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Patient-Provider Interaction System for Efficient Home-Based Cardiac Rehabilitation Exercise

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ABSTRACT This paper presents an efficient home-based cardiac rehabilitation (CR) exercise system for patient-healthcare provider interaction in cardiac management. The proposed system consists of a wearable device, a smartphone application, and a medical station. A CR specialist prescribes CR exercise for a patient through a medical station. The prescription information is sent to a patient's smartphone application with Internet's hypertext transfer protocol. The information is further transferred to a patient's wearable device via Bluetooth communication. A patient performs home-based CR exercise with the worn wearable device that measures instantaneous heart rates (HRs) accurately even during intensive physical exercise. During the CR exercise, the wearable device recommends appropriate exercise intensity in real time based on the prescribed target HR zone and the measured instantaneous HRs. Furthermore, the wearable device informs the current exercise stage (resting, walking, or running), allowing home-based CR exercise without the help of a medical staff. Upon completion of the CR exercise, exercise records are sent to a smartphone application so that a patient can monitor his or her own exercise records. Exercise records are also sent to the medical station where a CR specialist can monitor these records and provide new exercise prescription. In this paper, we have implemented and demonstrated the full functionality of the overall home-based CR exercise system consisting of a wearable device, a smartphone application, and a medical station. Moreover, we have verified the overall operation of the system and that the proposed system can be an efficient CR exercise tool for remotely sharing CR exercise prescription and exercise records between a patient and a healthcare provider.

INDEX TERMS Wearable device, medical Internet of Things, cardiac management, reflectance photoplethysmography, motion artifacts, cardiac rehabilitation exercise, heart rate.

I. INTRODUCTION

Wearable device has recently gained attention as a potential medical device since it can measure physiological signals without time or space constraints. The capability of ubiquitous measurement is currently being extended to telemedicine to structure medical Internet of Things (MIoT) [1], [2]. It includes a network architecture that allows connection between a patient and a healthcare provider [3], [4]. Recent advancements in the design of MIoT has included monitoring of a variety of physiological signals and features such as electrocardiography (ECG) [5], [6], polysomnography (PSG) [7], electroencephalography (EEG) [8], photoacoustic spectroscopy [9], and daily patterns [10], [11]. All of these can significantly reduce overall costs and increase the efficiency of prevention and management of chronic diseases [12], [13].

Among chronic diseases, cardiovascular disease (CVD) is the leading contributor to global burden of disease. The World Health Organization (WHO) has reported that 31% of all global deaths are related to CVD [14]. To lower the occurrence or recurrence rate of CVD, cardiac rehabilitation (CR) exercise is recommended by the American Heart Association (AHA) [15], [16] and European Society of Cardiology (ESC). CR exercise is prescribed by a CR specialist by providing a patient with appropriate exercise information such as exercise type (ex. jogging and cycling), exercise stage order and its duration (ex. 5 min. warm-up, 15 min. main-exercise, 5 min. rest, 10 min. main-exercise and 5 min. cool-down), and target heart rate zone (THZ) (ex. minimum and maximum allowed heart rates (HRs): 90 bpm and 120 bpm). In CR exercise, maintenance of adequate exercise intensity during the main exercise is the most important one because heavy exercise may increase the risk of CVD while too light exercise is inefficient [16], [17]. The exercise intensity is typically determined based on measured HR during exercise and THZ prescribed by a CR specialist. For instance, given the prescribed THZ, if the measured HR is greater than THZ, then the exercise intensity should be reduced to decrease HR. Many research results have indicated the importance and effectiveness of engaging in CR exercise [18]–[22]. Based on these reported benefits, CR exercise programs are used worldwide.

However, the participation rate of CR exercises is low due to many CR barriers including limited access and economic burden [23], [24]. In addition, a CR specialist has difficulty in prescribing the appropriate CR exercise since exercise record, one of the most important factors considering the future prescription, relies on patient's statement only. Thus, a home-based or self CR exercise system meeting those clinical needs for both a patient and a CR specialist is required. With such system, a patient should be able to achieve the CR exercise at an affordable cost without visiting a hospital. Such system also should be simple and user-friendly to operate without requiring assistance from medical staff. Furthermore, it should be interactive between a patient and a medical staff. Thus, the CR specialist should be able to monitor the patient's exercise records and prescribe appropriate CR-exercise in a timely manner.

In this paper, we proposed and developed a home-based CR exercise system consisting of a medical station, a smartphone application, and a wearable device. With our developed medical station, a CR specialist can review and monitor patient's exercise records and prescribe new CR-exercise which is sent to a patient via our developed smartphone application. With the smartphone application, a patient confirms the prescription and sends it to our developed wearable device. Then, a patient can perform the home-based CR exercise with the worn wearable device on wrist. During exercise, the wearable device not only measures instantaneous HRs, but also informs a patient which exercise stage he or she is currently exercising and whether the current HR is within the THZ in real-time. Upon completion of the CR exercise, performed CR exercise information is sent to the smartphone application where a patient can monitor his or her own exercise records. Furthermore, exercise records are sent to the medical station where a CR specialist can monitor the records.

In this paper, our proposed home-based CR-exercise system including wearable device, smartphone application and medical station is presented in Section II. Also, the accurate HR estimation algorithm during intensive physical exercise is presented. Section III presents the system evaluation, and the discussion and conclusion are drawn in Section IV.

The main contributions of this study are:

- We modified previous device presented in [25]. Based on the efforts in both hardware and software, the device can provide accurate HR estimation (average of absolute errors < 2 bpm) during intensive exercise.
- We adopted the high performance wearable device with the additionally developed a smartphone application and a medical station, which enables patient-provider interaction.
- We demonstrated the full functionality of our system, which was validated on 16 healthy subjects.
- We presented that all subjects could successfully complete the home-based CR exercise by maintaining instantaneous HRs within each prescribed THZ.

II. METHODS

A. PROPOSED SYSTEM FOR HOME-BASED CR EXERCISE

Fig. 1 illustrates our proposed self-CR exercise system with interaction flow between a patient and a CR specialist. In the next subsections, we describe in more detail how home-based CR exercise can be performed through the system, consisting of a wearable device, a smartphone application, and a medical station.

FIGURE 1. Overview of the system consisting of a wearable device, smartphone application, and medical station. Our proposed system enables a patient to perform home-based CR exercise based on interaction between a patient and a CR specialist anytime and anywhere without visiting a hospital.

1) PRESCRIPTION FROM MEDICAL STATION TO SMARTPHONE APPLICATION

In the beginning, a CR specialist prescribes CR exercise for a patient through a medical station. The prescription information includes prescription date and time, exercise type, exercise stage order and its duration, and THZ. The exercise stage order consists of warm-up, main exercise, rest, and cool-down as recommended by the American College of Sports Medicine (ACSM) guidelines [16], [26], [27]. The main exercise stage can be split into multiple shorter stages: warm-up, main exercise, rest, additional main exercise, and cool-down. For warm-up and cool-down, walking or light stretching is recommended. The prescription information is not only stored in a medical station, but also sent to a patient's smartphone application via Internet's hypertext transfer protocol (HTTP).

