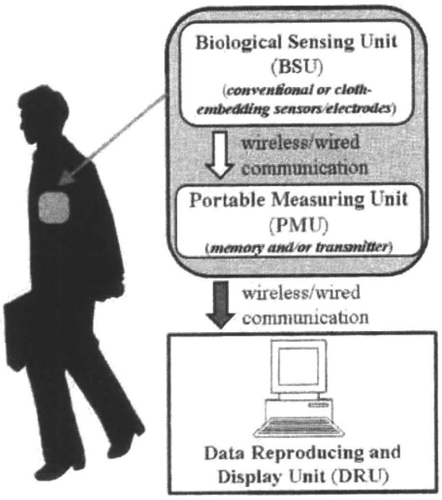

Fig. 1. Outline of basic construction of ambulatory/wearable monitoring system. The system mainly consists of a biological sensing unit (BSU), a portable measuring unit (PMU) and a data reproducing and display unit (DRU). See text for further explanation.

electrodes remain the most common approach, but efforts continue to be made to improve dry electrode designs as such an electrode is thought by some workers to offer good prospects of achieving long-term electrical stability for ambulatory use. As previously reviewed in this Spotlight column [7], [8], several approaches to measure ECG using dry electrodes have been introduced, although further improvements of the electrical characteristics were still required. Recently Gargiulo *et al.* [9] have reported an approach based on the use of conductive rubber electrodes together with an ultra-high input impedance ECG amplifier and, with Bluetooth wireless communication, have demonstrated 24 hours successful ECG monitoring. It is interesting to note that their system was actually applied to the measurement of the ECG during body-building and swimming exercises and they also claimed its usefulness to prevent an athlete's sudden death due to a syndrome called "athlete's heart" [10], [11].

An interesting approach to monitoring such vital signs as ECG and respiration was implemented within the WEALTHY project [12], [13], supported by the 5th Framework IST (Information Science and Technology) Programme of the European Union. In this research woven sensors that could be worn without any discomfort for the user were developed. The fabric sensors were woven from smart fibres and yarn having conducting and piezoresistive properties. These were formed and integrated into well-fitting garments and then used to obtain recordings of vital signs. It is reported that the system can provide reliable and satisfactory data as compared with conventional standard methods. It was also reported that the proposed system could assist patients during rehabilitation training or subjects working in extremely stressful environmental conditions, ensuring continuous surveillance.

There have been several recent attempts to use textile electrodes as wearable sensors. Mitchell *et al.* [14] devised a t-shirt embedding a textile-based piezoresisistive sensor together with a Zigbee wireless transmitter for the monitoring of breathing. Wireless communication was made between the sensor and a PC installed in a Zigbee receiver, where the respiration signal was displayed in real-time to present to a subject for breathing exercises. It is stated that this wireless biofeedback system could be useful for breathing training that is a part of the treatment for respiratory illnesses such as cystic fibrosis.

Just recently, Rantala *et al.* [15] designed an interesting wearable optical sensor sewn into clothing for the ambulatory monitoring of respiration and tidal volume. The sensor has 16 specially aligned optical fibres. The intensity of light passing through the fibres changes in response to fibre bending due to respiration and a signal representing changes in tidal volume is thereby obtained.

Photoelectric plethysmography is also promising as a convenient means for ambulatory use. As an interesting healthcare application, Fletcher *et al.* [16] developed a wearable photoplethysmographic sensor with wireless networking to monitor photo-pulsations. This is combined with a sensor for measuring electrodermal activity (EDA) from the wrist designed by Poh *et al.* [17], to evaluate autonomic nervous activity. They proposed two types of network systems; one was with IEEE 802.15.4 so as to apply multiple sensors and the other with Bluetooth to communicate directly with a mobile phone.

In contrast to these vital signs that can be monitored with relative ease, arterial blood pressure (BP) and cardiac output (CO) are the essential parameters for the detailed evaluation of cardiovascular haemodynamic functions. Through a considerable amount of research and development activity and effort, the ABPM has become one of the most successful examples of the commercialization of research outcome. This device is quite convenient for practical use, measuring BP at a set interval of 30 min or more. However, this means that it can acquire less than 48 data points per day [18], [19]. Because there are approximately 80,000–100,000 BP data points per day produced by individual cardiac beats, only about 0.05% of the complete BP data set can be obtained by ABPM. It is therefore desirable to acquire BP on a beat-by-beat basis. It is furthermore apparent that the acquisition of BP and CO data together on a beat-by-beat basis combined with other cardiovascular data would be much more powerful. For example, this could enable the detailed analysis of haemodynamic responses and autonomic regulation of the cardiovascular system to be carried out in response to various stressful daily activities.

With this as a background, the author's group has recently developed a new beat-by-beat cardiovascular haemodynamic monitoring system both for ambulatory and/or stationary use [20] on the basis of a technological combination of the volume-compensation [18], [19], [21] and transthoracic electrical admittance methods [18], [19], [22]–[24]. Recently, Ogawa *et al.* [25] have applied this system to the assessment of cardiovascular stress reaction on a beat-by-beat basis in response to daily activities using the recently proposed Gregg's method [26]. They clearly demonstrated the separation of active, passive and mixed stress coping during daily living.

B. Activity Monitoring

The importance of ambulatory activity monitoring is well recognized in the fields of gerontology, rehabilitation, exercise training and general healthcare. In the field of rehabilitation, for example, a therapist must evaluate motion characteristics, for example during standing up, walking, and other activities. However, it is very much a situation in which the therapist must usually make assessments subjectively by direct observation and quantitative assessment of activities is highly desirable. One method employed is to make recordings using a three-dimensional motion capture system, but the range over which such recording is possible is usually limited and data analysis is complicated, rendering this system unsuitable for use in practical rehabilitation.

Some wearable instruments capable of monitoring activity [27]–[32] and gait and posture [33], [34] using sensors such as an accelerometers, a gyro-sensors and so on, have been developed. One such development has been reported by Motoi *et al.* [35], and this enables the monitoring of static and dynamic posture changes in the sagittal plane together with gait and walking speed. The system uses three miniaturized units fixed to the trunk, thigh and calf and it measures their angles with respect to the gravitational direction using accelerometers and gyro-sensors. Each unit has these sensors as well as a Zigbee transmitter for wireless communication for real-time observation and a micro-SD card for long-term recording. The authors successfully demonstrated the viability of this system for the quantitative evaluation of the efficacy of rehabilitation programs as well as normal daily activities.

Another noteworthy attempt aimed at exercise training is reported by Lee *et al.* [36]. This system is capable of monitoring activity along with the ECG using a tri-axial accelerometer and conductive fabric electrodes embedded in a shirt. This sensing unit is networked with IEEE 802.15.4 Zigbee W-PAN (wireless personal area network). It is noted that this type of sensing network could be promising for many kinds of data acquisition by retrofitting a large number of miniaturized sensors.

C. Biochemical Monitoring

To date, numerous developments have been focused on physiological monitoring relating to cardio-pulmonary and activity information as mentioned above. However, there have been few attempts to monitor biochemical quantities for ambulatory use, despite its usefulness and importance to evaluate biochemical status for healthcare management. In this context, Yang *et al.* [37] recently attempted to fabricate a biosensor directly printed on underwear, similar to a screen-printing process onto the textile substrate. The authors described the detection of 0–3 mM ferrocyanide, 0–25 mM hydrogen peroxide and 0–100 M NADH. It is also noteworthy that the European Union project called "BIOTEX" developed biochemical-sensing techniques using a textile-based wearable biosensor to monitor pH and sodium (Na^+) in sweat [38]–[40]. Here, the sensing part consists of (1) a passive fabric pump made of a super absorbent material for the continuous suction of sweat from the skin, (2) a pH sensitive dye, and (3) an LED/photodetector pair to measure color changes of the dye due to the changes of the solute concentration in sweat. They also used a pair of gold electrodes and ion-sensitive membrane as the wearable sodium sensor.

