A Smart Health Monitoring Chair for Nonintrusive Measurement of Biological Signals

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***Abstract*—We developed nonintrusive methods for simultaneous electrocardiogram, photoplethysmogram, and ballistocardiogram measurements that do not require direct contact between instruments and bare skin. These methods were applied to the design of a diagnostic chair for unconstrained heart rate and blood pressure monitoring purposes. Our methods were operationalized through capacitively coupled electrodes installed in the chair back that include high-input impedance amplifiers, and conductive textiles installed in the seat for capacitive driven-right-leg circuit configuration that is capable of recording electrocardiogram information through clothing. Photoplethysmograms were measured through clothing using seat mounted sensors with specially designed amplifier circuits that vary in light intensity according to clothing type. Ballistocardiograms were recorded using a film type transducer material, polyvinylidenefluoride (PVDF), which was installed beneath the seat cover. By simultaneously measuring signals, beat-to-beat heart rates could be monitored even when electrocardiograms were not recorded due to movement artifacts. Beat-to-beat blood pressure was also monitored using unconstrained measurements of pulse arrival time and other physiological parameters, and our experimental results indicated that the estimated blood pressure tended to coincide with actual blood pressure measurements. This study demonstrates the feasibility of our method and device for biological signal monitoring through clothing for unconstrained long-term daily health monitoring that does not require user awareness and is not limited by physical activity.**

***Index Terms*—Ballistocardiogram (BCG), blood pressure, chair, ECG, healthcare system, heart rate (HR), nonintrusive, photoplethysmogram (PPG), through clothing, unconstrained.**

I. Introduction

BIOLOGICAL signal monitoring plays a critical role in health management processes including diagnosis, treatment, and evaluation of treatment efficacy. Conventional standard clinical measurement modalities such as electrocardiography and pulse oximetry are able to provide basic information regarding health status. However, these modalities are not applicable outside of hospital environments because they require user attention or cooperation in order to operate the required signal measurement devices. Reliance on such modalities restricts long-term and regular monitoring in healthcare. There are various methods and devices that have been developed for daily life biological signal measurements. Most of them use miniaturized devices and wireless transmission of monitored data (for example, Zephyr Bioharness or Nonin devices). Many are already commercially available and provide useful daily health-related information such as heart rate (HR), blood oxygen saturation level, or blood sugar level. However, they are often impractical as they also require certain level of user's awareness and cooperation for operating the device.

Unconstrained biological signal monitoring is emerging as an alternative to conventional clinical biological signal measurement systems. The principal goal of unconstrained measurement is to sustainably monitor health-related information through biological signals without interrupting the subject's ordinary daily activities and without requiring additional operations or cooperation in order to make signal measurements. This method enables daily recording of normal health status, and application of these data for healthcare purposes with minimal inconvenience to the patient. Eventually, the huge amount of data gathered from unconstrained continuous monitoring would be used to understand daily changes in health information that occur in response to disease, medication, infection, or stress. For example, clinicians may be able to use accumulated data to predict when heart attack may occur. Unconstrained system also prevents some bias problems in health information monitoring such as white coat syndrome in blood pressure (BP) monitoring. There are generally two concepts for unconstrained and nonintrusive measurements. The first is wearable sensor-type system utilize metal plates or conductive textile electrodes in clothing, accessories, or helmet, which are in direct contact with exposed skin [1], [2]. In this case, sensors are affixed to the body in order to acquire signals. Although these systems provide reliable performance compared to conventional clinical modalities, further research on wearable systems is required to improve shortcomings such as discomfort to the wearer, restrictions on wearer activity. Unlike these, recently, devices that enable biological signal measurement with sensors that are installed in everyday objects such as appliances, furniture, or clothing have been studied for unconstrained, long-term daily health monitoring [3]. These kinds of systems, referred to as fixed-on-environment systems, make signal measurements using installed electrodes. However, people normally wear clothes, exposing only small areas of bare skin, and therefore, a main concern of

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fixed-on-environment systems is the ability to record biological signals through clothing. The number of signals that can be recorded using fixed-on-environment systems is another concern. Because greater numbers of signals can provide more complete health information, simultaneous multiple signal recording is recommended for unconstrained health monitoring systems.

There have been a few studies regarding chair-based biological signal monitoring. People in industrialized societies spend a great deal of time sitting in chairs. Kim *et al*. developed a chair that uses pulse arrival time (PAT) calculation from ECG and photoplethysmogram (PPG) signals for unconstrained BP monitoring. ECG was measured using conductive metal and PPG was measured using a commercial sensor installed in the armrest [4]. Wu *et al*. constructed a similar chair [5], but instead of conductive metal, their device incorporated a capacitive coupling ECG sensor. Junnila *et al*. used electromechanical film (EMFi) sensors installed in a chair seat to measure ballistocardiogram (BCG) in an unconstrained manner [6]. Karki and Lekkala also recorded BCG using a chair, but their device utilized Polyvinylidenefluoride (PVDF) film instead of EMFi sensors [7]. Baek *et al*. attached capacitive coupling sensors to driver's seats for unconstrained ECG monitoring in automobiles [8]. While existing BP monitoring chairs like those described earlier were intended to be completely unobtrusive, some still require user attention and cooperation. For example, in a typical device, the user is required to place his or her finger on a sensor located in the armrest to measure PPG signals. Other designs are less intrusive, since they record biological signals while the subject simply sits on the chair. However, most of these systems provide limited health information, because each measures only one kind of signal. In the context of recent progress in unconstrained biological signal measurement techniques, further research is required to improve the nonintrusiveness of and amount of information that may be provided by fully unconstrained multiple biological signal monitoring chairs, to provide data necessary for long-term daily healthcare.