2) PRESCRIPTION FROM SMARTPHONE APPLICATION TO WEARABLE DEVICE

A patient confirms the prescribed CR exercise and transfers the information to a wearable device via Bluetooth communication. The transferred information includes exercise stage order, its duration, and THZ. Then a patient performs the self-CR exercise with the worn wearable device on wrist. Based on the transferred information, the wearable device informs a patient which exercise stage he or she is currently exercising. In addition, the device measures instantaneous HRs during the exercise, and informs a patient an appropriate exercise intensity based on the comparison between the current HR and the THZ in real-time. More specifically, given the THZ, if the measured HR is greater than the maximum of THZ, then the exercise intensity is too high and should be reduced. On the other hand, if the measured HR is less than the minimum of THZ, then the exercise will be inefficient, and the patient needs to exercise more intensively. Thus, with the current HR and the THZ, the wearable device provides a patient with the alarm indicating exercise pace reduction or increase.

3) EXERCISE RECORDS FROM WEARABLE DEVICE TO SMARTPHONE APPLICATION

Upon completion of CR exercise, the performed CR exercise information is sent to the smartphone application via Bluetooth communication in order that a patient review his or her previous exercise records. The information includes instantaneous HRs, exercise date, start time, end time, and exercise duration. With the measured instantaneous HRs, the smartphone application computes target heart rate retention ratio (THRR) as an additional exercise record. THRR is a quantitative measure that determines how a patient keeps HR within the THZ range during the main exercise as

$$THRR = \frac{Time_{HR\ within\ THZ}}{Time_{main\ exercise}} \times 100\,(\%)\,, \tag{1}$$

where $Time_{HR\ within\ THZ}$ is the time satisfying HRs within the prescribed THZ, and $Time_{main\ exercise}$ is the total time of main exercise performed. Note that the THZ is set between 50% and 70% of the maximum HR through a maximal exercise test. The higher the THRR, the more effective CR exercise is achieved. Along the THRR computation, the smartphone application asks to select the rate of perceived exertion (RPE) which is a quantitative measure of perceived exertion during physical activity as a way to measure exercise intensity level [28]. It is based on physical sensations a patient experiences, including increased HR, increased breathing rate, increased sweating, and muscle fatigue. In our developed application, RPE is categorized into *very very light*, *very light*, *light*, *fairly hard*, *hard*, and *very hard*. This can be selected by a patient after CR exercise. Together with THRR and RPE, the smartphone application manages exercise history metrics such as exercise trials, accumulated exercise time, and the average of THRRs for a certain period such as a week, month, and year that can be monitored by a patient.

4) EXERCISE RECORDS FROM SMARTPHONE APPLICATION TO MEDICAL STATION

Whenever new exercise records are updated in a patient's smartphone application, the updated information is sent to a medical station where a CR specialist can monitor the patient's exercise records. While a CR specialist monitors records of previously performed CR exercise, he or she can prescribe new CR exercise. Fig. 2 shows our designed smartphone application interaction with the wearable device and the medical station. We designed the medical station as a web application built on REST (REpresentational State Transfer) architecture to define a set of constraints and properties based on hypertext transfer protocol (HTTP). The medical station has three core components: web API (developed by ASP.NET Core), web interface framework (developed by Angular), and database (Microsoft SQL). The web API not only communicates with the smartphone application, but also communicates with the web interface framework which is an interface that enables a CR specialist to monitor exercise records and prescribe new CR exercise.

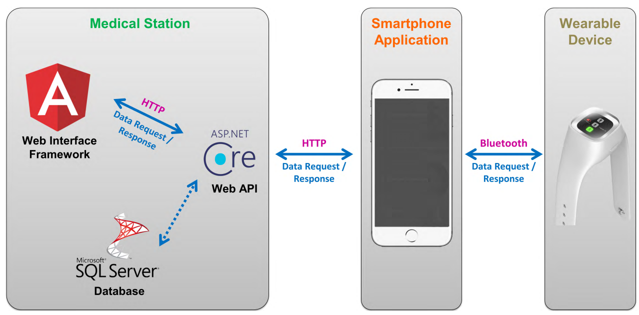

FIGURE 2. **Smartphone application communication with the wearable device and the medical station consisting of web API, web interface framework and database.**

B. WEARABLE DEVICE DESIGN

To perform home-based CR exercise, we have developed a wearable device that has the following features: 1) The device provides accurate HR estimation even during intensive exercise, 2) The device automatically recommends appropriate exercise intensity in real-time using light emitting diodes (LEDs) of various colors based on the prescribed THZ and the measured instantaneous HRs, 3) The device informs current exercise stage (resting, walking or running) using LEDs of various colors based on the prescribed exercise order and its duration, and 4) The device communicates with a smartphone application to receive the exercise prescription and send the performed CR exercise information.

For HR measurement, we acquired multiple photoplethysmographic (PPG) signals simultaneously using five photosensors with distance of 7 mm. By using the multiple photosensors, we could increase the chance to acquire clean signal even during intensive exercise. Recently, our group reported that the error decreased as the number of photosensors increased, especially during high-intensity exercise [29]. NJL5310R with built in green LEDs and a high sensitive photodetector was used as photosensor. Reflected light by wrist was obtained through each photodetector and converted into a voltage signal via a trans-impedance amplifier. The voltage signal was applied with the 4th order Butterworth filter with operational amplifiers (TSV524IQ4T, STMicroelectronics) for amplification with a gain of 100 and band-pass filtering at cut-off frequencies of 0.5 and 10 Hz. The filtered signal was subsequently converted to digital data using a 12-bit analog to digital converter (ADC) built in the microcontroller unit (MCU; STM32F413CGU6, STMicroelectronics). For motion artifact (MA) cancellation, a three-axis accelerometer (LIS3DHTR, STMicroelectronics) was embedded as a noise reference. Thus, five PPG signals and the three axis acceleration signals were obtained with a sampling rate of 100Hz. Signal processing techniques were applied for instantaneous HRs estimation via MCU. These are described in the next subsection.

The instantaneous HR is checked to determine whether it is greater, less, or within the prescribed THZ. According to the condition, exercise intensity recommendation is determined and alarmed to the patient using the LEDs of red (pace-down), yellow (pace-up) and green (keeping the pace) in the four sides of the top window. In addition, in the middle of the top window, exercise state is indicated using the LEDs of red (before exercise or exercise completion), yellow (warm-up or cool down), and green (main exercise). A beeping sound with a speaker (BMA-4003, KANGSEO EST) and vibration with a vibration motor (MB0407-03140V, Motorbank) are embedded and activated when exercise intensity recommendation or exercise stage is changed. In addition, instantaneous HRs are stored in the flash read-only-memory (ROM) built in the MCU and transmitted to our developed smartphone application via Bluetooth module (RN4871, Microchip) after completion of the exercise. Note that all of the catalog data sheets for electronic components used are presented in Supplementary material (https://github.com/HeewonChung92/CardiacRehabExercise).

