Cardiovascular Rehabilitation Equipment (CaRE)

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***Abstract*—Cardiac rehabilitation is a program where the patient is supervised by a physical therapist while doing the exercise routine designed by their doctor. In the Philippines, a stand-alone equipment that can automate the doctor's prescribed exercise routine while actively monitoring the patient's vital sign is needed. The equipment could enable a safe and effective recovery with minimal supervision from the medical practitioners. This project aims to provide an automated aerobic exercise for cardiovascular rehabilitation patients through an adaptive cardiovascular training device. The automated exercise is based on the patient's heart rate which would be effectuated through the automatic adjustment of the load resistance of the cycling equipment. The equipment also includes blood pressure and oxygen saturation monitors to actively monitor the patient's condition during the exercise.**

Keywords—cardiovascular, rehabilitation, exercise, adaptive, heart rate, cycling

I. Introduction

Hellerstein and Ford defined rehabilitation in 1957 as "the process by which a patient is returned realistically to his greatest physical, mental, social, vocational and economic usefulness and, if employable, is provided an opportunity for gainful employment in a competitive industrial world[1, 2]." However, in this paper, only the physical exercise component of the rehabilitation will be discussed. For simplicity, this structured exercise program will be referred to as "cardiac rehabilitation".

Aerobic exercise is the most commonly prescribed exercise for cardiac patients to gain fitness. The major components of aerobic exercise in cardiac rehabilitations are the treadmill and cycle ergometer training. There are standards that are observed in the performance of these structured exercises. This includes warm up (gradual increase of heart rate), main exercise (maintaining target heart rate), and cool down (gradual decrease of heart rate). Rehabilitation program of patients would differ depending on their medical condition and physical capabilities. Thus, the need for active monitoring of the different factors which include heart rate, blood pressure, and workload is being highly addressed for safe and effective training.

Today, cardiac rehabilitation in the Philippines are closely supervised by physical therapists; wherein a session duration ranges from 40-70 minutes and could be as frequent as daily. In the Philippines, only 1,324 physical therapists and 343 occupational therapists that have been newly registered in 2013. As such, the shortage of these professionals remains a big problem in the country[3]. Moreover, the current rehabilitation efforts are highly dependent on the supervising physical therapists and may result to either insufficient or excessive cardiovascular stress. As studies show, oxygen saturation and blood pressure readings can indicate cardiovascular abnormalities[4,5].

In the Philippines, there is no stand-alone equipment to aid in the recovery of cardiac patients during rehabilitation. Cardiac rehabilitation programs are currently being manually supervised by the limited number of professional physical therapists. In addition, the physical therapists are unable to quantitatively evaluate the patient's rehabilitation. Thus, an equipment that could be easily operated by medical experts and effectively provide the necessary cardiovascular training with minimal supervision will be developed.

II. Design

Cardiovascular Rehabilitation Equipment (CaRE) is an electro-mechanical stationary cycling equipment that has an automated load control, pulse oximeter module, blood pressure module, and can wirelessly connect to the computer through Bluetooth. Fig. 1 shows the system architecture of CaRE. Using CaRE, the patient will perform the exercise with initial supervision of the physical therapist which will provide the parameters of the exercise, such as the duration and the target heart rate, in the user interface. Throughout the exercise, the patient's heart rate, oxygen saturation, and blood pressure are monitored and are displayed in the user interface. The heart rate and oxygen saturation measurements are taken from the pulse oximeter and the blood pressure measurement are from its corresponding module.

The heart rate is used as the feedback to automatically adjust the load by correspondingly adjusting the resistance motor. The goal of the automated load exercise is to help the patient achieve the target heart rate and maintain it for the specified duration. The load of the bike will increase or decrease appropriately while the patient maintains the prescribed speed or cadence, which is measured through a reed switch. Cadence lights are also provided in the bike to signal the patient if he is pedaling below, above, or at correct speed. Finally, wireless communication is implemented, through a Bluetooth module located inside the system box, between the cycling equipment and the PC, where the graphical user interface is displayed. A visual layout of the parts previously discussed is shown in Fig. 2.

