ECG and EMG Monitoring with Smart Textile hitoe™

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1 Introduction

Ischemic heart disease and stroke were the top two global killers from 2000 to 2019. In 2019, they killed more than 15 million people worldwide [1]. It is known that stroke is often caused by atrial fibrillation (AF); however, heart disease is an indirect but significant factor in death by stroke. In view of these alarming statistics, there is growing interest in monitoring heart rates (HRs) and measuring electrocardiograms (ECGs) on a daily basis in order to reduce the risk of health problems. Furthermore, there is a growing need for individuals to be able to monitor their own biometric information during daily activities, not just for medical purposes but to better understand their health status, improve their lifestyle, and enhance their performance in sports and other physical endeavors. Because recent wearable technology makes it simpler to measure one's own biosignals, it is now possible to easily monitor and use this information in daily life.

The functional material hitoe™, developed by NTT Corporation and Toray Industries, Inc., is a conductive fabric that functions as an electrode in contact with our skin surface for measuring ECGs and electromyograms (EMGs). It is made of conductive polymer PEDOT-PSS (polyethylene dioxythiophene-polystyrene sulfonate) coated onto a polyester nanofiber fabric [2, 3].

The diameter of the nanofiber fabric used in hitoe™ is about 700 nm, which is smaller than that of polyester fibers used in general clothing, which is about 15 μm. This ultrasmall fiber diameter results in a larger contact area with the skin and a

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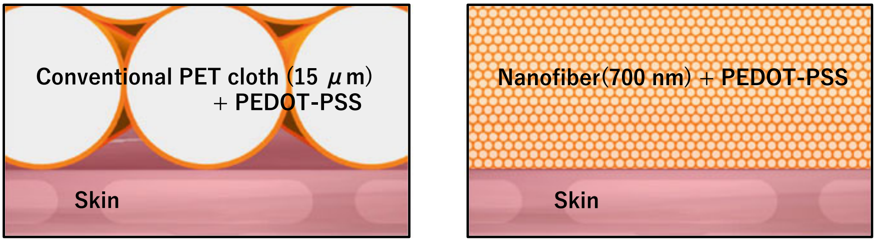


Fig. 1 Schematics of PEDOT-PSS-coated fabric on conventional PET cloth and on nanofiber (hitoe)

higher degree of adhesion compared to polyester fibers (Fig. 1). Additionally, the fabric is more comfortable to the touch than traditional polyester fibers owing to its softer texture. Also, unlike conventional metallic electrodes, hitoe™ electrodes absorb water well, as shown in Figs. 1 and 2; therefore, they absorb perspiration and blend well with the skin. The hitoe™ electrodes rarely cause rashes even when adhered to the skin for long periods of time and are gentle to the skin without any of the allergic reactions to metal.

Wearable sensing devices with hitoe™ electrodes have been commercialized as functional wear for measuring HRs during sports and for monitoring workers' vital signs, as well as for medical use of Holter ECGs. In these clothes, the hitoe™ electrodes are embedded inside shirts or belts. In developing this wear, related technologies were also important in terms of the intended use, such as electrode placement in the shirts and suitable garment materials that, for example, allow stretching with low tension with high fabric elasticity. Various hitoe™ weares have been developed considering the intended use case.

Section 2 introduces commercialized hitoe™ wear for ECG monitoring. Monitoring ECG on a daily basis requires not only sensing clothing but also wearable measuring devices that are lightweight and have long battery life. Section 3 describes how these requirements are met with transmitter technology saves power and reduces transmitter weight for daily measurements with hitoe™. Sections 4 and 5 describe examples of hitoe™ use cases for daily monitoring.

2 hitoe™ Electrode and ECG Sensing Wear

ECG measurements with shirts or belts are often performed with dry electrodes made of metal or conductive rubber. The most significant difference between hitoe™ and these materials is its hydrophilic properties, as shown in Fig. 2. Since 2014, various ECG measurement wear with hitoe™ have been developed and released in Japan. Here, we will introduce the basic properties of hitoe™ as a biological electrode and the lineup of commercialized garments.