III. Future Aspects

Recent developments and the present status of non-invasive and ambulatory/wearable monitoring were briefly introduced in this review. In the light of the growth of the aging society worldwide, such monitoring techniques will be increasingly required as a possible scheme for preventive medicine, early diagnosis, rehabilitation and sports medicine, as well as timely treatment of lifestyle-related diseases.

Several research approaches described herein appear innovative and groundbreaking, particularly in the developments of instrumented garment systems and wireless communication techniques with miniaturized sensors. Optimistically it might be anticipated that such convenient instruments could be made available at reasonable costs in the future, although there are still numerous challenging obstacles to be addressed, such as the rather conflicting needs for small size, wear comfort, simplicity of operating procedures, accuracy, power management, stability and so on for truly practical use.

Taking the availability and potential of these techniques to contribute in many biomedical fields into consideration, further comprehensive studies will still be required to realize this potential and thereby achieve an advanced and truly practical approach. Nevertheless, the considerable recent dramatic advances in microelectronic, micromechanical, information and communication technologies will doubtless resolve the problematic issues that still remain.

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Evaluation of Cardiovascular Stress Reaction Using HPCD Method on a Beat-by-beat Basis[1]

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Ken-Ichi Yamakoshi[6]

Abstract: In order to establish a bionic model/system in cardiovascular fields, comprehension of hemodynamics is important. In this study, a novel beat-by-beat hemodynamic system evaluation method named "beat-by-beat HPCD method" is proposed and evaluated. Gregg's theoretically driven model of hemodynamics which was called "HPCD method" is improved by using non-invasive and beat-by-beat cardiovascular measurement of mean blood pressure and cardiac output.

Continuous beat-by-beat measurements of MBP and CO were done on three healthy male subjects during three hours. In the measurement, a five minutes cold pressor test was executed in each subject and also each subject did exercise using a bicycle ergometer in five minutes and walked during 15 minutes. Measured beat-by-beat MBP and CO can derive beat-by-beat HP (hemodynamic profile) and CD (compensation deficit). Then, beat-by-beat changes clearly observed from plots on HP axis and CD axis plane. More vascular response can be observed on cold pressor and more myocardial response can be observed on ergometer exercise. During walking period, the response is intermediate between cold pressor and ergometer exercise. Finally, the proposed method can be considered as applicable to evaluate cardiovascular bionic system especially on evaluation of a person being subjected to stress.

Keywords: hemodynamics; stress; cardiovascular system; hemodynamic profile and compensation deficit model

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INTRODUCTION

In order to establish a bionic model/system in cardiovascular fields, comprehension of hemodynamics should be considered as important. In this study, a novel beat-by-beat hemodynamic system evaluation method named "beat-by-beat HPCD method" is proposed and evaluations of human hemodynamic status in three different stress loading status were attempted using the method.

MATERIALS AND METHODS

As known, there have been many attempts of measurement and/or estimating for hemodynamic parameters. Among them, Gregg et al. recently proposed a new theoretically driven model of hemodynamics and demonstrated its application for hemodynamic parameters (Gregg et al., 2002) which were called "HPCD method." The "HPCD method" is based on cardiac output (CO) and total peripheral resistance (TPR). Though it is not possible to measure TPR directly, TPR can be estimated from CO and mean blood pressure (MBP) as Eq. (1), as shown in Fig. 1.

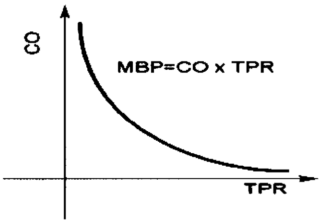

Figure 1: Three hemodymanic parameters; mean blood pressure (MBP), cardiac output (CO) and total peripheral resistance (TPR)

$$MBP = TPR * CO \qquad (1)$$

The baseline measurement gives MBP and CO on baseline MBPb and COb, giving TPR on baseline TPRb as Eq. (2).

$$MBPb = TPRb * COb \qquad (2)$$

Dividing Eq. (1) by Eq. (2) gives Eq. (3a) as below.

$$MBP/MBPb = TPR/TPRb * CO/COb \qquad (3a)$$

Eq. (3a) means relative reactivity of three homodynamic parameters, then the three terms of Eq. (3a) are expressed as MBPr, TPRr and COr (shown as Eq.(3b)).

$$MBPr = TPRr * COr \qquad (3b)$$

Then, logarithm of Eq. (3a) gives Eq. (4) of additive synthesis.

$$\log(MBPr) = \log(TPRr) + \log(Cor) \qquad (4)$$

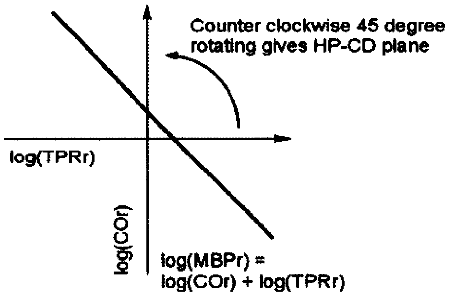

Figure 2: Hemodinamic parameters on orthogonal dimension consisted of logarithm of TPR and CO

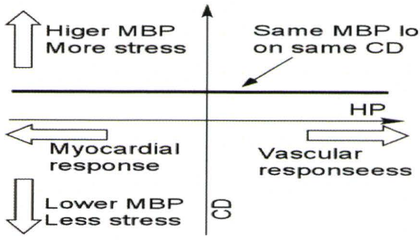

Figure 3: HP-CD plane: HP means "hemodynamic profile" and CD means "compensation deficit"

Now, Eq. (4) means orthogonal dimensions consisted of logarithm of TPR and CO as shown in Fig. 2. Finally, counter clockwise 45 degree rotating of this log-TPR axis and log-CO axis plane gives a new orthogonal dimensions consisted of logarithm of TPR and CO "hemodynamic profile (HP)" axis and "compensation deficit (CD)" axis, and the HP-CD plane can have information relating reactivity of hemodynamic parameters. In the HP-CD plane, CD axis gives relative stress reaction information and HP axis gives information of relative myocardial-and-vascular balance, as shown in Fig. 3.

Gregg et al. applied their method to evaluate hemodynamic status of human only intermittently. Consequently, their method remained one-shot evaluation and comparison of different hemodynamic statuses; i.e. comparison of before and after a stress loading. Meanwhile, we have been developed beat-by-beat continuous and non-invasive measurement methods and systems of cardiovascular/hemodynamic parameters that can measure blood pressure and cardiac output continuously (Nakagawara & Yamakoshi, 2000) whose measurement methodologies are based on volume-compensation method (Yamakoshi et al., 1979 & 1980) and transthoracic admittance plethysmograph method (Ito et al., 1976). Here, we thought inevitably that Gregg's HPCD method can be enhanced to beat-by-beat evaluation of hemodynamic by combining with our beat-by-beat measurement system.

Continuous beat-by-beat measurements of MBP and CO were done on three healthy male subjects (yrs. 21-23) during three hours. In the measurement, a five minutes cold pressor test was executed in each subject and also each subject done exercise using a bicycle ergometer in five minutes and walked during 15 minutes. For obtaining a baseline of the physilogogcal measurement, each subject was placed supine position in the first 5 minutes of the measurement. The cold pressor test is considered inducing mainly myocardial response and exercise using an ergometer is considered inducing mainly vascular response.

Continuous beat-by-beat hemodynamic measurement provides continuous plots on HP-CD plane. For evaluate distribution of those plots, principal component analysis (PCA) based evaluation is applied. In this paper, representative parameter of distributed plots is defined as an ellipse that drawn with PCA: That representative ellipse is drawn as follows (illustrated as Fig. 4):

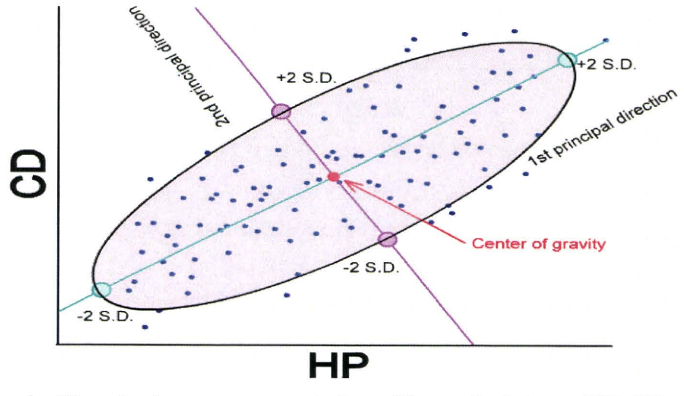

Figure 4: How to draw representative ellipse of plots on HP-CD plane

1. PCA is applied the plots then obtaining the 1st and 2nd principal direction.
2. The center of the ellipse is defined as the center of gravity the plot.
3. The long axis of the ellipse is defined as ±2 S.D. of the 1st principal component score.
4. The short axis of the ellipse is defined as ±2 S.D. of the 2nd principal component score.