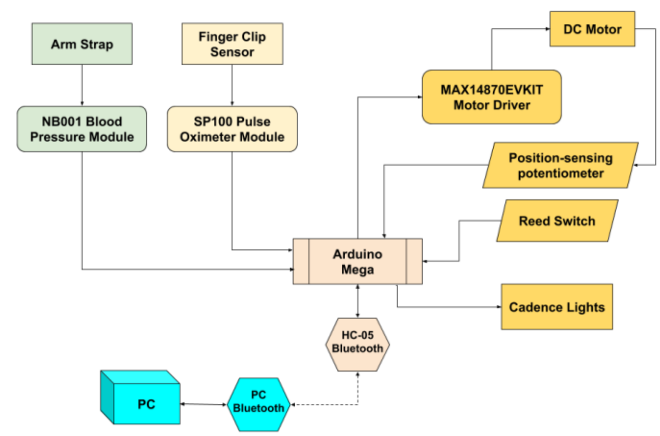

Fig. 1. CaRE system architecture.

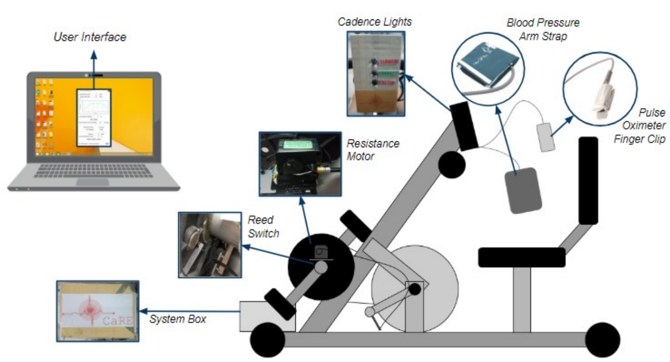

Fig. 2. CaRE system layout.

III. Implementation

A. Pulse Oximeter Module

During a rehabilitation session, it is important to monitor the patient's heart rate and oxygen saturation to avoid potential risk factors and provide the necessary exercise to the patient. In monitoring the heart rate and oxygen saturation level of the patient, a SP100 pulse oximeter (SpO2) module shown in Fig. 3 was used. It has the capability of measuring heart rate and oxygen saturation levels. A finger clip will be used as its sensor for the project.

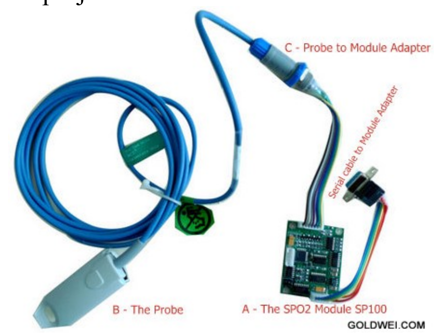

Fig. 3. SpO2 module SP100 [4].

B. Load Control

The recumbent bike used in this project has an electro-mechanical eddy current braking system, shown in Fig. 4. The key parts of controlling the load of the exercise bike are the microcontroller, motor driver, resistance motor, tension cable and magnet arm. When the current heart rate is not yet in the target heart rate range, the magnet arm will move accordingly to increase or decrease the load. The cadence lights, shown in Fig. 5, signals the patient to maintain a constant range of speed.

- Microcontroller - an Arduino was used to control the motor driver.
- Motor Driver - MAX14870EVKIT was used to drive the resistance motor of the bike.
- Resistance motor - consists of a DC motor that triggers the gears inside it to push and pull the tension cable. It also has a potentiometer that converts the rotation of the gears to a resistance value.
- Tension cable - its other end is attached on the magnet arm that gets closer or farther from the flywheel.
- Magnet arm - the load increases as the magnet arm gets closer to the flywheel.

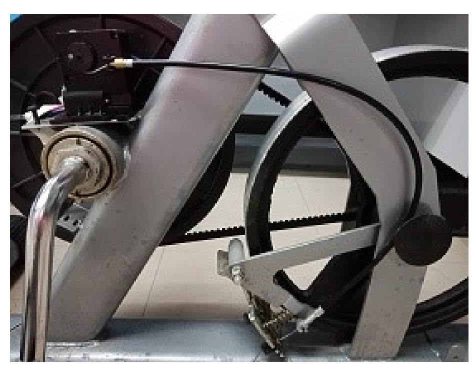

Fig. 4. Eddy current braking system of CaRE

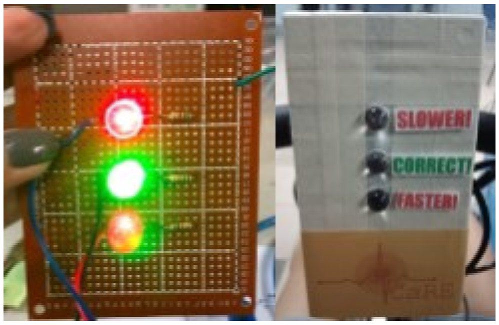

Fig. 5. Cadence lights.

