data but also to manage users and devices, monitor active users and assist them by sending helping messages and additional instructions. The remote BF training programs are also created, managed and assigned using the web interface.

**Biofeedback Training Programs:** Training sessions play a major role in every biofeedback system. The ability to do them remotely requires a carefully designed system. First of all, instructions need to be given to the user. Traditionally these are given by the therapists themselves. Since the system offers a communication channel between the user and the therapist over the aforementioned connection, this is still possible when the therapist is online at the same time as the user. If that is not the case and for a more diverse variety of practice sessions other forms of instructions are needed. First off, visual instructions can be given using the integrated screen on the biofeedback device. These instructions can vary from written text to more alternative approaches using images and other objects on screen. Using the integrated speaker on the device or connected headphones audio instructions can also be given depending on the locality the user is in. Next, to offering instructions, the interface can also be used to provide feedback for the biofeedback training itself. In this

context, haptic feedback can be given in conjunction with the previously mentioned methods. Examples include a target respiration rate provided via audial or haptic feedback that the users have to hit in order to move an object on screen. For each medical case that can be treated using BF, specialized training programs exist. The system gives therapist and doctors the ability to design specific training programs for each condition and reuse them on multiple patients suffering from the same issues saving a lot of time and money in the long run.

Having the ability to do biofeedback training without a therapist paves way for other possible use cases. Since the patient can be monitored during everyday activities, seizures can be sensed before they occur and preventive countermeasures in form of instructions can be sent to the mobile system (e.g. [10]). This can be messages from a therapist or doctor, or in the form of context-based training programs that automatically learn and notify the user. The data collected while the system is in operation can be analyzed and compared to the usage and workflow of traditional biofeedback systems. Modern machine learning approaches can do some of that analysis automatically to ensure that the operators do not have to spend more time in doing the same data evaluation tasks over and over again manually. Training program assignment can be done autonomously by the system itself to further reduce the workload on the specialist's side. Having the training program part covered, system usability considerations have to be considered.

*Usability:* A huge problem with the existing biofeedback systems is the tedious setup process and complicated operation in general. Since this system is mostly operated by untrained, not technology affine individuals, the setup process has to be as easy and streamlined as possible. Since the screen on the portable device is small, signing up has to be handled either by the mobile companion application or web application. After signing up, a six-digit authentication pin is provided that can be typed in on the mobile device easily. After the login procedure, the user has to connect the main BF device to the Bluetooth sensors. If only one sensor is in reach, it is connected automatically. If multiple are available, the user can select the appropriate ones. Once that is done, the data monitoring is started and the device displays basic health data like the HR if a heart rate sensor (external or smartwatch internal) is connected. The user is automatically reminded if he has to do a remote training session at specific points in time. With the device setup, he can start the session immediately. During the session, it is crucial that no further user interaction is needed to ensure that the results are not affected by the use of the system in any way. When the device is used for monitoring purposes only, the user should not be introduced to more stress than usual. This is ensured by the lack of notifications in the event of a disconnect for both the connection to the sensor and the backend server. The system retries to re-establish a connection silently without the need for any manual interaction.

Having a carefully designed system architecture, an affordable prototype using state of the art technology is implemented and evaluated as a proof of concept.

### *B. Prototype system using currently available technologies*

As specified before, the portable system for data collection needs to be very small and compact. Additionally, the software platform needs to be as open as possible to ensure a straightforward development process and the possibility to crowdsourcing further developments. Medical or professional grade devices for capturing health data turned to be a too expensive and hard to develop for. Recently, a lot of consumer health accessories and wearables emerged from a before not so prominent market ranging from the simple fitness tracker to more sophisticated smart watches. Due to a large number of competitors these devices have reached a high level of accuracy and are therefore a satisfying solution. Since a watch is portable and unobtrusive enough to be used on a daily business, the form factor is set to be just that. Although a lot of consumer specialized health monitoring devices exist and are generally well received, most of them do not have an open SDK and can therefore not be taken into consideration. Recently smart watches became popular and have reached a high level of technical sophistication. Android Wear with its wide selection of devices from multiple OEMs and its generally open development environment was selected as the operating system of choice for the proof of concept. Today, a wide variety of Android Wear smartwatches exist spotting different sensor configuration and versions of the Android Wear Operating System. Since the application for collecting biofeedback has to run on the watch itself natively, Android Wear 2.0 became another necessity since it allows the development of apps that run natively on the watch without the need for a smartphone. With the hardware for the main portable device selected (i.e. Huawei 2 smartwatch with its integrated sensors like HR, GPS, accelerometer, gyroscope, compass, ambient light and barometer), a suitable external sensor configuration needs to be found. The number of consumer-grade health monitoring sensors that can be attached to hidden spots on the patient's body is limited. In the end, we selected an additional heart rate chest strap to monitor heart rate and heart rate variability (i.e. Polar H7) at higher accuracy and resolution. Especially the heart rate variability can't be sensed by the smartwatch but is a quite important source of information for biofeedback training. The selected sensors are set at an acceptable price and offer multiple weeks of battery life. Some of them are water resistant and very comfortable to wear making them perfect for long-term monitoring sessions.