RESULTS AND DISCUSSION

Measured beat-by-beat MBP and CO can derive beat-by-beat HP (hemodynamic profile) and CO (compensation deficit). Then, beat-by-beat changes clearly observed from plots on HP axis and CD axis plane. In cold pressor phase, the plots on HP-CD plane move to more vascular direction. In contrast, the plots move to more myocardial direction in ergometer exercise. In waking period, the plots distributed on the area between cold pressor phase and ergometer exercise phase. An example of the plots and representative ellipses of each status are shown in Fig. 5. This suggests that cardiovascular reactions of stress on daily living as walking should be considered as mixed myocardial and vascular response. This must mean that same blood pressure response can be originated from different hemodynamic status. Then, the proposed method can be considered as applicable to evaluate cardiovascular bionic system in a dynamic sense, on a beat-by-beat base. For a future cardiovascular bionic system analysis/synthesis, the view of myocardial-and-vascular balance should be important.

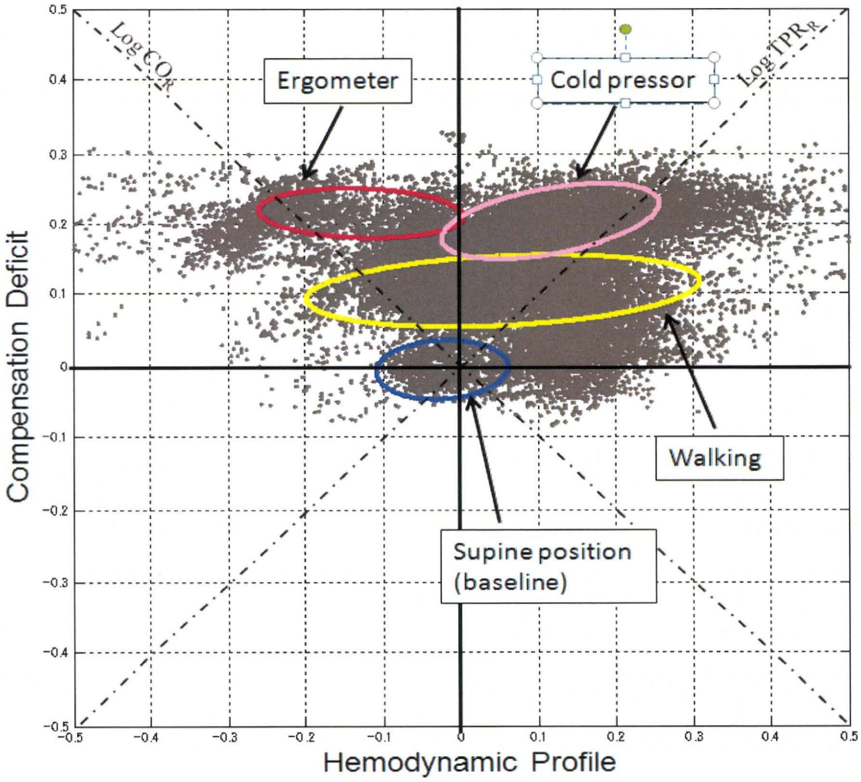

Figure 5: An example of beat-by-beat measurement based HP-CD plot and its evaluation. Gray dots are beat-by-beat plot of hemodynamic parameter, HP and CD. The blue ellipse shows distribution on supine position. The red, pink and yellow ellipses show cold pressor, ergometer exercise and walking respectively

CONCLUSION

Beat-by-beat HPCD hemodynamic evaluation method that was combination of Gregg's HPCD method and our beat-by-beat cardiovascular measurement was proposed and attempted. By the method, stress reactions can be observed clearly.

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Current Status of Noninvasive Bioinstrumentation for Healthcare

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Key words: noninvasive ubiquitous healthcare monitoring, ambulatory/wearable physiological monitoring, nonconscious physiological monitoring, medical crisis, preventive medicine, early diagnosis and treatment

In the so-called "super-aging society," noninvasive healthcare monitoring has been increasingly required as a possible scheme for preventive medicine, early diagnosis, and timely treatment of lifestyle-related diseases. As contributions towards the development of the most desirable aim of achieving ubiquitous healthcare monitoring, two promising systems, "ambulatory or wearable physiological monitoring" and "nonconscious physiological monitoring," which have recently been developed through modern technological advances, are introduced in this paper. Each of these two monitoring techniques appears to have the potential to contribute to the fields of personal healthcare, medical care, and rehabilitation among others. Nevertheless, further comprehensive studies will still be required to realize this potential and thereby achieve an advanced and truly practical approach. This is also discussed in this paper.

1. Introduction

In modern society, humankind has been confronted with a variety of serious issues needing to be addressed urgently, such as increasing energy demands, environmental deterioration including global warming, and healthcare provision. Among these, the ever expanding healthcare needs are challenging and of particular importance, because maintaining good health conditions throughout the natural human life span is a fundamental requirement in most societies. It is inevitable, however, that with the passage of time, health status gradually deteriorates owing to aging. There has therefore been an increasing need to provide effective, convenient, and, in particular, noninvasive means to self-check major health conditions over a long period of time during normal daily life.

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The use of technologies with which to carry out long-term, regular, noninvasive monitoring of health conditions during normal daily life has been increasingly raised as a possible scheme for the early diagnosis and timely treatment of lifestyle-related diseases. In addition, it has been conjectured that this could help prevent, or at least control, such diseases and reduce healthcare costs. Furthermore, there are also needs to perform such health status monitoring of in- and outpatients having disorders requiring either acute life support or chronic therapies. Within this context, ubiquitous healthcare monitoring by noninvasive methods would be the most desirable.

The concept of this ubiquitous healthcare monitoring is basically to check health conditions anytime and anywhere and to manage individual physiological data obtained using, for example, a network system in a fully automated manner. In this sense, one of the most feasible methodologies would be ambulatory or wearable physiological monitoring, which means that biological sensors and/or miniaturized measuring units are to be carried by a subject or embedded into the user's clothes. Regarding this subject, brief descriptions of several recent developments by many investigators(1–6) and our group(7,8) are firstly presented in this paper.

Although such ambulatory monitoring would be relatively straightforward to implement in subjects while outside their dwelling or workplace, it is not always easy to achieve continuous monitoring smoothly after returning home. As the home is a place to relax and the time spent at home is relatively long each day, another possible methodology is required. In fact, health monitoring at home is one of the hot topics in the field of biomedical engineering, a major goal of which is to enable such monitoring everyday over a long period to evaluate health conditions, as mentioned above. One widely used approach is simply to have basic healthcare devices for home use, such as a thermometer, a sphygmomanometer, and a weighing scale, to be operated by individuals themselves. This approach is, however, difficult and bothersome for individuals to continue over long periods.

A new concept has recently been proposed for monitoring physiological variables in a fully automated manner without the need either to attach any sensors to the body or for individuals to carry out any operations, simply using home facilities such as a bed, a bathtub, and a rest room.(7,9–17) The techniques used in this approach do not disturb normal daily activities; thus, the monitoring is carried out in an unconstrained manner. Therefore, this concept would also be applicable and useful for patient monitoring in a hospital room. In this paper, outlines of such a monitoring system named "nonconscious physiological monitoring," which was developed by our group,(7,14–17) are also briefly introduced.