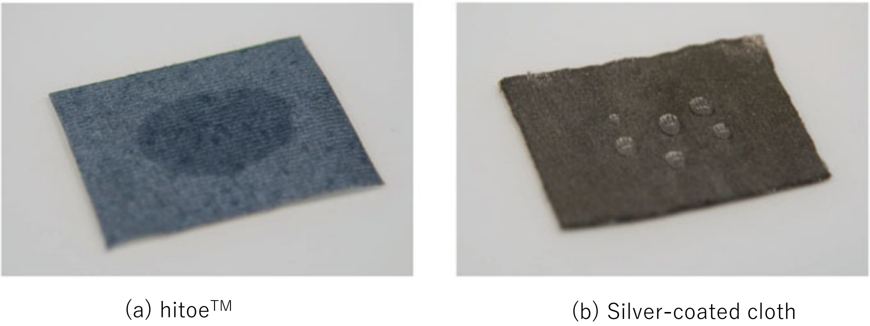

(a) hitoe™ (b) Silver-coated cloth

Fig. 2 Photographs showing how, **a** hitoe™ absorbs water droplets and **b** silver-coated fabric repels water droplets

2.1 Basic Properties of hitoe™ Electrode

The hitoe™ electrode is a fabric made of conductive polymer PEDOT-PSS coated onto a polyester nanofiber cloth. The electrical properties of hitoe™ fulfill the requirements of disposal medical electrodes, which were evaluated based on ANSI standards for disposable electrodes for ECG (Table 1).

For an electrode material for daily use, besides the electrical properties for measuring biological signals, comfortableness for users and washing durability are very important. The hitoe™ electrode has a soft texture due to its nanofiber construction and hydrophilic properties. This allows for a good feel on the skin and absorption of perspiration, resulting in a comfortable fit. Regarding durability, the conductive polymer is less likely to peel off because it is firmly impregnated in the small gaps between the nanofibers. Tests have confirmed that ECGs can be measured even after 100 washes in a home washing machine.

Table 1 Electrode characteristics and ANSI/AMI requirements for disposable ECG electrode. After Ref. [4]

	Textile	ANSI/AAMI
DC resistance	<0.1k Ω	<2k Ω
AC impedance	1.26 ± 0.18K Ω	<3K Ω
Internal noise	1–3 μV	<150μV
Defibrillation discharge at 200 V		
Recovery polarization potential	1.95 ± 0.80 mV	<100 mV
Rate of change of polarization potential	No change	<1 mV/s
AC impedance after test	1.14 ± 0.07 KΩ	<3 KΩ
DC offset voltage	0.0028 ± 0.0020 mV	<100 mV
	Data are reported as means ± SD	

2.2 ECG Sensing with hitoe™ Wears for Various Purposes

In wearable sensing devices with hitoe™, the conductive hitoe™ fabric is attached inside shirts or on belts and used as electrodes for detecting the electrical potential on the surface of human skin. In the system, good contact between the skin and electrode is essential for acquiring clear signals without noise; therefore, in addition to the hitoe™ electrode itself, garment properties such as compressibility and shape to fit the body are important.

"C3fit IN-pulse" (GOLDWIN), a garment with hitoe™ electrodes and a dedicated transmitter (hitoe transmitter 01, NTT DOCOMO) that can measure HRs, was released as sports shirts in 2014 and then as sports bras for women in 2015 in Japan (Fig. 2a and b). These compression-type shirts/bras fit the contours of the torso, and thus the electrode has good contact to the skin during even rather hard sports activity. The basic properties of C3fit IN-pulse for measuring ECGs were evaluated for supine and seated users and for various body motions, such as upper body twisting, and foot stomping exercises, assuming movements in daily life (Fig. 4). The results showed that when the electrode was moistened with glycerin solution in advance to inhibit drying and maintain continuous contact with the skin, the signals obtained with this wear were almost comparable to those measured by a Holter ECG recorder (Kenz Cardy 303 Pico+®, SUZUKEN Co., Ltd., Nagoya, Japan) with medical gel electrodes patched directly to the skin [4].