To achieve PPG signal acquisition, instantaneous HR measurement, exercise stage indication, exercise intensity recommendation, and Bluetooth communication, we implemented three double-sided printed circuit boards (PCBs) inter-connected via mezzanine connectors. Fig. 3 shows the implemented PCBs. The first layer (bottom layer) of the PCB layer was 30 mm × 30 mm. On the bottom surface, five photosensors were mounted. They had contact with wrist to acquire multichannel PPG signals. In addition, a USB connector was mounted for battery recharge. On the top surface, an analog filter including a LED driver and a vibration motor were mounted. The second layer was 25 mm × 14 mm. The MCU was mounted on the bottom surface while the speaker was mounted on the top surface. Both surfaces were connected to the first and third layers via mezzanine connectors. The third layer (top layer) was 30 mm × 30 mm. On the bottom surface, Bluetooth module was mounted. On the top surface, LEDs in the middle and the four sides were mounted for exercise stage indication and intensity recommendation, respectively. The accelerometer was also mounted on the top surface. A 3.7V 180mAh Lithium polymer battery (DTP

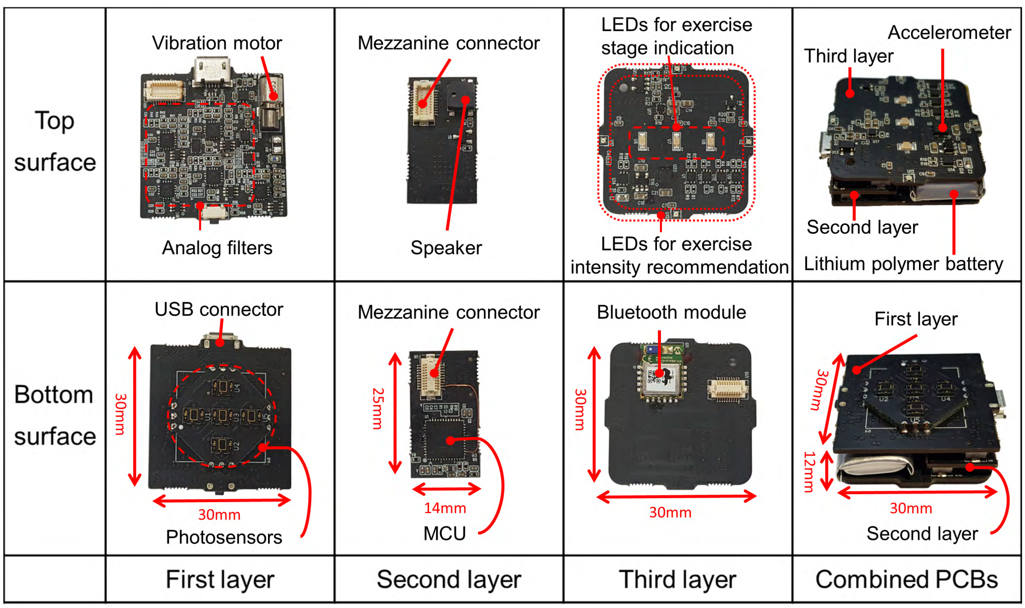

FIGURE 3. The implemented three double-sided PCBs to achieve PPG signal acquisition, instantaneous HR measurement, exercise stage indication, exercise intensity recommendation, and Bluetooth communication.

551430, DTP Battery) was placed in the space next to the second layer between the first and the third layers.

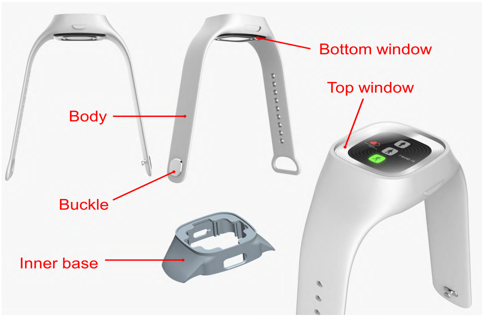

FIGURE 4. **Our designed appearance schematics of the wearable device.**

Fig. 4 shows our designed appearance of the wearable device which has main five parts of components: a body, a bottom window, a top window, an inner base, and a buckle. The body part surrounds and fixes the whole device. It was fabricated with urethane-based rubber resin through a vacuum casting process. Its surface was coated with urethane by soft feel coating which transformed hard surface into smooth texture. The bottom window covers photosensors to prevent sweat penetration. It was fabricated with 100μm thickness acryl through computerized numerical control (CNC) machining with ultraviolet coating. The top window covers LEDs for indicating exercise stage and exercise intensity recommendation. It was also fabricated with 100μm thickness acryl through CNC machining with ultraviolet coating. The inner base was fabricated with acrylonitrile butadiene styrene (ABS) located in the body part to cover PCBs. The buckle fixes the body part when it is worn on wrist. It was fabricated with ABS by CNC machining with additional chromium plating.

C. INSTANTANEOUS HR MEASUREMENT METHOD

During home-based CR exercise, the accurate instantaneous HR measurement is one of the most important factors in determining patient's exercise intensity. For instantaneous HR estimation, we used window length of 8s with shift of 2s: instantaneous HRs are provided every 2 seconds. Given the five-channel 8s-PPG signals $\boldsymbol{S}_n(i)$ at the i^{th} window, where $n = 1, 2, 3, 4$ and 5, we applied singular value decomposition (SVD), which separates the fundamental structural modes constituting a variety of signals. From the observation that the pure pulse is concentrated mostly within the first largest singular value with the corresponding two eigenvectors, we performed the de-nosing using the truncated SVD with the rank one [29].

With the de-noised PPG signal $\boldsymbol{S}(i)$ via truncated SVD and the 8-s three axis acceleration signals $\boldsymbol{A}_m(i)$, where $m = 1, 2,$ and 3, we filtered all four signals using a fourth-order Butterworth band pass filter (BPF) with cutoff frequencies of 0.4 and 4 Hz, which preserves the HR range (40-200 bpm) of subjects of all ages, both at rest and when engaging in physical activities [30], [31]. We then downsampled $\boldsymbol{S}(i)$ and $\boldsymbol{A}_m(i)$ to 25Hz, and obtained each periodogram via a 2,048-point Fast Fourier Transform (FFT): $\boldsymbol{P}^s(i)$ from $\boldsymbol{S}(i)$ and $\boldsymbol{P}_m^A(i)$ from $\boldsymbol{A}_m(i)$. Given the downsampled data with the number of bins, we can obtain the frequency resolution of 0.0061 Hz (12.5Hz/2,048), which is approximately equivalent to 0.37 bpm. We normalized $\boldsymbol{P}^s(i)$ and $\boldsymbol{P}_m^A(i)$ with minimum value of zero and maximum value of one. Given the normalized signals $\bar{\boldsymbol{P}}^s(i)$ and $\bar{\boldsymbol{P}}_m^A(i)$, MA cancellation starts as in [32]:

$$\boldsymbol{P}^C(i) = \bar{\boldsymbol{P}}^s(i) - \frac{1}{3}\sum_{m=1}^{3}\bar{\boldsymbol{P}}_m^A(i), \tag{2}$$

where $\boldsymbol{P}^C(i)$ is the power spectrum of the pure PPG signal. Then, $\boldsymbol{P}^C(i)$ can be re-expressed as

$$\boldsymbol{P}^C(i) = \left(1 - \frac{\frac{1}{3}\sum_{m=1}^{3}\bar{\boldsymbol{P}}_m^A(i)}{\bar{\boldsymbol{P}}^s(i)}\right)\bar{\boldsymbol{P}}^s(i) \tag{3}$$