C. *Blood Pressure Module*

For the blood pressure monitor, the NB001 Module shown in Fig. 6 was used. The data flow for the blood pressure will start from initialization of the module to the host. The module will send a frame that establishes a connection and is ready to receive commands. This is a two-way communication because the host or the PC also sends frames that commands the module of the rate of pressure, mode of measurement, time period and etc. The arm cuff will inflate at the start of the measurement, and a frame will be sent by the module containing the actual systolic and diastolic measurements.

Fig. 6. NB100 blood pressure module [5]

D. *Wireless Connectivity*

This feature is implemented in order to streamline the addition of multiple CaRE hardware in future research and development. The system uses the ubiquitous Bluetooth technology due to its relative ease to implement. The wireless module used in the system simply acts a Bluetooth bridge that streams serial data coming from the Arduino. Before being sent out to the channel, sensor-specific packets are appended with a header to facilitate the parsing on the PC side of the system.

The system used a HC-05 Bluetooth module for communications. It works on the 2.4 GHz ISM band, has an asynchronous speed of 2.1 Mbps, and it could interface with UART with any baud rate.

The Bluetooth connection between the PC and Arduino is a Standard Serial over Bluetooth Link. In order for PC side to interact with the Arduino side with Bluetooth, it needs to access functionalities abstracted as serial. The package *pySerial* is used to create serial object to create a link between the two devices. The baud rate is set to 115200 which is much greater than the rated baud rate of the other peripherals connected to the Arduino serially. This is to evade data loss conditions from data contention or buffer overflow. The port number is chosen arbitrarily.

E. *User Interface*

The user interface (UI) is implemented using Qt 4 with Python as the main programming language. The wrapper, PyQt, is used in order to use Qt methods and functions to be implemented. To design the UI, all widgets and layoutting was done in the free tool Qt Designer. The initial design is exported as an XML file so in order to use the designed UI, the file is exported using the *pyuic* module which is included in the PyQt package. The scheme of the code separates the logic side (gives functionalities to the widgets) from the design side similar to a frontend - backend approach in software development. The generated python code is inherited in the main code and is given functions and methods associated with it. The design to logic code relationship is shown in Fig. 8.

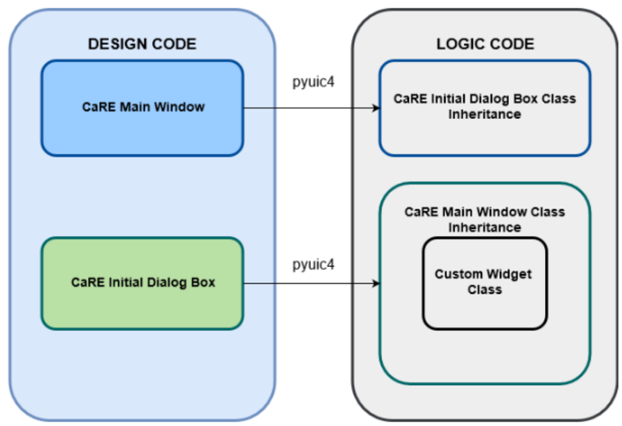

Fig. 7. Design and logic code relationship.

1) Input dialog box: The parameters of the exercise are provided before the start of the exercise through the input dialog box as shown in Fig. 8.