2. Ambulatory/Wearable Physiological Monitoring

Within the sphere of ambulatory monitoring, the Holter-type electrocardiogram (ECG) recorder, originally proposed by Holter,(18) and the portable sphygmomanometer called "ambulatory blood pressure monitor (ABPM)," which is based on the auscultation and/or cuff-oscillometric method,(19,20) are widely used in clinical medicine as key devices. Modern microelectronics and mechanical technologies have enabled us to produce more compact and convenient devices for home use. Firstly, a few attempts at monitoring vital signs including ECG are briefly described.

2.1 *Recent attempts to monitor vital signs*

An interesting approach to monitoring ECG using textile electrodes has been reported by Rantanen *et al.*(1) Just recently, Biodevices S. A. in Portugal has commercialized a wearable ECG monitor based on this concept, as shown in Fig. 1. Developing both textiles and electronic miniaturization techniques has made it possible to incorporate electrodes into a T-shirt and much smaller electronic devices that can be worn and carried for long periods of time. As an application, the authors described the design of a survival clothing prototype for arctic environments, which could achieve ECG monitoring together with communication, including an emergency message, positioning, and navigation aids for the user.

The WEALTHY project, supported by the 5th Framework Information Science and Technology (IST) Programme of the European Union, is also noteworthy. Within this project, a new concept in healthcare was proposed, whereby the subject's vital signs were monitored through a groundbreaking woven sensor that could be worn without any discomfort for the user. This fabric sensor made of smart material in fiber and yarn form and integrated into a well-fitting cloth could be endowed with a wide range of electrophysical (such as conducting and piezoresistive) properties to obtain the simultaneous recording of vital signs. Figure 2 shows a prototype of the garment monitoring system,(2,3) which allows ECG and respiratory measurements. It is reported that such measurements provide reliable and satisfactory data as compared

Fig. 1. Wearable ECG monitoring system with textile electrodes incorporated into a T-shirt,(1) recently commercialized by Biodevices S. A., in Portugal [http://inventorspot.com /articles /wearable_heart_monitor_vital_jackets_fashionable_vital_monitorin_24622].

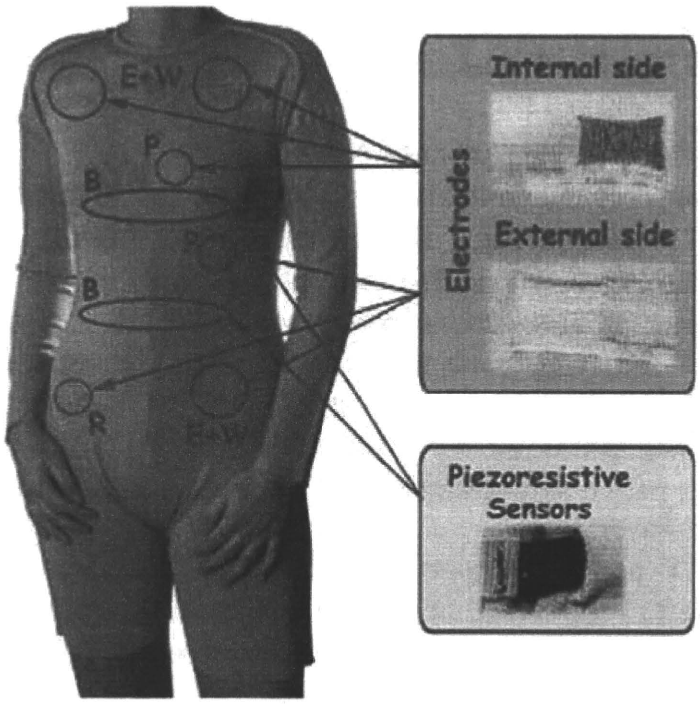

Fig. 2. Garment ECG and respiratory monitoring system with a woven sensor made of smart material in fiber and yarn form with conducting and piezoresistive properties (http://www.wealthy-ist.com/index.php?action=show_bversion). E+W, Einthoven-Wilson electrodes configuration; R, reference electrode; P, precordial leads; B, piezoresistive sensors for detecting breathing.

with a conventional standard method. The researchers of this project also state that the proposed system could assist patients during rehabilitation training or subjects working in extreme stressful environmental conditions, ensuring continuous surveillance.

In contrast to these monitoring concepts, miniaturized wireless sensor networks capable of autonomously controlled monitoring of vital signs and telecommunications for healthcare have recently been proposed.(4–6) A number of miniature wireless sensors placed on the body form a wireless body area network (W-BAN) that can monitor various vital signs, providing real-time feedback to the user and medical personnel. A conceptual diagram is shown in Fig. 3,(5) in which a subject carries an ECG measuring unit, a pulse oximeter (providing SpO_2), and trunk-angle and motion sensors along with a personal server to compose W-BAN using the ZigBee protocol.

2.2 *Ambulatory cardiovascular hemodynamic and activity monitoring*

Besides these innovative approaches described here, we have also continued developing ambulatory monitoring systems suitable for both clinical and home use, focusing particularly on the acquisition of data for the evaluation of cardiovascular hemodynamics and human activity. Following our earlier developments of ambulatory cardiovascular hemodynamic(20–24) and activity monitoring systems,(25–28) we have recently improved these two systems for more practical use.(7,8) Detailed operational performance, accuracy, and reliability of the two have already been successfully demonstrated and reported in the literature.(7,8,20–28) Brief descriptions of each system are therefore given below.

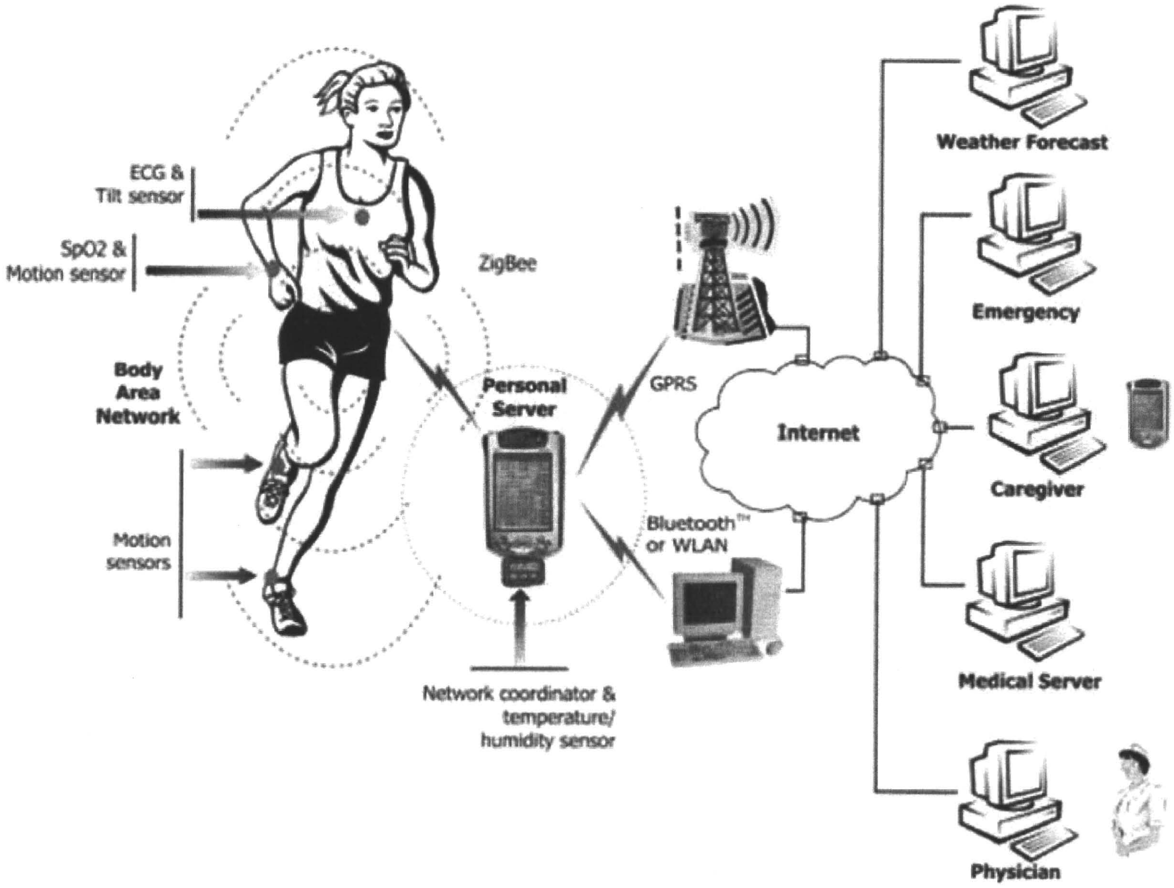

Fig. 3. Conceptual diagram showing wireless sensor network system. A user carries a number of tiny wireless vital sign sensors together with a personal server to create a wireless body area network (W-BAN) using the ZigBee protocol (from Fig. 1 in ref. 5).