This paper was motivated by the following two functional aims: 1) the obtainment of fully unconstrained ECG, PPG, and BCG measurements through clothing without requiring user awareness or cooperation; and 2) monitoring of BP using the proposed biological signal recording methods. In this paper, we present methods to measure ECG, PPG, and BCG without skin contact, describe a novel chair-based unconstrained measurement system, and assess their abilities to provide useful health information.

II. Materials and Methods

In our previous studies [9], [10], we described new ECG and PPG measurement methods that enable signal recording without direct skin to sensor contact. In those studies, each method was tested and validated through experiments using prototypes of back and seat cushions designed for use in future chair-based devices. Since our first attempt is to construct an unconstrained biological signal monitoring chair, we have modified our designs through trial and error to produce a practical system that can be used not only in research but also in daily life. The goal of this study is focused on real-world commercialization.

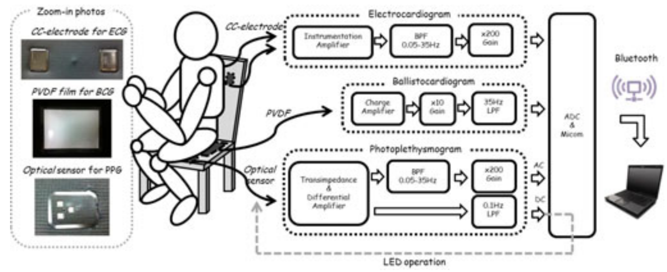

Fig. 1. Diagram of proposed smart healthcare system.

We integrated three methods for obtaining simultaneous unconstrained ECG, PPG, and BCG signal measurements using a chair-based device, and also surmounted some supplement points of previous system. The final version of the device that we present in this paper is referred to as a "smart healthcare chair" (see Fig. 1).

A. ECG Measurement Through Clothing

An ECG is a recorded electrical signal that can be measured through clothing using the concept of displacement current through capacitive coupling. The insulating effect of clothing creates relatively high impedance between sensor and skin. Therefore, a high-input impedance amplifier that converts displacement current into voltage through clothing was used in each sensor as an active electrode. Each sensor was shielded by an aluminum case that surrounded the rear of the sensor. The sensors were installed into the back of a chair, as shown in Fig. 1, to detect differential signals. Output signals from each electrode were amplified and filtered. Our capacitive ECG measurement system is weak for the common mode noise due to high impedance between the capacitive electrode and the body. Moreover, the impedances between each capacitive electrode and the body may vary. Thus, the system requires excellent common mode noise cancellation. In an earlier version of our chair system [10], the third electrode, a ground plate installed into the seat of the chair, was connected to the system ground by a cable. However, because impedance between the body and the full ground is not reduced in this manner, the common mode signal in the body cannot be decreased. In addition, when there are different impedances at each electrode, this noise in the body is not equivalent to the common mode signal in the differential amplifier, and the differential noise is, therefore, greatly amplified in the gain amplifier. In this study, to effectively cancel the common mode noise in the body, we employed a driven-capacitive-ground circuit [11]. The driven-capacitive-ground circuit that we used is similar to the driven-right-leg circuits that are used for conventional clinical ECG measurements. The summated common mode signal from two capacitive electrodes is capacitively transmitted to the body through conductive fabric on the chair seat as negative feedback with a gain of 1000. Therefore, problems of common mode noise rejection can be significantly improved. A brief configuration designed for recording ECG through clothing is shown in Fig. 2.

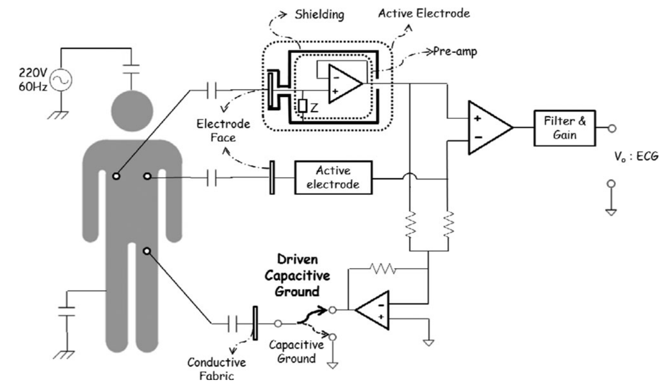

Fig. 2. Schematic circuits for capacitive electrocardiogram measurement and driven-capacitive-ground configuration.