Subsequently, we replaced $\bar{\boldsymbol{P}}^s(i)$ in the first term with the averaged power spectrum of $\bar{\boldsymbol{P}}^s(i)$ in the previous windows, including the i^{th} window. Then, $\boldsymbol{P}^C(i)$ can be formulated as

$$\boldsymbol{P}^C(i) = \left(1 - \frac{\frac{1}{3}\sum_{m=1}^{3}\bar{\boldsymbol{P}}_m^A(i)}{\frac{1}{C}\left(\sum_{c=1}^{C}\bar{\boldsymbol{P}}^s(i-c+1)\right)}\right)\bar{\boldsymbol{P}}^s(i) \tag{4}$$

The averaging scheme reduces the effect of MAs and preserves HR frequencies because MAs are with more dynamic frequency changes comparing to the HR frequency in pure PPG signal. The first term in (4) can be considered as a Wiener filter coefficient weighting $\bar{\boldsymbol{P}}^s(i)$ to determine $\boldsymbol{P}^C(i)$ [32]. We denote the coefficient by $\boldsymbol{W}_1(i)$.

Along with the formulation in (4), we also can formulate $\boldsymbol{P}^C(i)$ by substituting $\bar{\boldsymbol{P}}^s(i)$ in the first term in (3) with $\boldsymbol{P}^C(i) + \frac{1}{3}\sum_{m=1}^{3}\bar{\boldsymbol{P}}_m^A(i)$. Then, $\boldsymbol{P}^C(i)$ can be re-expressed as

$$\boldsymbol{P}^C(i) = \left(\frac{\boldsymbol{P}^C(i)}{\boldsymbol{P}^C(i) + \frac{1}{3}\sum_{m=1}^{3}\bar{\boldsymbol{P}}_m^A(i)}\right)\bar{\boldsymbol{P}}^s(i) \tag{5}$$

Similar to (4), we denote the first term in (5) by $\boldsymbol{W}_2(i)$. Here, we replaced $\boldsymbol{P}^C(i)$ in the first term in (5) with the averaged power spectrum of the previously obtained $\boldsymbol{P}^C(i)$, again because the power spectrum of clean PPG signals changes slowly, assuming that the HRs in consecutive windows are close. Then, $\boldsymbol{P}^C(i)$ can be formulated as

$$\boldsymbol{P}^C(i) = \left(\frac{\frac{1}{C}\left(\sum_{c=2}^{C+1}\boldsymbol{W}_2(i-c+1)\bar{\boldsymbol{P}}^s(i-c+1)\right)}{\frac{1}{C}\left(\sum_{c=2}^{C+1}\boldsymbol{W}_2(i-c+1)\bar{\boldsymbol{P}}^s(i-c+1)\right) + \frac{1}{3}\sum_{m=1}^{3}\bar{\boldsymbol{P}}_m^A(i)}\right)\bar{\boldsymbol{P}}^s(i) \tag{6}$$

In our developed algorithm, we used $C = 15$ in both (4) and (6) [32]. If $i < 15$, then only the accumulated spectral envelopes are averaged. Finally, we obtained a final clean power spectrum by normalizing the two power spectra in (4) and (6) followed by averaging them. Finally, we found the dominant frequency between 0.6 and 3.3 Hz.

The MA cancellation is effective to provide accurate HR estimation results. However, in some cases, HR results are inaccurate despite the efforts. For instance, very intensive physical exercise may cause the PPG signals to be overwhelmed by MAs, rendering the SNR too low for the MA cancellation. Also, the acceleration signals may not correctly represent true MAs (e.g. finger-tapping, wrist-twisting, and fist clenching/unfolding). In addition, the dominant frequencies from the acceleration signals may overlap with the true HRs. To overcome the issue, we also adopted finite state machine (FSM) framework, which was recently reported in [33]. Four states are defined in the framework, namely, the stable, recovery, alert, and uncertain states. After the HR estimation with MA cancellation, the FSM framework is used to determine the state and validate the estimation result in real-time. A stable state indicates that the estimated HR is very likely to be accurate and it is thus declared valid. The framework determines the state based on the crest factor of power spectrum in the measured PPG signal, and the change value of HRs in consecutive windows. If the state is declared stable, then the corresponding HR estimation result is valid. Otherwise, the result is discarded. Thus, the FSM automatically validates the estimation results without the true HR value, and ignores inaccurate estimation results caused by very low SNRs in PPG signals or MAs uncorrelated with accelerometer signals. The details of the framework are available in [33].

III. SYSTEM EVALUATION AND DISCUSSION

A. SYSTEM EVALUATION SETUP

To investigate the system performance, 16 healthy subjects participated in the home-based CR exercise. In total, 5 males and 11 females with an average age of 26.3 ± 4.3 years participated. For the exercise, the subjects interacted with a CR specialist, who monitors the exercise records and prescribes new CR exercise. For the first CR exercise prescription, the maximal exercise testing was adopted with the Q-Tel RMS program (Mortara Inc., Milwaukee, WI, USA), which is a telemetry monitoring system for exercise parameters for CR monitoring. The participants first underwent maximal exercise testing, and the THZ was subsequently set between 50% and 70% of the maximum HR. A CR specialist monitored the participant's exercise records in the medical station, and provided new CR prescription if it is required. In this way, the participants performed the home-based CR exercise during 3 months. The protocol for data collection and analysis was approved by the Institutional Review Board of Wonkwang University. The participants provided written informed consent.

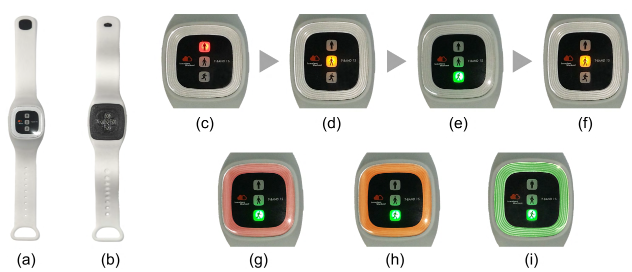

FIGURE 5. Our developed wearable device. (a) front view, (b) rear view, (c) before exercise, (d) warm-up, (e) main exercise, (f) cool-down, (g) pace down recommendation during main exercise, (h) pace up recommendation during main exercise, and (i) keep the pace recommendation during the main exercise.