2) Main window: The measured values of heart rate, oxygen saturation, time elapsed, cadence, and resistance level are displayed every second, while the blood pressure is measured and displayed every 3 minutes. The heart rate is also plotted throughout the whole duration. A *Reset* button is also available which allows the restart of the session

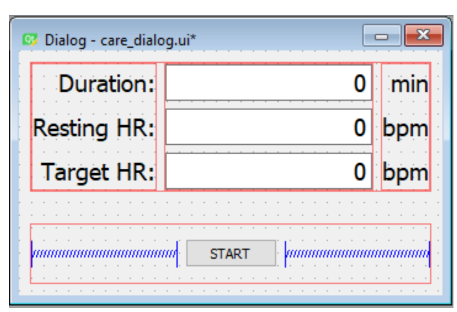

Fig. 8. Qt designer preview of CaRE initializing dialog box

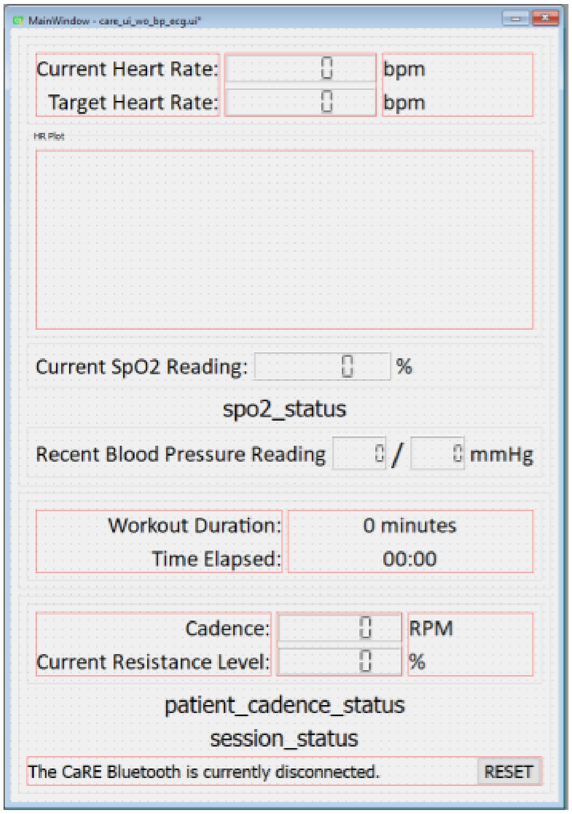

Fig. 9. Qt designer preview of CaRE main window

F. *Abbreviations and Acronyms*

The whole system algorithm is preprogrammed on the Arduino. As the hardware system is powered up, the Bluetooth module will establish connection with the PC.

The resistance motor will also initialize to its minimum resistance. Then, the system will wait for the resting heart rate, target heart rate, and duration to be inputted in the user interface which will prompt the start of the session. The blood pressure, heart rate, oxygen saturation, and resistance level are periodically measured and sent to the user interface for display. The cadence is measured with a reed switch via an interrupt and its measurements are also sent the interface and is also used for the cadence lights. The hardware setup of the CaRE system is shown in Fig. 10.

Fig. 10. Actual CaRE system setup

IV. ELECTROCARDIOGRAM MODULE FOR INTEGRATION

The Electrocardiogram (ECG) module that was used for this project is the UN-M7104. It has built-in ECG waveform filtering and heart rate measurements. The module was connected to the Arduino as shown in Fig. 12.

Fig. 11. ECG module connected to the Arduino

For the testing of the ECG module, the Fluke Prosim 8 Simulator was used. The device can simulate heart signals at different heart rates and could also include different artifact types such as Muscular and 60Hz that might be encountered on the ECG of a patient during exercise.

Fig. 12 shows the ECG plot measured by the module with the muscular noise from the simulator at 150 bpm. On the other hand, Fig. 13 shows the measured ECG plot of the simulated 150 bpm heart rate with 60 Hz noise. The ECG module was able to minimize the inference from the 60 Hz and Muscular artifacts of the simulator.

The module was also tested on actual participants. Using the Lead II configuration placement, the measured ECG is shown in Fig. 14. The chosen ECG module was able to provide good measurements with its adopting filter capability.