B. PPG Measurement Through Clothing

The most common PPG recording method relies on the Beer–Lambert law of spectrophotometry that relates the concentration of solute to the intensity of transmitted light through a solution [12]. Conventional PPG measurements are achieved by illuminating the tissue bed and measuring the transmitted or reflected light that is not absorbed by the tissue. To measure PPG through clothing, we assumed that clothing behaves like a homogeneous additive tissue layer that absorbs additional emitted light. Therefore, higher emitting light intensity is required than for conventional PPG measurement. Additionally, the intensity automatically varies according to clothing type, since the absorptive characteristics and optical path lengths of clothing will vary depending on the type of cloth that is used. To meet these requirements, we constructed an adaptive system to control light source intensity that employed a microprocessor and digital-to-analog converter (DAC). Because the DAC can provide different output voltages, LED intensity can be controlled by its use. Based on the fact that the dc component of a PPG signal is constant for a given nonpulsatile medium, changes in dc voltage due to variation in emitted light intensities were investigated using different types of clothing in our previous study [9]. Maximum and minimum dc voltage thresholds were empirically determined from these investigations. Then, using a programmable microprocessor, we developed an adaptive light intensity control system and successfully acquired PPG signals through various types of clothing. However, heat generation by the LED was a serious problem with the earlier versions of our system. Although the PPG signal was clearer when maximum LED intensity was emitted through relatively thick clothing, the LED heat also increased with the light intensity level. Therefore, it was difficult to measure PPG signals at maximum intensity for long periods of time. For this reason, PPG sensor modules with heat dissipation units were applied in the current study. PPG sensors made of metal printed circuit board (PCB) were substituted for sensors made of conventional FR4-based PCB (total sensor size 3.5 cm $\times$ 1.5 cm). In addition, a heat sink was attached beneath each metal PCB surface. Conventional heat sink units (4 cm $\times$ 4 cm $\times$ 0.8 cm) and custom-made aluminum blocks (30 cm $\times$ 30 cm) that were slightly smaller than the seat area of the chair were tested and compared.

C. BCG Monitoring Through Clothing

A BCG is the recording ballistic force imparted by the motion of blood and heart during each cardiac cycle [13]. PVDF film was used for BCG measurements (Measurement Specialties, Inc., PA). PVDF film is thin, elastic, and permanently charged semicrystalline piezoelectric film. The outputs of PVDF film are charge changes. The external physical strength compressing film generates voltage output that is characterized by dynamic changes of applied pressure. When the heart beats, blood is ejected into the arteries, which causes action–reaction processes such as vibrations of the body surface according to Newton's third law [14]. A PVDF film 19 mm in width, 26.7 mm in length, and 28 μm in thickness is placed under the thighs in the seat of the chair to detect the vibrations. The vibrations compress the PVDF film, which in turn generates charge changes that are proportional to the applied force. In our device, the PVDF film was wrapped in a silicon pad for protection and enhancement of the sensitivity of output signal detection. Although BCG could be measured using PVDF film without requiring any analog circuits, a charge amplifier, and analog band pass filter with cutoff frequencies of 0.5 and 30 Hz were employed for ac amplification and possible noise reduction.

D. Mock-Up Process

Fig. 1 shows a conceptual diagram of our chair system with sensors installed for unconstrained health monitoring. Two capacitive coupled ECG electrodes are attached to the back of the chair. Each electrode is connected to a specially designed controller that uses a screw for subject-specific adjustment of electrode height to enhance contact between the electrode surface and clothing. A push switch is inserted between the two ECG electrodes for subject detection and is connected to screw-type height controllers like those used for ECG electrode adjustment. The switch is pushed when a subject sits on the chair, activating and controlling the chair system. PVDF film that is sandwiched between two silicon pads, conductive fabric and a PPG sensor are installed in the seat of the chair. Conductive fabric is used as a third electrode in the ECG measurement system for the driven-capacitive-ground circuit. Our PPG sensor consists of three LEDs symmetrically distributed around a photodiode. The sensor is installed in the seat of the chair, and is automatically activated by the subject's thigh while the subject sits on the chair. For practical purposes, we implemented a fully wireless system powered by a portable, rechargeable lithium ion cylindrical cell battery (7.4 V, 10.4 A) with a wireless communication unit for data transmission. Since all circuits for smart healthcare chair system were made using micro power operational amplifiers that are specifically designed for battery powered portable applications, we can reduce power consumption. In our experiments, the chair system could be operated for more than 1 week without recharging the battery used intermittently during business hours (9 AM--6 PM). Our chair system was designed to select a communication method (Bluetooth or Zigbee) as a wireless personal area network (WPAN) according to the intended purpose [15]. For example, Bluetooth is selected when the chair system is used along with applications that have built in Bluetooth adapters, including laptops and smart phones. Zigbee may be selected when single node control of multiple other nodes is required. For instance, Zigbee can be used with multiple chair systems in office environments. The signal viewer program was developed with Visual Studio 2008 (Microsoft, Redmond, WA) and TeeChart pro (SteeMa Software, Spain). In the viewer program, ECG, PPG, and BCG signals and HR, BP, and PAT are displayed in order (see Fig. 3). The program uses simple icons that are easy to understand and that nonexpert users will understand intuitively. Pressing each icon loads an easily understandable graphical interpretation of the requested information.

E. Experiments

This study included five male volunteers who had no history of cardiovascular disease. A conventional physiological signal acquisition system (MP150, BIOPAC) was used to measure reference ECG and PPG signals. Beat-to-beat BP was measured using a FINOMETERPRO (Finapres Medical System) attached to the left middle finger for comparison with simultaneously estimated BP. The subjects wore normal street clothes and were instructed to perform Valsalva maneuvers to alter HR and BP. The Valsalva maneuver is forced expiratory effort. When subject forcefully expires against a closed airway, it will elicit the cardiovascular responses such as venous return, cardiac output, arterial pressure, and HR. In experiments with smart healthcare chair, subjects quietly rested on the chair for 2 min and executed the Valsalva maneuver for 20–30 s, and finally, subject rested on the chair again for about 3 min to stabilize the changes in BP. For signal analysis, data from Valsalva phase III to IV showing the BP increase and recovery period were analyzed. Beat-to-beat HRs calculated during RR intervals by the reference and chair systems while the subjects altered their HR were compared. PAT represents the speed at which the arterial pressure wave travels and is defined as the time delay from ECG *R*-peak to the characteristic pulse wave point in the peripheral artery. Since PAT is inversely proportional to BP, it is widely used for cuffless BP monitoring [16], [17]. Previously, we reported a new approach for estimating BP for enhancement of BP estimation performance [18], [19]. Additional parameters, HR and TDB, which represent the arterial stiffness index as shown in Fig. 4, were employed in regression analyses. was used to estimate BP ($BP = \alpha \times PAT + \beta \times HR + \gamma \times TDB + \delta$; α, β, γ, and δ are calibration constants) and its performance was compared to that of conventional single linear regression analysis ($BP = \alpha \times PAT + \beta$; α and β are calibration constants). In calibration experiments, data acquired Valsalva maneuver were used to determine calibration constants in regression analysis. The cuffless BP estimation performance was evaluated using data acquired during Valsalva maneuver after calibration experiments.