B. DEVELOPED WEARABLE DEVICE

Fig. 5 shows our developed wearable device for home-based CR exercise. Front and rear faces of the device are shown in Figs. 5(a) and 5(b), respectively. On the front face, the LEDs in the middle are for exercise stage indication, and the LEDs in the four sides are for exercise intensity recommendation. In the beginning, red LED on the mid-front face is turned on (Fig. 5(c)). After 2 seconds, the yellow LED turns on indicating warm-up exercise stage (Fig. 5(d)). When the main exercise starts, the green LED turns on (Fig. 5(e)). After the main exercise stage, the yellow LED turns on indicating cool-down exercise stage (Fig. 5(f)). Also, another LED may turn on depending on the next stage prescribed: red LED on for exercise termination, or green LED on for another main exercise. In this way, the LED on the mid-front face changes according to the prescribed exercise stage order. Note again, to efficiently provide a patient with exercise stage information, the device vibrates for one second with a beeping sound whenever the stage is transited. During the main-exercise stage (Fig. 5(e)), the wearable device compares measured HR with prescribed THZ. If the measured HR is greater than the maximum value of the THZ, red LEDs on the four sides will blink, informing the patient to reduce the pace (Fig. 5(g)) to decrease HR. If the measured HR is lower than the minimum value of the THZ, yellow LEDs on the four sides will blink, informing the patient to increase the pace (Fig. 5(h)) to increase HR. If the measured HR is within THZ, green LEDs on the four sides are turned on, telling the patient to keep the pace (Fig. 5(i)). These alarm signals help the patient to adjust exercise intensity so that the patient's HR is within the THZ range by providing appropriate exercise intensity feedback during exercise.

C. HR ESTIMATION PERFORMANCE DURING EXERCISE

The participants ran on a treadmill with the worn wearable device on wrist for the prescribed home-based CR exercise, which consisted of a rest, warm-up (walk), main-exercise (running), and cool-down. To evaluate HR estimation performance, electrocardiography (ECG) data (Lead-I) were recorded simultaneously using a 24-hour Holter monitor (SEER Light; GE Healthcare, Milwaukee, WI, USA) as true HR reference, $HR_{true}(i)$. Fig. 6 shows one of the HR trace result examples: the 10-min. main exercise from one subject. Note that we showed the results during the first 500 seconds.

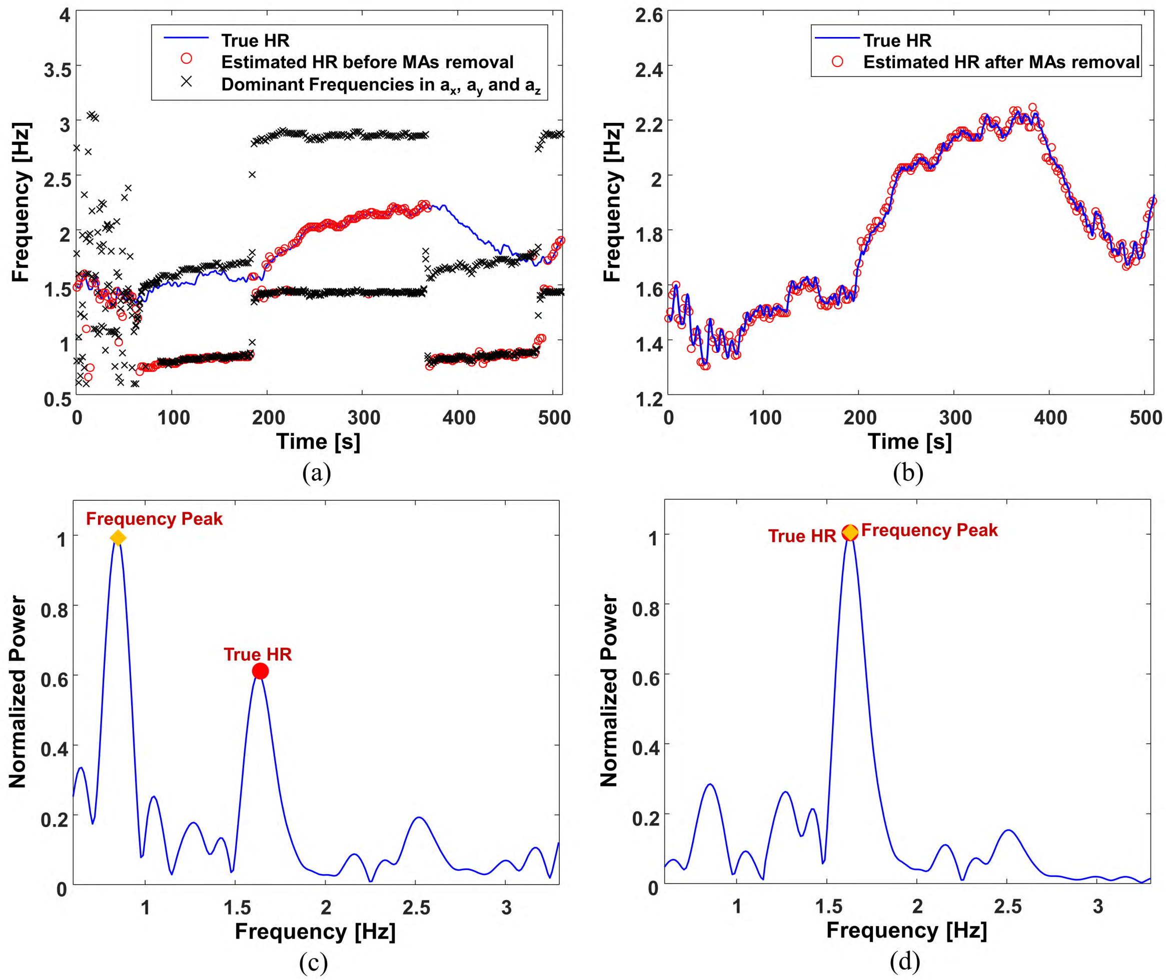

FIGURE 6. HR estimation performance, a male subject with age of 40 years ran on a treadmill with the worn wearable device on wrist for 500 seconds. (a) true HR (blue line), dominant frequencies from the accelerometer signals (black 'x' marks) and the estimated HRs without the MA removal (red circles (b) the estimated HRs after MA removal (red circles), (c) the periodogram without MA removal around 50 seconds, (d) the periodogram after MA removal around 200 seconds.

Fig. 6(a) shows the true HR (blue line), dominant frequencies from accelerometer signals (black 'x' marks), and estimated HRs without the MA removal (red circles). For estimated HRs, $HR_{est}(i)$, dominant frequencies over the range 0.6-3.3 Hz were found in the periodogram directly obtained from (2). It is shown that some estimated HRs were close to dominant frequencies obtained from accelerometer signals, resulting in inaccurate HR estimation. Fig. 6(b) shows resultant estimated HRs by applying (2) through (7). It shows that most estimated HR results (red circles) after MA removal were close to true HRs. More specifically, Fig. 6(c) shows the periodogram without MA removal around 200 seconds. The frequency peak originated from MAs is stronger than that from the true PPG signal, resulting in inaccurate HR estimation. Fig. 6(d) shows the periodogram after MA removal. The dominant frequency peak overlapped with the true heart rate by minimizing MA.