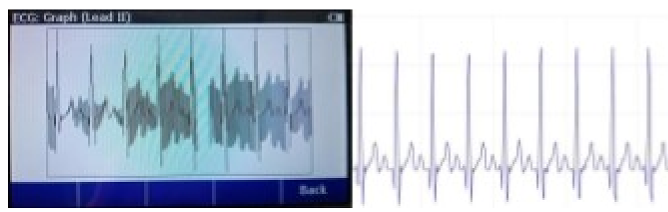

Fig. 12. Simulated and measured ECG with muscular noise

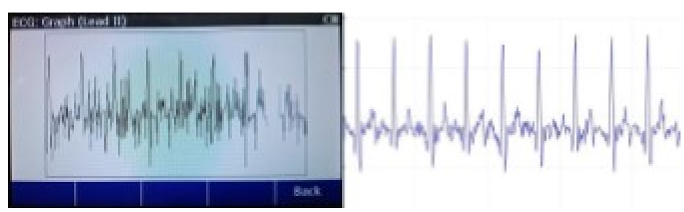

Fig. 13. Simulated and measured ECG with 60Hz noise

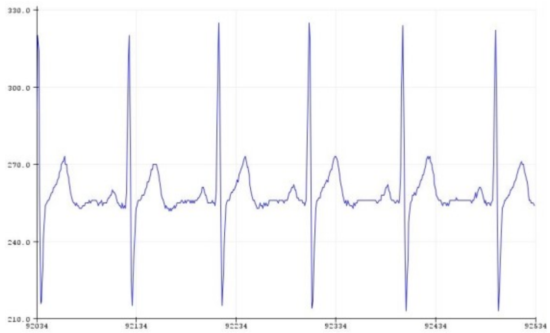

Fig. 14. Measured ECG from participant

V. Results and Discussions

A. Heart Rate and Oxygen Saturation Measurements

The Fluke Prosim 8 Simulator was also used to test the heart rate and oxygen saturation measurements of the SpO2 module. Shown in Fig. 15 is the plot of the simulated oxygen saturation vs. the measured oxygen saturation. Within the oxygen saturation range of 80%-100%, the pulse oximeter module had at most +/- 2% inaccuracy in its readings. On the other hand, the heart rate data plot of the SpO2 module is shown in Fig. 16. The heart rate measurement of module was tested on the range of 60-220 bpm, which is the range of resting and active heart rate. As shown in the plot, the heart rate measured from the SpO2 module has at most -3 bpm inaccuracy, which is at 150 and 180 bpm.

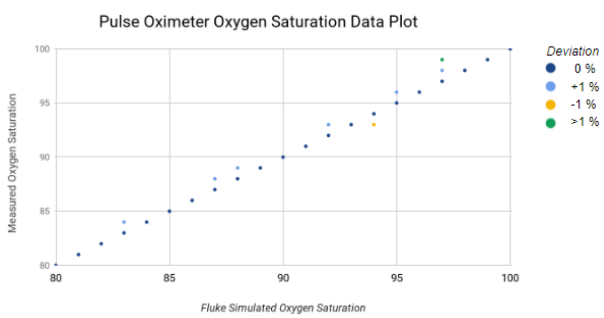

Fig. 15. Simulated vs. measured Oxygen saturation data of SpO2 module.

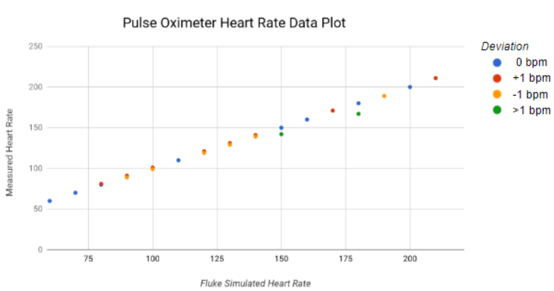

Fig. 16. Simulated vs. measured heart rate data of SpO2 module.

B. Blood Pressure Measurements

The blood pressure module was tested using the Fluke Simulator. Fig. 17 shows the comparison of the measured and the simulated systolic and diastolic data of 70/100 mmHg. There is an at most +10 bpm deviation between the measured and the simulated values.

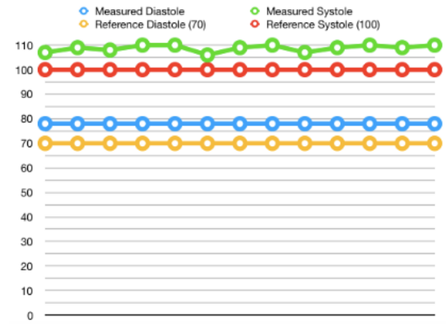

Fig. 17. Measured and simulated systolic and diastolic data of BP module

C. System Usability Test

Responses from participants were collected and was converted to the corresponding percentile scores. There were a total of 10 participants. Table I shows the feedback percentages of the participants based on the System Usability Scale (SUS) developed by John Brooke[8]. The total average percentage of the tests is 86%. This shows that the participants were generally satisfied with the CaRE system.