The prototype also features a basic backbone server for data storage and a web application. The later can be used by the operators to access the archived data on a per user bases, monitor every user live, send messages and deactivate sensors. It also offers a set of functions for the user. First of all, the login procedure for the smartwatch application is handled partly by the web application generating a six-digit code that has to be entered on the smartwatch as described earlier. The users can also access their archived data and live transmissions



Fig. 4. Web-based live data visualization of the heart rate variability using the prototype system during the stress test on the trainer's interface.

inside the web application in an easy to use dashboard. After developing the proof of concept prototype, we tested it in a controlled environment to ensure that it is evaluated properly.

### III. EXPERIMENT

Since the system is designed to be used in addition to existing, clinical biofeedback training system, it has to provide at least similar results. In order to test that, an experiment is set up, comparing the newly developed proof of concept prototype against an existing BF training system. To achieve this, an example biofeedback training program was used, showing the effectiveness of the system (presented Table I).

#### A. Experimental setup

In order to achieve meaningful results, the system has to be set up properly with as little distraction as possible. The mobile part of the system is unchanged, using an Android Wear 2.0 smartwatch in conjunction with a Polar HR chest strap collecting HR and HRV data. All of the watches background services were deactivated. This should also be the case when used in the wild, preventing any additional influences of the system on the user. During this test, the watches deep sleep functionality was deactivated to ensure a more stable operation at the cost of battery life.

To prevent any outside influence to the tests' results, the server is set up locally on a dedicated laptop. The web interface is also opened up on the machine as shown in Fig. 4. To allow the smartphones to connect to the backend server, a WiFi AP is set up with the notebook connected via ethernet. The smartwatches are then connected to the access point which does (for test purposes) not provide an internet connection.

In this case, the instructions during the session are given by the operator remotely from another room, comparable to a baseline therapy session giving the therapists a useful baseline value to design and compare subsequent training sessions.

#### B. Test procedure

The goal of the session is to obtain information about the patients' reaction when they are put in a stressful situation in terms of changes in biological signals. The goal is to test the prototype's ability to visualize complex bio-information showing the user's ability to deal with stressful situations. The

described test procedure is largely inspired by tests conducted before biofeedback training sessions. It is crucial that the test subject has no previous knowledge about the procedure since that could influence the test results drastically. As previously mentioned, all of the following instructions are given by the operator with the systems integrated remote messaging capabilities. In summary, the test takes roughly 16 minutes

TABLE I  
BIOFEEDBACK TEST SEQUENCE

1.	Resting phase to get baseline rating	2 min
2.	Mental Arithmetic: The user is given a large number (e.g. 2000) and has to count down in steps of a prime number (e.g. 7). Every time a step is wrong, the subject has to restart from the beginning. To up the stress level, the operator lets the subject restart randomly, even if the result was correct	1 1/2 min
3.	Resting phase	2 min
4.	The user has to think about a stressful or unpleasant situation. Focusing on the details is very important	1 min
5.	Now, the users have to describe the situation they were previously thinking about.	1 1/2 min
6.	Resting phase	2 min
7.	The user has to think about a pleasant or joyful situation. Focusing on the details is again very important	1 min
8.	Again, the users have to describe the situation they were previously thinking about, this time in a foreign language.	1 1/2 min
9.	Resting phase	2 min

including the process of attaching the sensors and giving the subject a quick introduction. The session should take place in a quiet environment with as little distraction as possible. Results in terms of accuracy and resolution must at least match traditional biofeedback devices.

#### C. Results & Summary

To evaluate the system, a user study is conducted consisting of a group of four people. All of them are between 21 and 24 years old, male. The fitness level varies but none of them has any heart disease or circulation problems. The study took place in a quiet, average sized bedroom (20m<sup>2</sup>) without any outside distractions. Instructions are given as described in Table I by the operator of the system. During the session, the users cannot see their own heart rate to avoid any influences on the results. In advance, a biofeedback session using a professional biofeedback system was conducted, similar to the one in this test. The results can be seen in Fig. 5. This acts as a baseline to which this prototype is compared to. As only HR and HRV are captured by the prototype and HR, skin conductance, respiration rate and muscle tension by the BF device, only HR is used to compare the two.