For the performance evaluation, we tested 16 subject datasets. For all 8-s windows, we computed absolute errors (AEs) and evaluated the overall HR estimation performance using average AEs (AAE) (bpm) and valid HRs (VHR) as the percentage of valid results among all windows [32], [33]. We compared the performances with and without MA cancellation for each exercise stage. The performance is summarized in Table 1. During the resting stage, the AAE and VHR with MA cancellation were 1.65 bpm and 85.20%, respectively, versus 1.75 bpm and 76.47 % without MA cancellation. During the walking stage, the AAE and VHR with MA cancellation were 2.44 bpm and 85.18%, respectively, versus 8.74 bpm and 59.77 % without MA cancellation. During the main exercise (jogging) stage, the AAE and VHR with MA cancellation were 1.47 bpm and 96.73%, respectively, versus 33.14 bpm and 70.57 % without MA cancellation. The results show that the MA cancellation provides more accurate HR estimation for all the exercise stages. Especially, the MA cancellation is more effective when subjects run. Note that the performance during the jogging stage is better than that during the walking stage. When walking with an arm

TABLE 1. Comparison of the performances with and without MA cancellation for each exercise stage in terms of average absolute errors (AAE; bpm) and valid HRs (VHR; %): 16 datasets.

Subject	Resting				Walking				Jogging			
	Without MA cancellation		With MA cancellation		Without MA cancellation		With MA cancellation		Without MA cancellation		With MA cancellation	
	AAE	VHR	AAE	VHR	AAE	VHR	AAE	VHR	AAE	VHR	AAE	VHR
1	1.17	54.05	1.63	100.00	**54.49**	**54.58**	**1.50**	**79.17**	**42.23**	**97.14**	**1.03**	**100.00**
2	1.58	100.00	1.53	100.00	6.49	63.75	2.54	90.83	**58.01**	**94.29**	**1.34**	**97.86**
3	1.33	87.80	1.35	80.49	1.51	37.92	1.80	92.92	0.99	55.71	1.15	100.00
4	1.16	100.00	1.23	87.80	**23.33**	**36.67**	**4.20**	**78.75**	**54.48**	**100.00**	**1.04**	**100.00**
5	**10.65**	**8.11**	**1.60**	**72.97**	**34.87**	**52.08**	**6.09**	**75.00**	**64.66**	**98.57**	**2.09**	**100.00**
6	2.06	86.49	1.57	54.05	8.85	46.67	2.06	86.25	**92.17**	**37.86**	**1.59**	**92.86**
7	2.61	62.16	1.68	56.76	7.90	55.42	6.42	65.00	**78.87**	**86.43**	**1.91**	**92.86**
8	2.22	78.38	2.37	100.00	1.88	76.25	2.27	89.58	1.53	68.57	1.61	100.00
9	2.73	72.97	1.52	72.97	1.49	49.58	1.93	82.92	1.28	60.71	1.45	85.00
10	1.48	67.57	1.68	100.00	**5.61**	**69.17**	**1.87**	**85.42**	**42.11**	**67.14**	**1.61**	**96.43**
11	1.27	67.57	1.57	100.00	1.60	80.00	1.82	93.33	1.08	61.43	1.41	93.57
12	1.77	100.00	1.63	97.30	1.55	94.58	1.88	87.92	1.50	88.57	1.54	100.00
13	0.86	75.68	1.45	86.49	**6.35**	**34.58**	**1.46**	**97.08**	**12.71**	**49.29**	**1.34**	**97.86**
14	1.88	100.00	2.00	78.38	1.73	78.75	1.83	88.75	**10.75**	**47.86**	**1.43**	**100.00**
15	1.99	86.49	1.92	86.49	1.34	87.50	1.52	88.75	1.22	89.29	1.21	100.00
16	1.33	76.32	1.61	89.47	1.06	38.75	1.61	81.25	1.38	41.25	1.81	91.25
mean	**1.75**	**76.47**	**1.65**	**85.20**	**8.74**	**59.77**	**2.44**	**85.18**	**33.14**	**70.57**	**1.47**	**96.73**
std	**1.57**	**23.24**	**1.24**	**15.09**	**10.43**	**19.31**	**4.04**	**8.01**	**22.67**	**21.83**	**1.18**	**4.44**

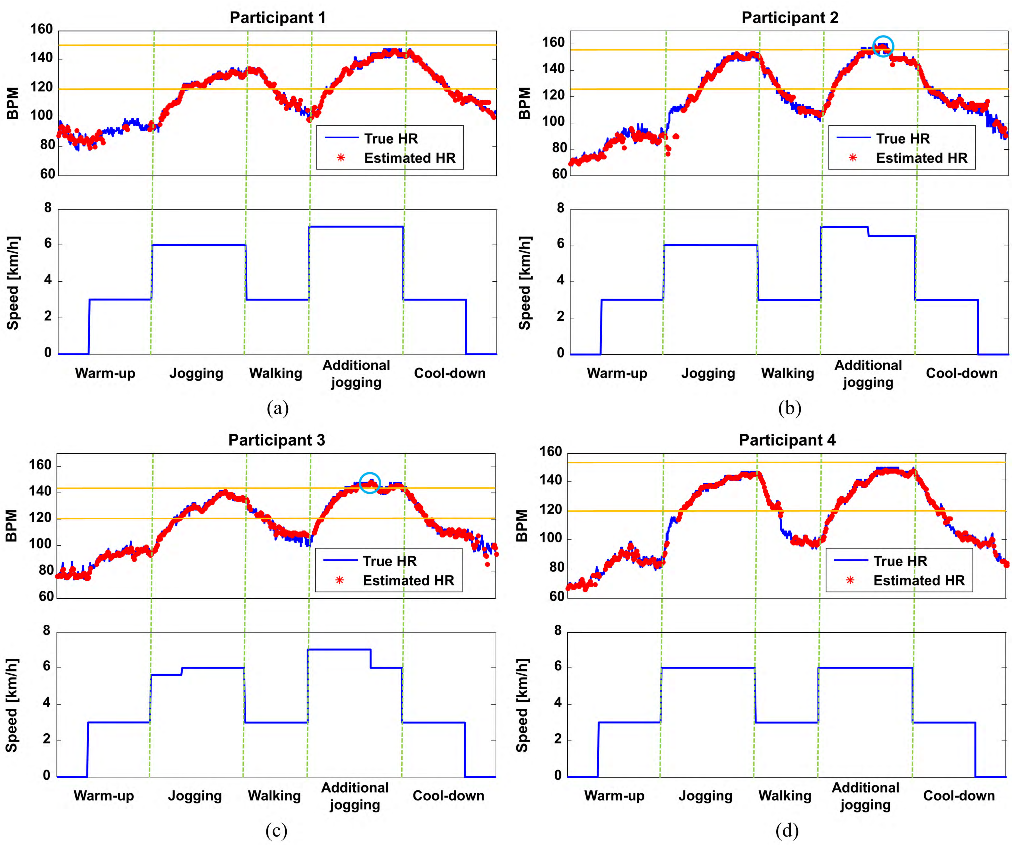

FIGURE 7. Examples of the individual HR traces obtained with the Holter monitor and our developed wearable device. All subjects could successfully maintain the instantaneous HRs within the THZ during the main exercise (The circle indicates that the wearable device blinks the red LED on the four sides informing the patient to reduce the pace).

swinging, one cycle of wrist movement occasionally results in two cycles of dominant acceleration signals from one of axes [34], which limitation was recently identified. To overcome the issue, a gyroscope has recently been proposed as an alternative to an accelerometer. In the future work, we plan to combine a gyroscope for better MA cancellation.