Since the release of C3fit IN-pulse, it has been utilized for ECG monitoring in various sports with hard body motion such as in baseball, skiing, snowboard jumping [5], and badminton. Although the first version of C3fit IN-pulse was released as sportswear, it was also used in medical research to evaluate the feasibility of a T-shirt-type wearable ECG monitor. This research included ECG monitoring during a full marathon race to create novel preventive strategies against sudden cardiac events [6], as well as clinical research for the detection of covert atrial fibrillation [7] and analysis of autonomic nervous system functions during natural defecation in patients with irritable bowel syndrome [8].

Though C3fit IN-pulse has been accepted by most athletes who regularly wear compression-type inner shirts, it is a little tight for everyday wear. With a focus on wearing comfort in daily life, less compressive wear was developed with the introduction of new materials and the design of the compression of the body fabric. Comfortable all-day wear is expected to expand the utilization scenarios of ECG monitoring for various purposes. After several attempts, a new type of C3fit IN-pulse was released in 2020 (Fig. 3c) along with a new transmitter TX02 (details of the TX02 are described in Sect. 3.1). The new wear significantly improved comfort as innerwear without compromising HR measurement accuracy. This opened the possibility of widespread use among field workers who require a garment that can be worn all-day (this wear is suitable for worker monitoring, as described in Sect. 4.1). HR detection from ECG signal was evaluated with this innerwear especially for worker-specific movements such as applying external vibration and lifting and lowering loads, assuming real-world cases of physical load in light to moderate intensity tasks

[9]. The accuracy of the obtained HR values was competitive with that of conventional gel-type electrodes (Fig. 5).

Daily monitoring in rehabilitation wards is desired as well (see Sect. 4.2). For stroke rehabilitation, users will mostly be elderly or paraplegic, unlike the users of sportswear or work clothes. Improvements have been made for practical use in rehabilitation wards, such as an opening at the front to make it easier for caregivers to put it on and allowing only the top of the electrodes to be fastened with a belt (Fig. 3d) or by wear shape (Fig. 3e) so that both comfortableness with a loose-fit and clear ECG can be taken.

In addition to the several types of sensing wear shown above, belt-type wear that can be used in a variety of situations has also been developed and marketed. To reduce