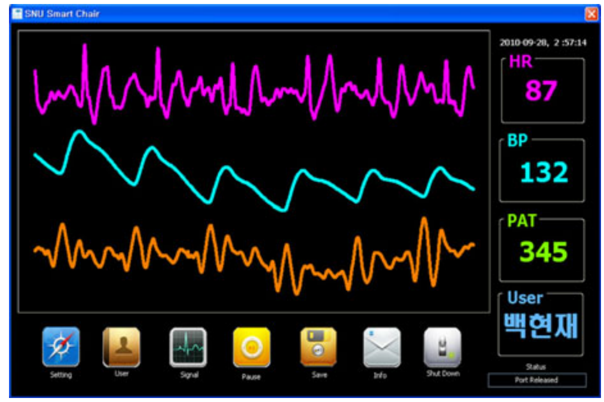

Fig. 3. Signal viewer program of our smart healthcare chair system designed for recording ECG, PPG, and BCG signals without skin contact.

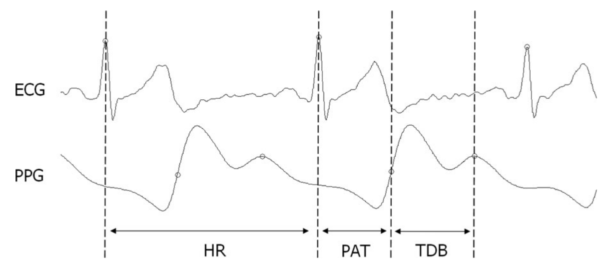

Fig. 4. Parameters for cuffless BP estimation using multiple regression analysis: HR, PAT, and arterial stiffness index (TDB) [19].

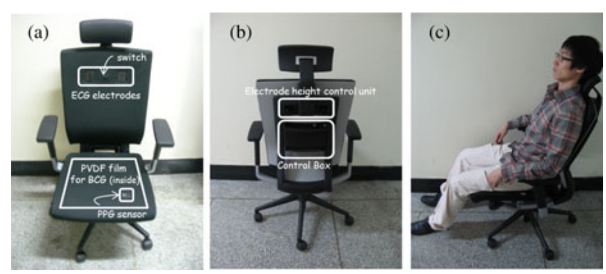

Fig. 5. Photograph of a proposed smart healthcare chair for recording ECG, PPG, and BCG signals without requiring skin contact. (a) Frontal view. (b) Rear view. (c) Subject sitting on the chair while clothed.

III. Results

A. Unconstrained Biological Signal Monitoring Chair

Fig. 5 shows photographs of our smart healthcare chair that can simultaneously measure ECG, PPG, and BCG signals. Only ECG electrodes, the PPG sensor and control box containing amplifiers, the communication module, and sensor height control units were exposed externally. Sheet materials such as PVDF film, silicon pads, and conductive fabric as well as all wires were connected internally and therefore were not visible. A specially designed control box was located on the back of the chair, as shown in Fig. 5(b). Our data transmission system is fully wireless, and therefore, the chair can be moved freely. A movie demonstrating the use of the proposed healthcare chair can be found on our website at http://baek.re.kr as well as http://www.youtube.com/watch?feature=player_detailpage&v=eVPX_2MjeK8. When a subject sits on the chair, one to two min of stabilization time are required for clear signal measurement. During this period, variation in impedance between capacitive ECG electrodes and the body due to the motion of sitting down is stabilized, and the optimal light intensity for PPG measurements is identified.

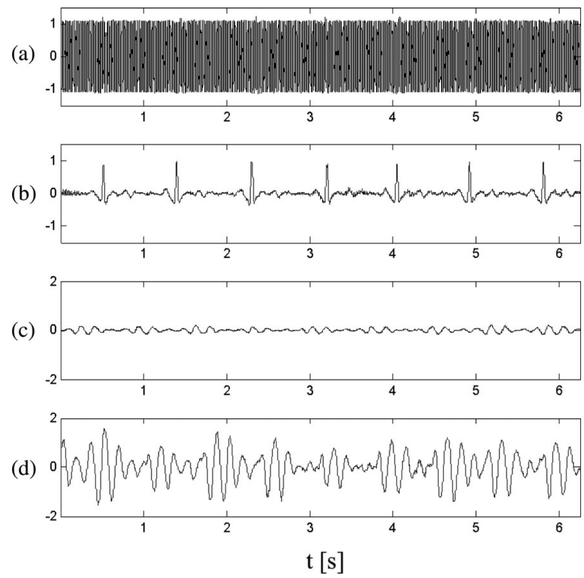

Fig. 6. ECG signal measured with (a) Capacitive ground. (b) Capacitive driven. BCG signal measured (c) Without charge amplifier. (d) With charge amplifier.