After collecting data with the test sequence shown in Table I, it can be visually compared to the baseline provided by the traditional system. As presented in Fig. 6, the increase in HR can be seen in all cases pretty drastically. Even when keeping this in mind, the resting phases are still easily distinguishable from more stressful ones and have a similar visual appearance with a depicted peak and a significantly lower HR after the stressful situation. Compared to the baseline collected by the

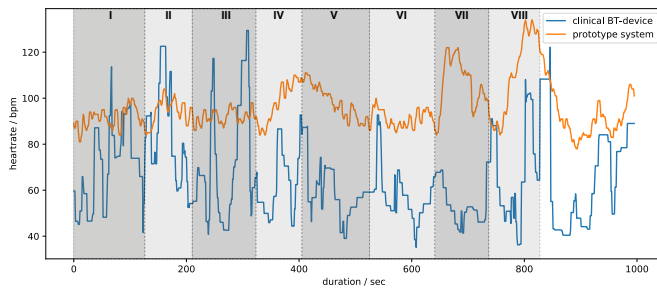


Fig. 5. HR data collected with the clinical BF system (blue) with an overlay of the data collected by our prototype system (orange) during the baseline biofeedback session with corresponding training phases (see Table I).

clinical system, the prototype works very well, offering a higher resolution and very comparable results (see Figure 5). Obviously, this varies between different users based on the signal dynamics. Pearson correlation coefficient (PCC) shows between subjects  $s1/s2:0.05$ ;  $s1/s3:0.21$ ;  $s2/s3:-0.28$  over the full training phases, and  $s1/s2:0.49$ ;  $s1/s3:-.42$ ;  $s2/s3:-0.87$  only over phase I. The PCC for the comparison to the clinical BF system is 0.15, arguable by the poor resolution of the clinical system. If a user's collected biofeedback data is completely different to the one shown here, it is possible that something is wrong with the user's health status. Using machine learning approaches or correlation measurements, the system can be trained to detect these abnormal states and warn the therapist, helping with the whole concept of efficient remote monitoring and training. One example can be found in Fig. 6, comparing phase I of subject 3 with the two other subjects. Subject 1 does not feature a proper resting heart rate at the beginning. Beside health-related issues, this can either come from distractions during the session, a high caffeine consumption or other external influences.

Next, to the analysis of the performance of the system, other factors like usability and overall perception of the system were evaluated using a questionnaire consisting of 20 questions. The subjects were asked about topics like usability, visualization, everyday practicality and their previous experiences with BF. The results show that the usability including the login procedure and connecting the external Bluetooth sensors is very user-friendly and is already far ahead of what existing systems offer today. The same can be said about the everyday usability in public. With the sensor strap and the watch considered unobtrusive and comfortable to wear, using the system during everyday activities is not considered a problem based on the given answers. It also has to be noted that with the exception of one participant, nobody had any prior experience with BF. It can be said that the system offers enough accuracy to provide the user with a sufficient biofeedback training solution. The system highlights that BF training can be enhanced by modern approaches using state of the art wearable and health monitoring technology.

#### IV. CONCLUSION AND OUTLOOK

With the presented system, already being stable and accurate enough to run through multiple test sessions without any

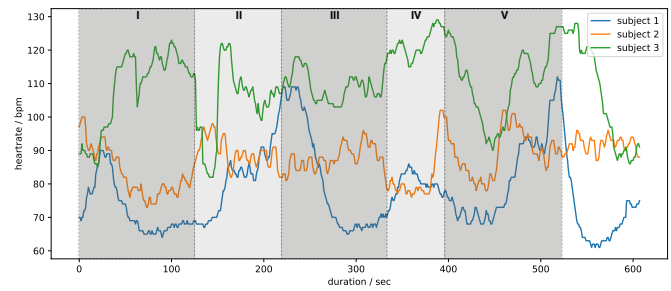


Fig. 6. Comparison of collected HR data with the prototype system during the user study presented for three different users with corresponding training phases (see Table I).

issues, the presented concept will be further enhanced by integrating multiple state of the art technologies in the field of computer science and data engineering. Using machine learning methodologies, the system is supposed to learn and analyze the data to predict future unfortunate incidents (e.g., epilepsy seizures, heart attacks, etc.) based on individually learned BF-markers. Furthermore, since the system was built to scale, utilizing a wider range of BF data collection devices is encouraged to gather and make use of as much data as possible. With the basic functionality already given, additional features can be added including custom training programs and a more robust messaging service. This, in addition to machine learning approaches, will make proper, remote biofeedback training in the wild possible and effective.

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