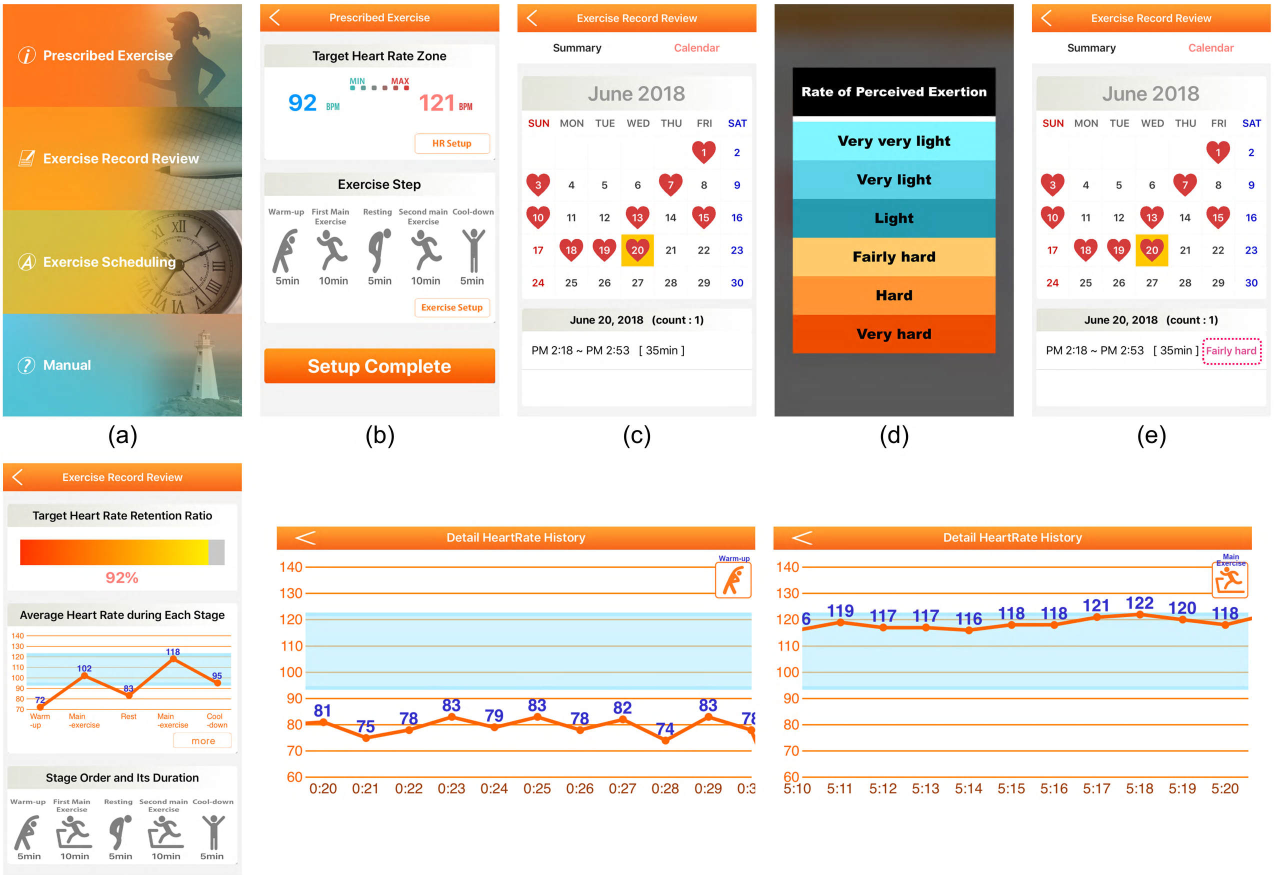

FIGURE 8. Smartphone application. (a) the application first page with buttons for prescribed exercise, exercise record review, exercise scheduling, and the application manual. (b) the prescribed exercise page enables user to confirm or update the prescribed exercise such as THZ, exercise type, exercise stage order, and its duration, (c) the exercise record review page in summary and calendar, (d) RPE selection page, (e) the display of exercise time information with RPE, (f) more detail exercise record page, and (g) instantaneous HR trace page.

During the main exercise stage, our developed wearable device compared the measured HR with the THZ, and recommended the appropriate exercise intensity by blinking red, yellow or green LEDs on the side. Fig. 7 shows the home-based CR exercise result examples from four subjects. The estimated HRs were compared with the results from the Holter monitor (reference) during the exercise stages. The circle indicates that the wearable device blinks the red LED on the four sides informing the patient to reduce the pace. We presented the results from all 16 subjects at https://github.com/HeewonChung92/CardiacRehabExercise. In the results, all subjects could successfully maintain the instantaneous HRs within the THZ during the main exercise.

D. EXERCISE RECORDS IN SMARTPHONE APPLICATION

Fig. 8(a) shows the main page of our developed smartphone application. The first top panel is to review or change the prescribed exercise. When the panel is clicked, a patient can monitor the prescribed exercise as shown in Fig. 8(b). THZ, exercise type, exercise stage order, and its duration are displayed. If a patient clicks the button "Setup Complete", the prescribed information is transferred to the wearable device. After completion of the exercise, a patient can monitor or review his or her own exercise records by clicking the second top panel in Fig. 8(a). Fig. 8(c) shows exercise record review page which can be viewed in two ways: summary and calendar. If "Calendar" is clicked, exercise dates are marked with red hearts in a calendar. When the red heart on the exercise date is clicked, exercise time information such as the exercise start time, end time, and duration is displayed at the bottom. If RPE is not recorded, new page is loaded to select the RPE: *very very light*, *very light*, *light*, *fairly hard*, *hard*, and *very hard* as shown in Fig. 8(d). After a patient selects the RPE, the selected one is displayed next to the exercise time information as shown in Fig. 8(e) (highlighted with red box). In addition, by clicking exercise time information, more detail exercise records can be reviewed as shown in Fig. 8(f), including THRR, average HR during each exercise stage, the performed exercise stage order, and its duration. Furthermore, by clicking "more" button, instantaneous HRs can be reviewed as shown in Fig. 8(g). More description regarding the application is presented in Supplementary material (https://github.com/Heewon Chung92/CardiacRehabExercise).