TABLE I
TEMPERATURE OF THE LED UNIT ACCORDING TO SENSOR MATERIALS

Thermometer	Turn-off		Only PCB		METAL PCB with Heat Sink	
	FR4	*METAL*	*FR4*	*METAL*	*plate*	*pad*
Infrared	21.2	21.1	67.4	57.4	44.8	33.2
thermistor	21.1	20.69	67.66	63.29	42.35	38.07
Mean	21.15	20.9	67.53	60.35	43.58	35.66

TABLE II
HR ESTIMATES USING THE CHAIR SYSTEM AND REFERENCE SYSTEMS

Subject	Chair Signal	Beat-to-beat heart rate		
		Difference [mean(SD), beat/min]	*Error [mean, %]*	*Correlation [r]*
A	ECG	0.043(0.048)	5.06e-02	1.000
	PPG	0.424(0.307)	0.56	0.999
	BCG	0.546(1.757)	0.52	0.992
B	ECG	0.031(0.031)	4.78e-02	1.000
	PPG	0.640(0.695)	0.96	0.996
	BCG	1.281(2.207)	1.87	0.979
C	ECG	0.032(0.078)	4.38e-02	0.999
	PPG	0.515(0.405)	0.79	0.997
	BCG	1.857(2.595)	2.78	0.935
D	ECG	0.029(0.047)	4.55e-02	1.000
	PPG	0.566(1.229)	0.85	0.997
	BCG	0.867(2.941)	1.11	0.979
E	ECG	0.031(0.078)	4.34e-02	0.999
	PPG	0.517(0.408)	0.79	0.996
	BCG	1.412(2.084)	2.17	0.951

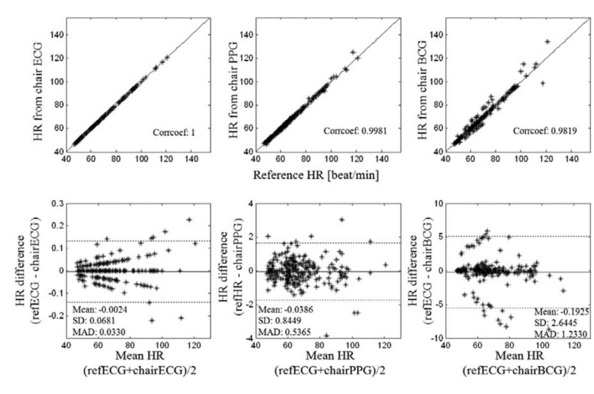

Fig. 7. Results of validation analyses of HR measured using our proposed chair system. The top row shows scatter plots of reference ECG and chair signals, and the bottom row shows Bland–Altman plots.

B. Improvement in Signal Measurements

The effects of driven circuits on capacitive coupled ECG recording are shown in Fig. 6(a) and (b). Waveforms are presented without any postdigital processing. Clear ECG signals were obtained using a driven circuit configuration. Changes in pressure on the PVDF film generate charges on its electrically conductive surfaces, and this charge can be measured more clearly as a voltage signal when a charge amplifier is used. This result is illustrated in Fig. 6(c) and (d). The heat generated by the LEDs was greatly reduced when heat sink configurations were installed beneath the PPG sensors. Table I shows temperatures that were measured during device turn OFF and turn ON with maximum LED light intensity for 5 min. Temperature was measured by both infrared and thermistor-based thermometers, and average values were calculated. Integrated heat sink and metal PCB construction improved heat dissipation performance, especially when large heat sinks that covered almost of the entire chair seat (pad) were used rather than much smaller conventional heat sink units (plate).

C. HR Monitoring

Estimates of HR that were calculated from reference ECG, measured ECG, PPG, and BCG were comparable. The cardiac cycle was calculated using intervals between adjacent R peaks of ECG, J peaks of BCG, and peaks of the derivative of PPG. A comparison of these measures is summarized in Table II. The maximum differences between beat-to-beat heart rate measurements were 0.043, 0.640, and 1.857 beat/min for ECG, PPG, and BCG, respectively, and the error was less than 3.0% for all cases. The correlations between reference ECG and signals measured by our chair system were greater than 0.9 for beat-to-beat HR in all cases, as illustrated by the agreement analysis shown in Fig. 7. Bland–Altman plots show considerable correlations between the values estimated by all three methods, as we expected. As shown in Fig. 8, HR could be calculated using only one of the successfully measured signals, even if other signals were not obtained due to motion artifacts or poor contact between sensors and body.

D. BP Estimation

The single- and multiple-regression correlation coefficients between the actual and estimated BP during Valsalva-induced BP variation for all five subjects are presented in Table III. The R^2 and adjusted R^2 are also given. The R^2 gives information about the goodness of fit of the model and the adjusted R^2 compensates for a number of explanatory terms. The R^2 increases when the regression line provides a good approximation of the actual data points. The adjusted R^2 increases only if a new term improves the model by more than would be expected by chance. Therefore, the increased values of R^2 and adjusted R^2