2.2.1 *Beat-by-beat cardiovascular hemodynamic monitoring*

A conventional ABPM can measure blood pressure (BP) at a set interval of 30 min or more for convenient practical use and can thus acquire less than 48 data points per day owing to the limitations imposed by the measurement principle.(7,20) Because there are approximately 80,000–100,000 BP data per day produced by individual cardiac beats, only about 0.05% of the complete BP data set can be obtained by ABPM. It is logically desirable to acquire BP on a beat-by-beat basis. It is furthermore apparent that the acquisition of BP and cardiac output (CO) data together on a beat-by-beat basis combined with other cardiovascular data would be much more powerful in the detailed analysis of hemodynamic responses and autonomic regulation of the cardiovascular system in response to various daily activities.

With these as a background, we have recently developed a new beat-by-beat cardiovascular hemodynamic monitoring system both for ambulatory and stationary or medical use on the basis of a technological combination of the volume compensation(7,29) and transthoracic electrical admittance methods.(7,20,21,23,24,30,31) Figure 4 shows an overview of the monitoring situations for the system.

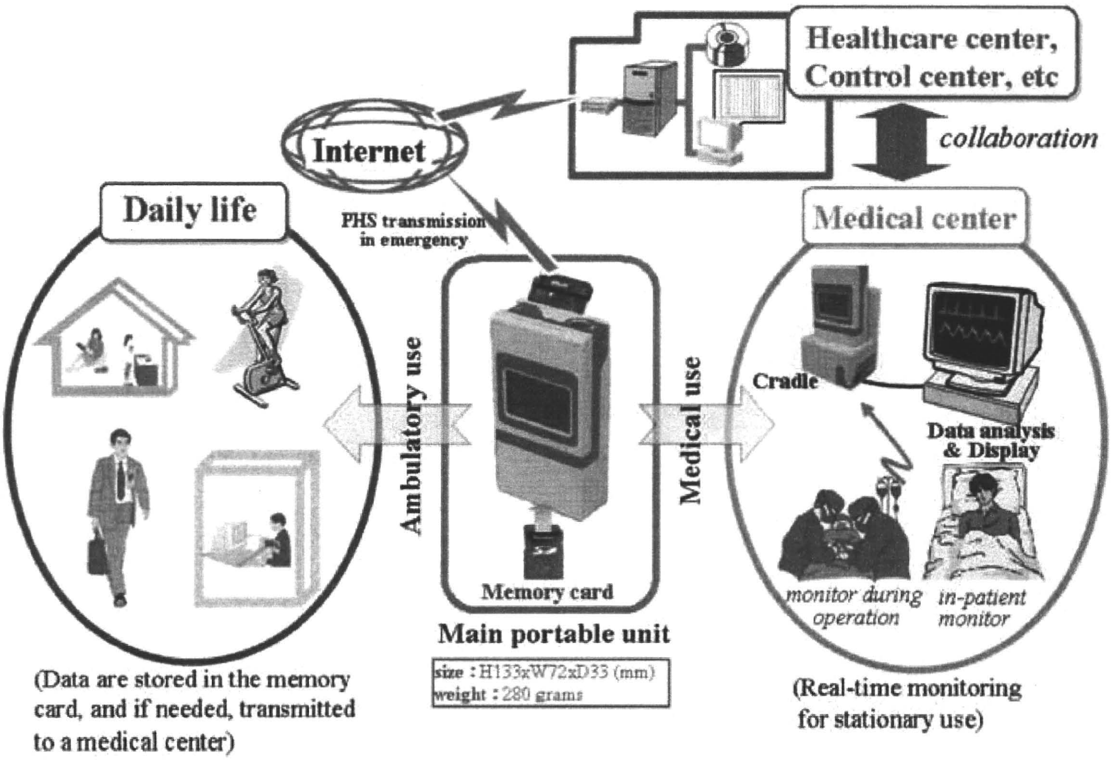

Fig. 4. Overview of beat-by-beat cardiovascular hemodynamic monitoring system both for ambulatory and stationary use. For further explanation, see text.

The essential parts of this system are (i) tetrapolar spot electrodes for CO measurement, (ii) a finger cuff unit with a photoplethysmographic sensor and a local pressurization cuff for the BP measurement, (iii) a cuff pressure controller, (iv) a main portable unit, (v) a cradle, and (vi) a conventional personal computer for data analysis and display. For ambulatory use, the subject carries the portable unit (133×72×33 mm^3; 280 grams including the battery) in a breast pocket together with the necessary sensors for the CO and BP measurements and the collected data are stored in a memory card. During operation, BP is compensated for the individual's heart level by measuring the hydrostatic pressure difference between the measuring site and the heart. For stationary or medical use, the portable unit housed in its cradle is connected to the computer for real-time monitoring of data as a time series during situations such as surgical operation and cases in intensive care unit (ICU) and coronary care unit (CCU) in a medical center.

The portable unit has eight functions: (1) BP measurement, (2) CO measurement, (3) signal processing and control of each measurement using a microprocessor unit, (4) data storage using a memory device, (5) data display using an LCD, (6) interactive communication between the unit and the cradle using a serial interface, (7) data transmission using a mobile phone system (PHS) for emergency situations, and (8) power supply using a lithium-ion rechargeable battery that is capable of continuous use for more than 6 h at present.

In the case of ambulatory use, the data stored in the portable unit are retrieved by the personal computer and an appropriate analysis is carried out to display the resultant cardiovascular variables. The following 13 variables are processed on a beat-by-beat basis: systolic (SBP), mean (MBP) and diastolic BP (DBP), ECG R-R interval (RR), instantaneous heart rate (HR), stroke volume (SV), cardiac output (CO), pre-ejection period (PEP) as an index of sympathetic activity, ventricular ejection time (Ts), pulse transit time (PTT), peripheral vascular resistance (TPR), rate pressure product (RPP) as an index of cardiac oxygen consumption, and respiration rate (Resp). Using the derived data, the computer can then show the 13 processed variables on the display.

Figure 5 is an example of a 6-hour trend chart, showing 7 of 13 hemodynamic parameters, RR, BP (SBP/MBP/DBP), SV, CO and TPR, obtained in a healthy male subject (22 yrs) during a part of his normal daily activities (from 10:00 to 16:00 h). He was instructed to move freely and perform various normal activities, such as walking, desk work, exercise, and postural changes from sitting to standing for example, as indicated in the uppermost part of this figure. It is clearly observed that the increases in BP and CO during bicycle riding, as well as the fluctuations in each of the parameters produced by postural changes such as sit-to-stand motion, sit-to-lie motion, and so on, demonstrate the dynamic changes in chosen parameters in response to various activities.