TABLE I. Feedback Results Using SUS

Participant	Feedback Percentage
A	87.5 %
B	87.5 %
C	87.5 %
D	80.0 %
E	85.0 %
F	90.0 %
G	95.0 %
H	92.5 %
I	87.5 %
J	90.0 %

D. System Test Results

The setup of a test run is shown in Fig. 18. The results of one of the test runs is shown in Fig. 19. The heart rate of the participants were generally able to follow the target heart rate profile. The resistance level and the heart rate of a session is plotted together as shown in Fig. 20. It can be observed that as the resistance level increases, the heart rate of the user also increases. When the set target heart of 120 bpm was exceeded, the load resistance began to decrease. At instances where the heart rate of the user slows down at values below the target, the load resistance would increase.

Fig. 18. System test setup

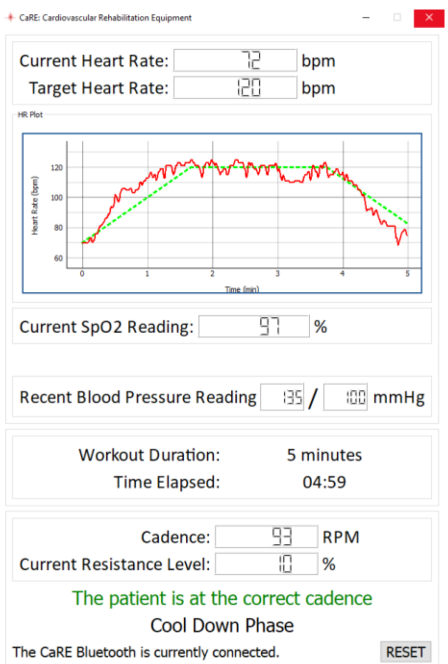

Fig. 19. End of session results on user interface

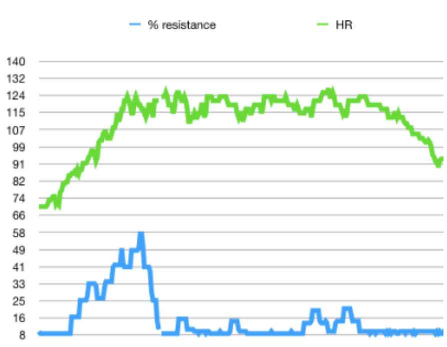

Fig. 20. Heart rate and resistance level plot of the whole exercise

VI. Conclusion and Recommendations

CaRE, an adaptive cardiovascular training equipment for cardiovascular rehabilitation was developed. It provides a customizable exercise based on the duration and target heart rate of the patient. Oxygen saturation, heart rate, cadence, and resistance level are measured every second, while blood pressure is measured every 3 minutes. As a recommendation, the ECG should be added to monitor heart abnormalities. Also, the system should be tested to at least 15 male and 15 female healthy participants.

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References

[1] H. Bethell, "Exercise in cardiac rehabilitation", *British Journal of Sports Medicine*, vol. 33, pp. 79-86, April 1999.

[2] P. Ades, "Cardiac rehabilitation and secondary prevention of coronary heart disease", *The New England Journal of Medicine*, vol. 345, pp. 892-902, September 2001.

[3] M. Jaymalin, "Shortage of physical therapists looms", *The Philippine Star*, January 2013.

[4] G. Parati, J. P. Saul, M. D. Rienzo, and G. Mancia, Spectral analysis of blood pressure and heart rate variability in evaluating cardiovascular regulation, Hypertension, vol. 25, pp. 1276-1286, June 1995.

[5] E. D. Chan, M. M. Chan, and M. M. Chan, Pulse oximetry: Understanding its basic principles facilitates appreciation of its limitations, Respiratory Medicine, vol. 107, pp. 789799, June 2013.

[6] "Spo2 module model sp100 (pn: Mo-sp100) evaluation kit." http://www.goldwei.com/products/item.asp?itemid=422\&catid=19. Accessed: 2018-02-20.

[7] "Nibp module model nb001 (monm-bn001)." http://www.goldwei.com/products/item.asp?itemid=299&catid=20. Accessed: 2018-01-15.

[8] Sus: The system usability scale. https://www.trymyui.com/sus-system-usability-scale. Accessed: 2018-05-20.