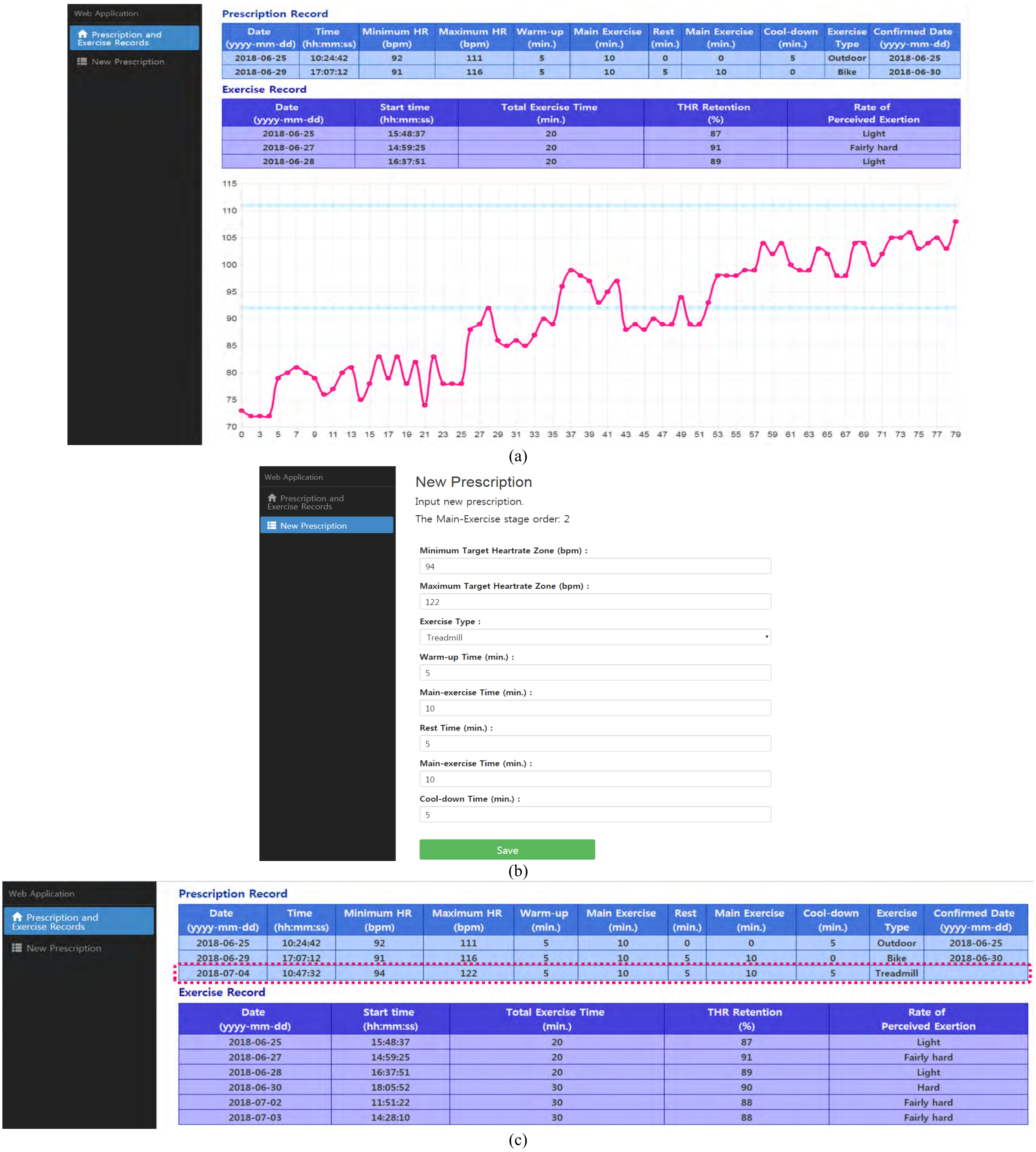

FIGURE 9. **Medical station monitored and prescribed by a CR specialist. (a) prescription and exercise records page, (b) new prescription input page, and (c) updated prescription record.**

E. EXERCISE RECORDS AND NEW PRESCRIPTION IN MEDICAL STATION

Fig. 9(a) shows the main page of our developed medical station for a CR specialist to monitor patient's exercise record, review previous CR exercise prescription, and prescribe new CR exercise. On the left top panel, when "prescription and exercise records" is clicked, the previously prescribed exercise and performed exercise records can be monitored. The prescription record includes prescription date and time, THZ, exercise stage order and its duration, exercise type, and the patient's confirmation date for each prescription. The exercise record includes the performed exercise date, start time, total exercise time, THRR, and RPE. By clicking one of the lines in the exercise record, a CR specialist can monitor instantaneous HRs that will be displayed at the bottom. In the left panel, by clicking ''New Prescription'', a CR specialist can input the new exercise prescription as shown in Fig. 9(b). For the exercise stage order, a CR specialist first selects the number of main-exercises and then the exercise stage is ordered accordingly. Once the form is filled out and the ''Save'' button is clicked, the new prescription is added into the prescription record as shown in Fig. 9(c) (highlighted with red box). More description regarding the medical station is presented in Supplementary material (https://github.com/HeewonChung92/CardiacRehab Exercise).

IV. DISCUSSION AND CONCLUSION

We presented our developed cardiac management system for a patient-CR specialist interaction. Our proposed and developed cardiac management system consists of a wearable device, a smartphone application, and a medical station. It enables interactions between a patient and a CR specialist so that they can provide feedback to each other for effective home-based CR exercise. Our developed cardiac management system is available when a cardiac patient leaves a hospital or at any other time to help prevent future heart problems. Furthermore, it is available for healthy individuals to ensure efficient exercise by indicating an appropriate exercise intensity. In this study, to validate our developed system, we have tested 16 healthy subjects, and showed that all subjects successfully completed the home-based CR exercise by maintaining the instantaneous HRs within the each prescribed THZ. Recently, electrocardiography (ECG) based wearable devices for HR estimation are commercially available. The devices can be adopted in our proposed system, but PPG devices have more advantages over ECG devices for our proposed home-based CR exercise. The ECG devices are with patch-type attaching on a chest or with watch-type attaching on a wrist. With the patch-type ECG device, an additional watch-type device is required to monitor the exercise stage and intensity recommendation. For the watch-type ECG device, it is difficult to measure continuous HRs because one has to keep touching the opposite side finger to the device.

For the efficient energy consumption of wireless communication, the communication between a wearable device and a smartphone application was activated only when a patient connected a smartphone application with a wearable device via Bluetooth communication. Upon the completion of the data transfer, the Bluetooth communication was disconnected. The communication between a smartphone application and a medical station was activated only when a patient launched a smartphone application. Similarly, upon the completion of the data transfer, the connection was disabled. In this way, our system was designed for more efficient energy consumption. In the future work, we will consider more strategies to optimize energy consumption for more efficient and convenient wireless communication.

As a pilot study, we presented the system including a wearable device functionality and showed clinical potential that the system could be positively applied for home-based CR exercise. While a patient performs the home-based CR exercise, a variety of exceptional cases can occur. For instance, a patient cannot fully perform the prescribed exercise because he or she is tired or sick. Conversely, a patient may be prepared to perform more exercise than the prescribed exercise. For future research, we will consider more complete systematic algorithms to ensure that the system responds to all scenarios. In addition, we will recruit CR patients to rigorously validate the efficiency of the system. In addition, we plan to investigate how the system effectively lowers the recurrence of cardiovascular event in short and long terms [35]–[37].

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