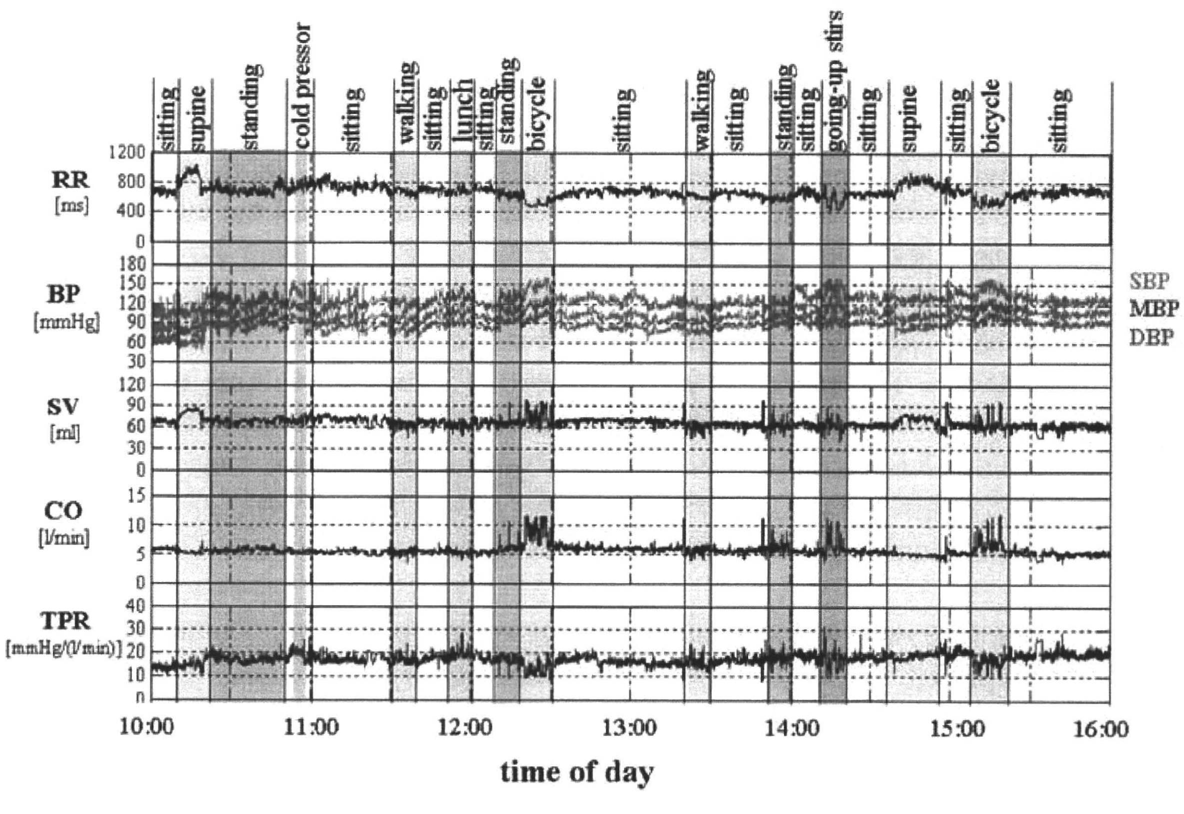

Fig. 5. Example of 6-hour trend chart, showing hemodynamic parameters ECG R-R interval (RR), blood pressure (BP; systolic (SBP), mean (MBP) and diastolic BP (DBP)), stroke volume (SV), cardiac output (CO) and total peripheral resistance (TPR) obtained in a healthy male subject (22 yrs) during a certain time of the day (from 10:00 to 16:00). Various activities are indicated in the uppermost part of this figure.

2.2.2 *Human posture and activity monitoring*

The importance of ambulatory activity monitoring is well recognized in the fields of gerontology, rehabilitation, and general healthcare. In the field of gerontology, for example, one of the key aims in the care of the elderly is to maintain their daily activities at an appropriately high level and to particularly prevent their becoming bedridden.(32) In the rehabilitation field, a therapist must evaluate motion characteristics during standing up and walking among others; however, it is very much a situation in which he/she must usually make assessments subjectively by direct observation. Therefore, the quantitative assessment of activities is highly desirable. One method employed is to record using a three-dimensional motion capture system, but the range over which such recording is possible is usually limited and data analysis is complicated, rendering this system unsuitable for use in practical rehabilitation.

Some wearable instruments capable of monitoring activities using an accelerometer, a gyrosensor and so on have been developed.(33–38) Such wearable systems have not yet become practical in the rehabilitation field owing mainly to awkward and unsuitable means for the physically challenged or the elderly. With the aim of improving the quality of life for these persons, we have developed a portable and handy device for monitoring postural changes and activities by measuring the trunk, thigh, and calf angles with respect to the gravitational direction.(25–28) This device has recently been improved to make it more convenient for rehabilitation training as well as for collecting a daily record of activity scenarios.(8)

The principle of the measurement of posture together with walking speed is quite simple, as shown respectively in the left and the right panels of Fig. 6. If we can measure the angles of three anatomical parts, such as the trunk, thigh, and calf, with respect to the gravitational direction, we can discriminate almost all the human postures in the sagittal plane, which are possible under normal daily life. Using the thigh (θ_{21} and θ_{22}) and calf angles (θ_{31} and θ_{32}) at 'heel contact' and 'off' together with the subject's thigh (L_1) and calf length (L_2), the length of one stride (D_e) can be calculated using the two-link gait model. Therefore, the walking speed (V_e) for one walking cycle can also be calculated from D_e divided by the time of one step (T_e). The accuracy of the walking speed thus obtained has been shown to be highly precise over a wide range from 0.5 m/s or less (relatively slow pace of physically challenged or elderly people) to 2.0 m/s or more (considerably quick pace of healthy subjects) as compared with a video camera system.(27,28)

In Fig. 7, an overview of the wearable sensor system is shown. The accelerometer, gyrosensor, amplifier, micro-SD card, transmitter, battery, CPU, and other parts are installed in each of the sensor units, and the units are attached onto the subject's trunk, thigh, and calf. The subject's motion when in the medical center is monitored in real time using a telemetering system such as a W-BAN, and the activity data collected during normal daily living is saved on the micro-SD card.

The system can discriminate among postures, from walking, sitting, lying down, standing up, sitting down, and standing on the basis of the angle changes in the sagittal plane calculated from the low-frequency signals (DC, 0.5 Hz) of the accelerometers attached to each part. In the static postures of standing, sitting, and lying down, the angle

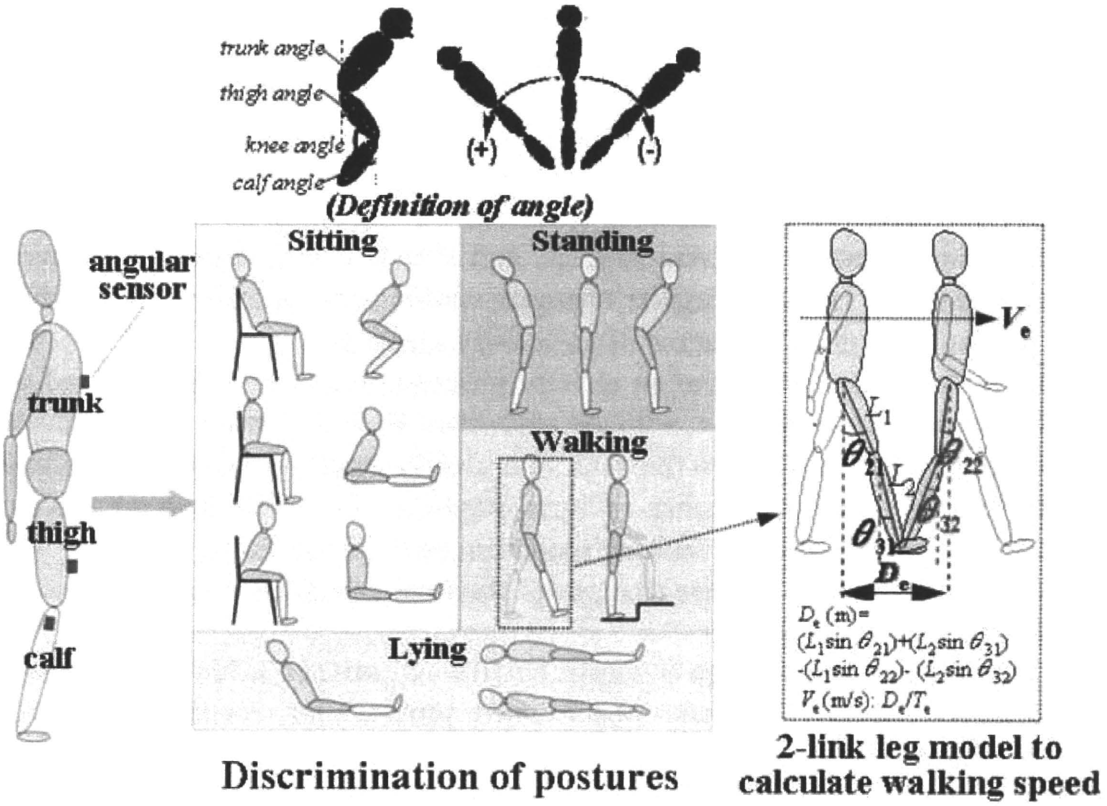

Fig. 6. Principles of determination of posture in sagittal plane by measuring trunk, thigh and calf angles with respect to gravitational direction (left panel), and walking speed for two-link leg model (right panel). The uppermost part shows the definition of angle for each anatomical segment. See text for explanation.