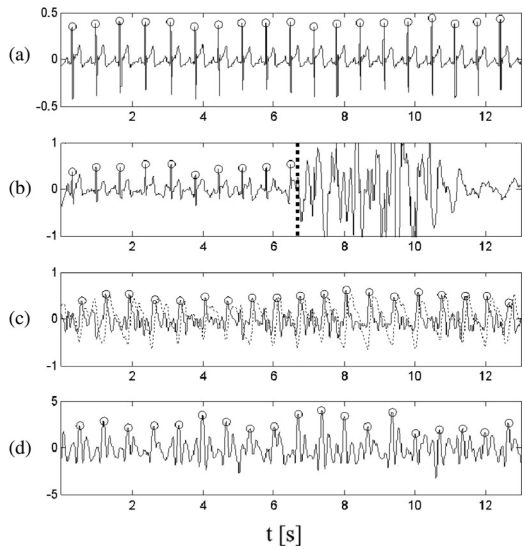

Fig. 8. Peak detection for HR monitoring: (a) Reference ECG. (b) Chair ECG. (c) Chair PPG. (d) Chair BCG. The dotted line in (b) indicates poor contact with the capacitive electrode due to motion. Note that HR can be monitored using only one of the successfully measured signals. In (c), the dotted line indicates the original PPG, and peaks were detected using its first derivative signal.

showed that the multiple regression method improves the BP estimation in both systolic and diastolic. When HR and TDB were included in the BP estimation, the correlation coefficients between the measured and estimated BP were improved.

In Fig. 9, the estimated BPs from all subjects were derived using different subject-specific regression equations but plotted together. The solid line indicates perfect estimation ($y = x$), while the dotted line indicates differences in the range of 10 mmHg. The total BP beat was 1147, and the number of estimation errors that exceeded 10 mmHg was reduced by employing a multiple regression approach, 207 to 171 for SBP and 90 to 71 for DBP, respectively. A Bland–Altman plot was constructed, and errors between measured and estimated BP were shown to be distributed within reasonable ranges (see Fig. 10).

E. Long-Term Monitoring of Blood Pressure

One of the subjects who participated in the above experiments agreed to carry out daily measurements during office hours. Daily BP monitoring experiments were performed for 2 months after the calibration experiments. The subject used smart healthcare chair as a regular chair in the office from 09:00 AM to 09:00 PM. In this experiment, we did not instruct experimental protocol such as Valsalva maneuver and let subject live as usual. During office hours, the subject experienced events that could have induced variations in BP, including eating, drinking coffee, and sleepiness [20]–[22]. The actual BP and the estimated BP that were calculated by multiple regression are described in Fig. 11. The actual BP was measured every hour on the hour for 5 min. Subject's BP was estimated using pulse arrival time, HR, and TDB parameters measured in present experiment and regression constants derived in previous calibration experiment. Then, both beat-to-beat reference BPs and estimated BPs during this 5 min were averaged. Remarkably, the estimated BP tended to conform to the actual measured BP.

IV. Discussion

In order to determine optimal specifications for our proposed healthcare chair system, several preliminary experiments were performed using our previous back and seat cushion prototypes before construction of the final version of the system. Since our goal was nonintrusive and unconstrained biological signal recording through clothing, the most important aspect of our system is consistency in performance regardless of measurement conditions.

Capacitive measurement of ECG was mainly affected by clothing thickness, gain of the driven circuit, and electrode size. Thicker clothes caused capacitive electrode gain as well as decreased signal amplitude. Signal components such as P, Q, S, and T waves were also significantly affected by clothing thickness. The ECG signal was noisy, but clear R peaks could be recorded even through thick clothing. The thickest clothing tested in our preliminary study were 2050 μm cotton T-shirts and business attire including suit jackets and cotton shirts. Electrode size showed opposite tendencies to clothing thickness; electrode gain and signal amplitude were correlated well with electrode size. However, we hoped to determine the optimal electrode size for use in the chair system given the curvature of the torso, including clothing. Because the surface of the human torso is curved, air gaps were created between the capacitive electrode face and the subject's back, resulting in poor contact and a low SNR signal, which made signal measurement impossible. Therefore, electrodes that were 3 cm $\times$ 4 cm in size were used in the chair system. In order to satisfy both large electrode size and good contact conditions, we will consider the future applications of flexible electrodes [23] or capacitive textile electrodes that use printed circuit on fabric technology [24]. The use of a driven circuit showed enhanced noise cancellation performance compared to conventional capacitive grounding configurations, and its performance was improved when the driven gain value was employed.

As mentioned earlier, heat generation by the LED unit was the main obstacle to recording PPG through clothing. Instead of the multiple LEDs with centered photo detector sensor configurations that were employed in this study, the configuration of multiple photo detectors with centered LED was tested in a previous study [25]. The experimental results showed that it was possible to measure PPG signals using multiple photo detectors with centered LED sensors with low heat generation and low power consumption, but the maximum clothing thickness that PPG could successfully be measured through was thinner than that of multiple LEDs with centered photo detector sensor. Therefore, if clothing thickness is not a crucial factor in PPG systems, such as during inpatient monitoring in hospitals (because patient gowns are thin), multiple photo-detector configurations are preferable since they offer reduced power consumption and LED heat generation. However, such systems offer limited performance for unconstrained daily monitoring because of their inability to measure PPG signals through thicker clothing. If sensor size is not a limiting factor in indirect-contact PPG systems, we expect that multiple light sources with multiple photodetector configurations may provide the best performance.