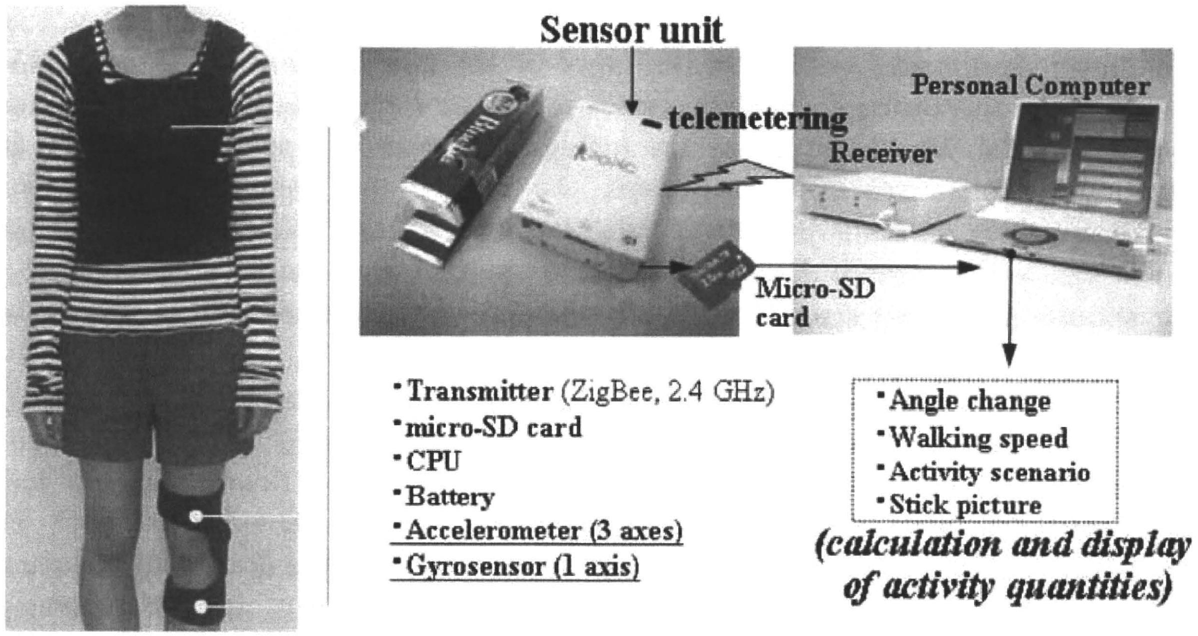

Fig. 7. Overview of wearable sensor system: Photos of user wearing sensor units in jacket pocket and knee support (left part), sensor unit (middle), and receiver together with personal computer (right).

of each part with respect to the gravitational direction is obtained from the low-frequency signals from the accelerometers. Additionally, to calculate the angular changes in the trunk, thigh, and calf during dynamic situations such as walking, the angular velocity outputs of the gyrosensors attached to each part are integrated. The initial angle is obtained from the accelerometer signal immediately before walking.

From the angular changes, activity scenarios are displayed as color bars (standing, walking, sitting, lying down, standing up, and sitting down) using the conventional personal computer. Detailed angular changes, walking speed, and motion pictures can also be displayed by clicking the bar of an activity scenario.

Figure 8 shows typical data of an activity scenario, thigh angle changes and walking speed during each walking cycle, with the associated stick pictures during six postures in a female subject with hemiplegia (84 yrs). It is clearly observed that although the subject was mostly living in either sitting or lying position, the cyclic angular changes and stable increase and decrease in walking speed can be detected during walking. The stick pictures derived from the angular changes of the trunk, thigh, and calf can also provide useful details of posture.

To investigate the system's applicability to patient activity monitoring in rehabilitation programs, we have successfully carried out clinical studies at some rehabilitation centers.(8,27,28) Through experiments in various situations including those in daily life, the system has been found to be promising for the quantitative evaluation of the efficacy of rehabilitation programs as well as human daily activities. As a future prospect, it is moreover desirable to obtain motion information with six degrees of freedom, and this will be realized by the use of a triaxial gyrosensor into the sensor unit.

3. Nonconscious Healthcare Monitoring at Home

As mentioned in the Introduction section, we have recently developed a home healthcare monitoring system on the basis of the new concept of "nonconscious physiological monitoring." This involves a procedure carried out in a fully automated manner without the attachment of any biological sensors to a subject's body or any troublesome operations of measurement. To achieve such monitoring, all sensors and instruments are built into home facilities, such as the toilet, bathtub, and bed, which are used in normal daily life. Thus, the subject does not need to be aware of the measurement being made, and the physiological data collected and stored are truly representative of ordinary daily living.

The daily use of the toilet by the subjects provides convenient opportunities for monitoring. We have developed a body and excretion weight monitor based on a highly accurate weighing scale device installed in the lavatory floor around the toilet bowl. Also, we have installed a BP monitoring system into the toilet seat.(7,14,15) For monitoring cardiac pulse and respiration, we have used vinyl tubes filled with silicone oil under a pillow.(16) For the care of the elderly, there is an important need for a drowning alarm in the bathtub, and we have designed a bathtub monitoring system capable of simultaneously detecting ECG together with respiration in the bathtub.(17)