TABLE III
SINGLE- AND MULTIPLE-REGRESSION ANALYSIS OF PAT AND CONFOUNDING FACTORS FOR BP ESTIMATION USING DATA FROM OUR SMART HEALTHCARE CHAIR SYSTEM

Subject	Single regression: SBP			Multiple regression: SBP			Single regression: DBP			Multiple regression: DBP		
	R	R^2	*Adj.*R^2	*R*	R^2	*Adj.*R^2	*R*	R^2	*Adj.*R^2	*R*	R^2	*Adj.*R^2
A	0.927	0.859	0.858	0.928	0.861	0.859	0.852	0.725	0.724	0.873	0.762	0.758
B	0.699	0.448	0.446	0.707	0.449	0.494	0.437	0.191	0.188	0.630	0.397	0.390
C	0.716	0.513	0.510	0.716	0.513	0.506	0.520	0.270	0.267	0.607	0.369	0.360
D	0.724	0.524	0.522	0.873	0.763	0.760	0.518	0.268	0.265	0.528	0.279	0.269
E	0.763	0.582	0.581	0.800	0.641	0.636	0.398	0.158	0.155	0.527	0.277	0.268
Mean	0.766	0.585	0.583	0.805	0.645	0.651	0.545	0.322	0.320	0.633	0.417	0.410

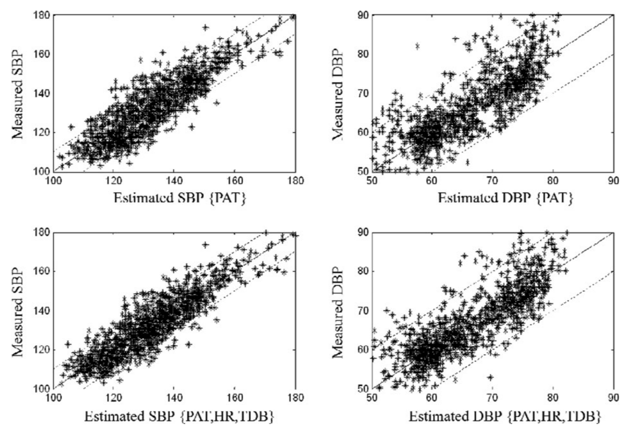

Fig. 9. Scatter plots of measured and estimated BP by single regression using PAT (top row) and multiple regression using PAT, HR, and TDB (bottom row).

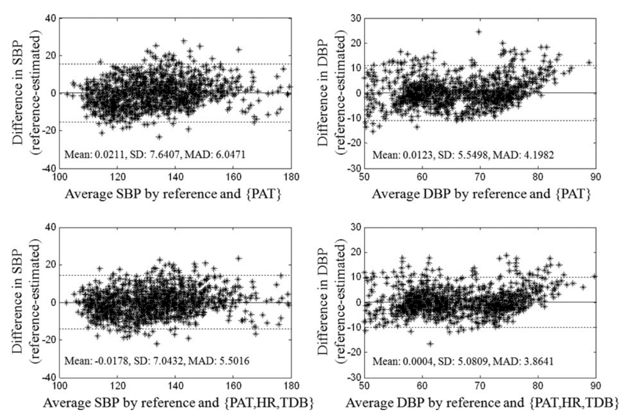

Fig. 10. Bland–Altman plot of reference and estimated BP. Estimation errors were reduced by the inclusion of additional parameters in regression analysis. The solid line indicates bias (mean difference) and the dotted line indicates 95% limits of agreement.

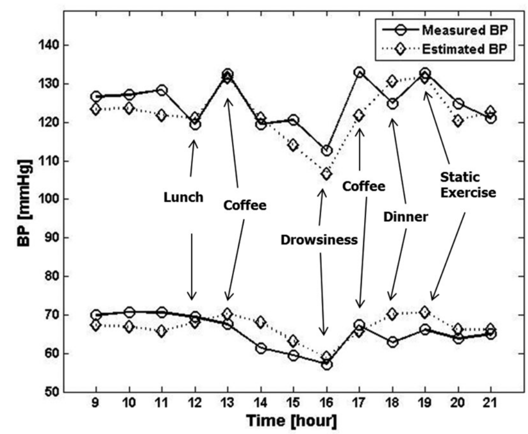

Fig. 11. Comparison of BP that was measured using our proposed chair system and a reference system during extended office hours, from 09:00 AM to 09:00 PM. The top row shows SBP and the bottom row shows SBP. The solid line indicates actual measured BP and the dashed line indicates estimated BP.

The size of PVDF film affected the BCG signal quality. PVDF film has strong piezoelectric properties with regard to force in length expansion, and the applied strain increases [26]. Therefore, PVDF film used for chair seat applications should be of a size that covers both thighs regardless of seat position. The size of the PVDF film employed in our system is to that of A4 paper and covers the whole area of the chair seat. Therefore, it satisfied the size requirements regardless of sitting position. The J peak of the BCG signal was not clearly detected when smaller PVDF film (9 cm × 5 cm) was used in the chair system. The effectiveness of the charge amplifier is similar to that reported by Shirinov *et al*. [27], who compared three kinds of analog amplifiers for signal amplification. The output voltage of the charge amplifier is calculated using the charge generated by the PVDF film, divided by capacitance in the corresponding electronic circuit. Therefore, the BCG signal could be effectively amplified without distortions such as resistance drop in the voltage divider configuration.

Using the proposed chair system, the ECG, PPG, and BCG were simultaneously measured without skin contact for subjects wearing casual clothes. The relationship between BP and PAT was examined for each subject under conditions of Valsalva-induced BP variation. Our results showed that PAT measurements obtained through clothing using the proposed system were correlated with BP in an established negative relationship. A multiple regression analysis of PAT, HR, and the arterial stiffness index for BP estimation resulted in improved estimation of both SBP and DBP through clothing measurement. The performance of the system in BP monitoring during normal business hours using a regression equation that was evaluated 2 months prior to the experiment demonstrated the reproducibility of the proposed BP estimation system. Recent studies have shown that BCG signals can be used instead of PPG signals for cuffless BP monitoring systems [28]. PAT was substituted by RJ interval (RJI), defined as the time interval from ECG R peak to BCG J peak. We expected that BP estimation performance would be better enhanced by employing additional parameters from the BCG signal to regression analysis, since our chair system could monitor three kinds of signals simultaneously. Table IV

TABLE IV
PERFORMANCE OF CUFFLESS BP ESTIMATION WITH REGARD TO COMBINATIONS OF PARAMETERS USED IN REGRESSION ANALYSIS

Variable	SBP			DBP		
	R	R^2	Adj.R^2	R	R^2	Adj.R^2
PAT	**0.803**	**0.644**	**0.640**	**0.747**	**0.558**	**0.554**
RJI	**0.581**	**0.337**	**0.330**	**0.540**	**0.292**	**0.284**
PAT+RJI	0.852	0.726	0.720	0.793	0.629	0.621
PAT+TDB	0.814	0.663	0.656	0.759	0.576	0.567
PAT+HR	0.804	0.646	0.638	0.749	0.561	0.552
RJI+TDB	0.590	0.348	0.334	0.548	0.300	0.285
RJI+HR	0.597	0.357	0.343	0.582	0.339	0.325
TDB+HR	0.212	0.045	0.024	0.244	0.059	0.039
PAT+RJI+TDB	0.863	0.745	0.736	0.804	0.646	0.635
PAT+RJI+HR	0.852	0.726	0.717	0.799	0.638	0.626
PAT+TDB+HR	**0.816**	**0.665**	**0.654**	**0.760**	**0.578**	**0.564**
RJI+TDB+HR	0.605	0.367	0.346	0.588	0.346	0.325
PAT+RJI+TDB+HR	**0.863**	**0.745**	**0.733**	**0.809**	**0.654**	**0.639**

shows the BP estimation results for a typical subject using several combinations of regression parameters, PAT, HR, TDB, and RJI. These results indicate that the estimation performance was improved when the parameter RJI was added to the regression analysis. A combination of all parameters resulted in the highest correlation, however, it is difficult to estimate BP for the full period of measurement since all of the signals should be recorded without distortion. Problems of missing data and compensation of motion artifacts or external electromagnetic noise must be considered for practical implementation of our healthcare chair system.

Unlike other similar biometric chair systems, proposed smart healthcare chair provides fully unconstrained multiple biological signal measurements and personalized access to monitor health information such as HR and blood pressure. Users do not need to place his hands or fingers on the sensors to acquire biosignals. The only thing that users do to measure biological signals is just sitting on a chair. A screw for subject-specific adjustment of ECG electrode height enhances contact between the electrode surface and subject's back, therefore, clearer ECG signal can be recorded regardless of different subject's different curvature of the torso. Also, using proposed subject-specific calibration with multiple regression method for BP estimation, more accurate BP can be estimated.

Current chair system also has limitations to overcome through future works. We attempt to reduce heat generation by LEDs using heat sink configurations installed beneath the PPG sensor. Although heat sink method decreased temperature of PPG sensor, it still needs to decrease it more. Current heat sinking status is probably not favored in the summer time and can potentially induce safety issue. The through clothing PPG system adapted in this study employed continuous wave method to measure attenuation changes in the blood vessels by recording changes in the output light intensity of continuous input LED light. Most of the LED electrical input power is converted into heat, therefore, continuous wave operation of LED results significant heat generation. We expect that time resolved method to measure the temporal distribution of output light resulting from an ultrafast pulse LED light may strongly reduce heat generation and currently, we are doing this research for efficient thermal management of through clothing PPG system. This pulse modulated operation also expected to reduce power consumption since LED consumes a large amount of power when emitting light continuously. Motion artifacts also need to be removed. Since people normally sit on a chair at resting state without bulk movements and detection of a motion-free period may be enough for the application of this method in healthcare, we did not apply any motion artifact removal methods in current chair system. The minimization of motion artifacts has been addressed through many studies [29], [30]. Consequently, biological signals during movement can be properly measured on a proposed biometric chair using various techniques and methods. Finally, it is necessary to conduct the method on a wider population including groups with different age, gender, and cardiovascular disease.

V. CONCLUSION

Recent improvements in biological signal recording through clothing enables many applications for unconstrained biological signal monitoring in healthcare. By integrating these technologies into a chair system, we successfully and simultaneously measured ECG, PPG, and BCG through clothing in a nonintrusive fashion. Continuous beat-to-beat HR and BP were also successfully monitored using the obtained signals. The proposed healthcare chair system may be used to reliably monitor users during daily activities. Unlike conventional medical devices, this system does not require active user input and is therefore suitable for long-term daily health monitoring. Our results demonstrate the validity of proposed system for nonintrusive monitoring of health information during daily activities.

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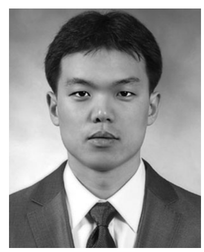

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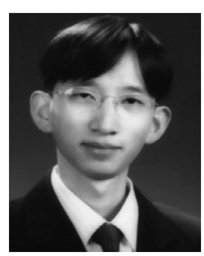

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