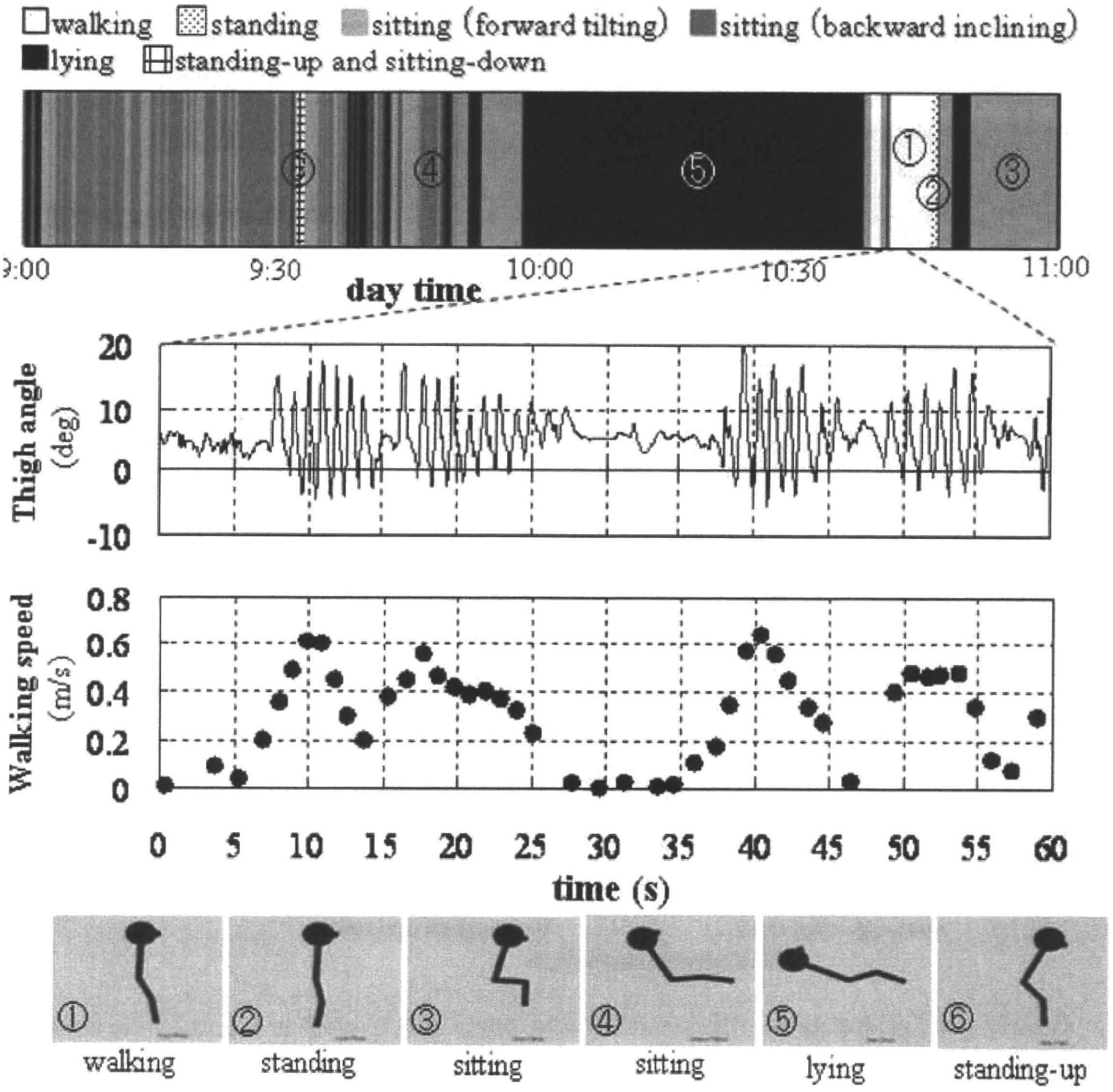

Fig. 8. Typical recordings obtained from a female subject with hemiplegia (84 yrs), showing activity scenarios from 9:00 to 11:00 a.m. (top panel), thigh angle change and walking speed during each walking cycle for a period of 60 s indicated by two dashed lines (middle part), and postural stick pictures (lowest panel), the numbers in which correspond to those in the scenario record. Various activities are indicated in the upper part of the scenario record.

To realize the whole concept, we have developed a new prototype healthcare monitoring room in which the systems for bathtub, toilet, and under-pillow monitoring are installed. We have evaluated the measurement accuracy and validity of these devices by simultaneous recordings of standard biological sensors directly attached to the subjects' body surface, and the results indicate that the new monitors do indeed allow accurate and reliable measurements.(7,14–17)

Figure 9 shows an overview of the prototype healthcare monitoring room, which has been constructed in a part of our laboratory in Kanazawa University. All the sensors and instruments are installed in the toilet space, the bathtub, and the bed. The obtained

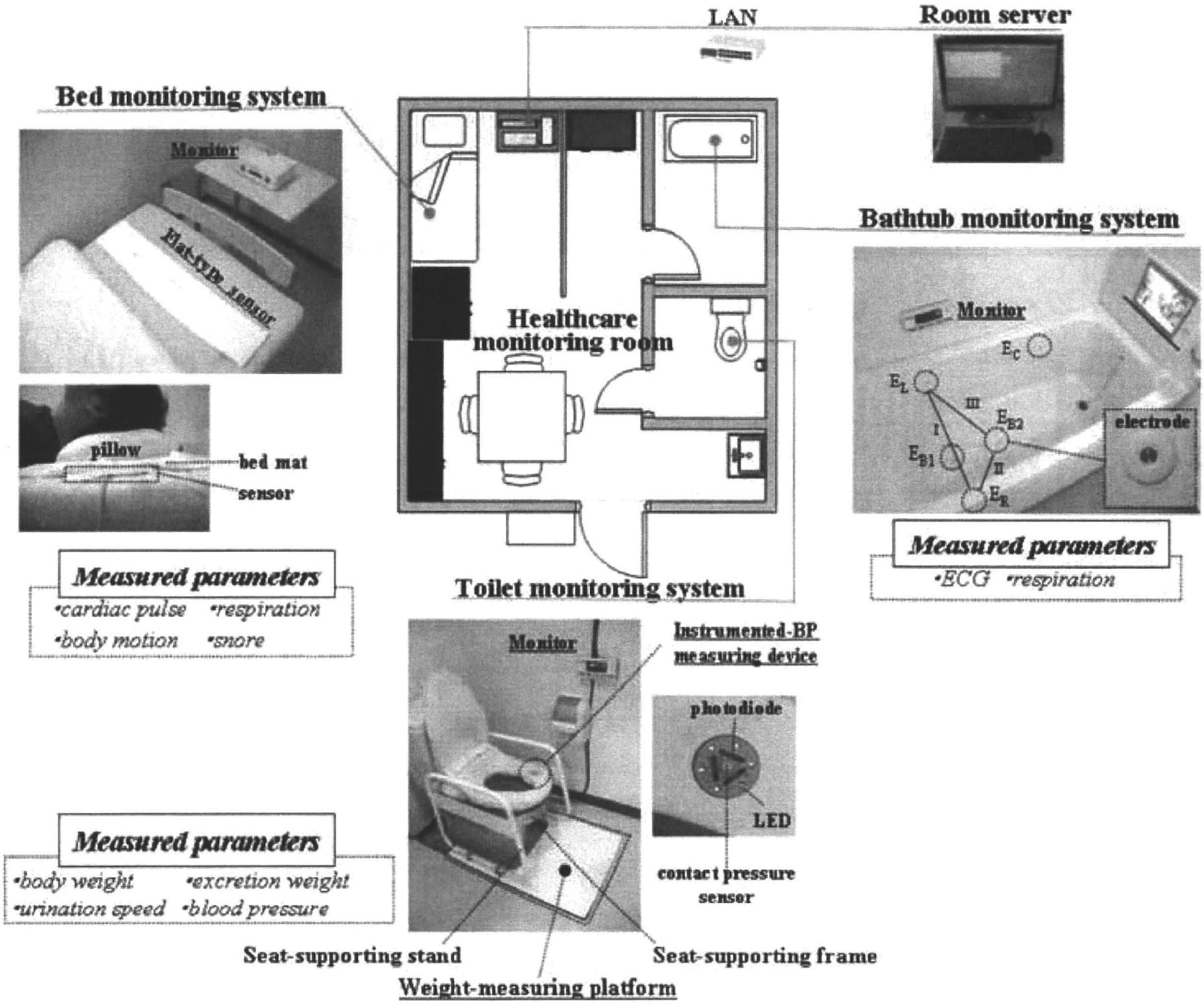

Fig. 9. Overview of prototype healthcare monitoring room constructed in a part of the author's laboratory in Kanazawa University. All the sensors and instruments are installed in the toilet space, bathtub, and bed. Measured parameters are shown for each system.

data are automatically analyzed and displayed using a monitoring system equipped with amplifiers for the sensors, a computer, memory, an LCD, and a LAN module. Analytical results from each sensor are stored and displayed using the room server.

In the toilet space, a platform-type scale with a weighing resolution of 5 grams is placed around the toilet bowl and is arranged to support the toilet seat using a frame. With this arrangement, the scale can accurately detect the total body weight before and after excretion, thereby obtaining excreta weight by subtracting body weight.

BP measurement is achieved using the volume-oscillometric principle, previously proposed by us.(7,20,21,23,39) A pusher plate is installed in the toilet seat, which applies local pressure against the back of one thigh pushed up by a pantagraph mechanism. The photoplethysmogram in the perforating arteries of the thigh is measured using six high-luminance near-infrared LEDs and three high-sensitive photodiodes affixed to the plate, which also houses a contact pressure sensor for measuring the pressure applied to the back of the thigh.