(a) C3fit IN-pulse shirts released in 2014 **GOLDWIN**

(b) C3fit IN-pulse bratop released in 2015 **GOLDWIN**

(c) C3fit IN-pulse shirts released in 2020 **GOLDWIN**

(d) Wear for stroke rehabilitation **Toray**

(e) Wear for stroke rehabilitation and for general purpose **Toray**

(f) Belt wear **Toray**

(g) Medical wear **Toray Medical**

(h) Medical wear **Toray Medical**

Fig. 3 hitoe™ wear for various purposes

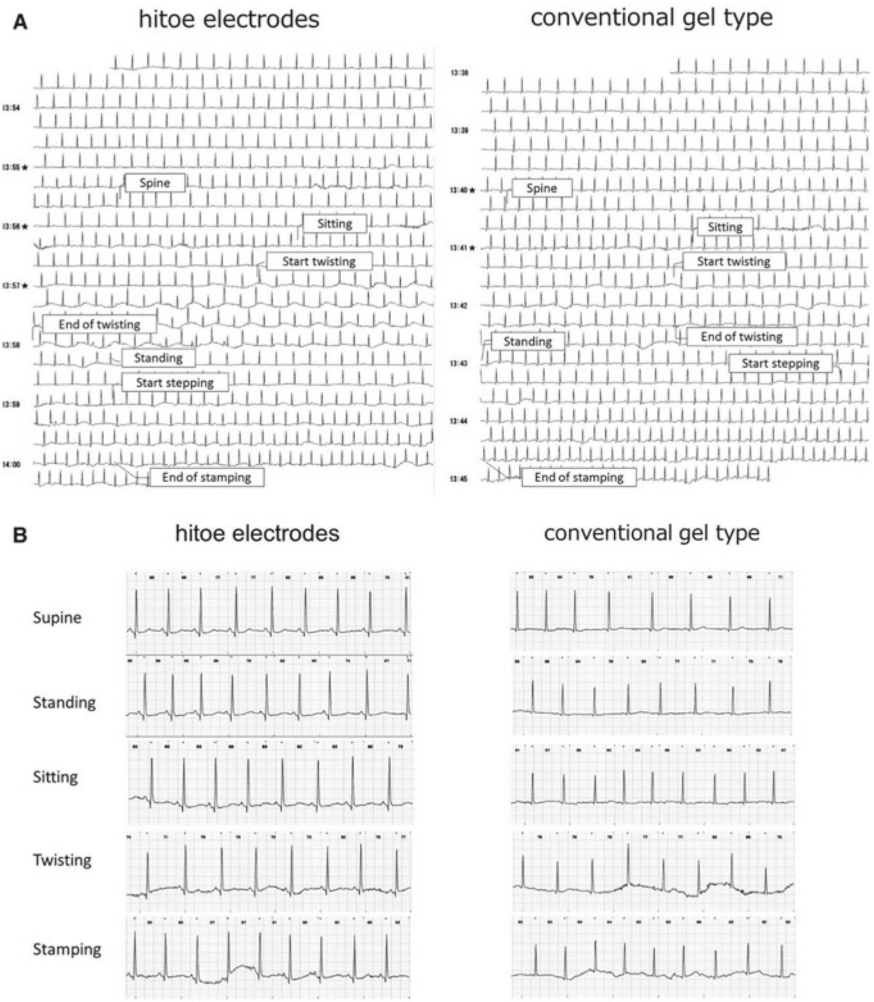


Fig. 4 ECG signals detected with hitoe™ electrodes (C3fit IN-pulse and transmitter 01) and conventional gel-type electrodes in various body motions: supine, seated, upper body twisting, and foot stomping exercises. After Ref. [4]

the influence of electrode displacement caused by body movement, the position of electrodes is designed to be less susceptible to belt expansion and contraction, and the belt itself is designed to be less prone to twisting (Fig. 3f).

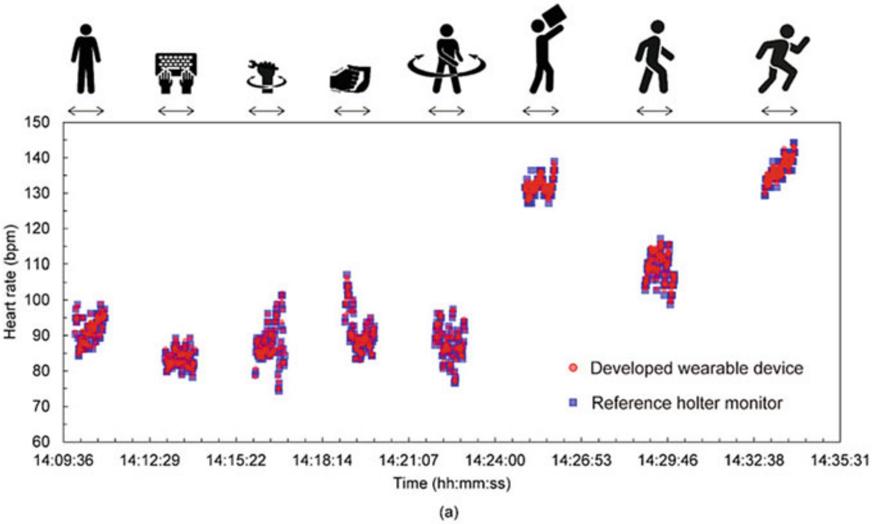


Fig. 5 Example of time-series of HR data obtained from the wearable device, C3fit IN-pulse 2020 with TX02, and gel-type Holter monitor at each movement. After Ref. [9]

2.3 *hitoe™ Medical Wear*

The hitoe™ medical electrodes and lead wires have been approved for use as general medical devices in Japan. Toray Medical Co. Ltd. has been distributing the hitoe™ Wearable ECG Measurement System since 2018 (Fig. 3f).

This system can be used for Holter ECG examination with the bipolar lead CC5 condition. The dedicated ECG logger is capable of continuous ECG measurement for up to 14 days without recharging. The hitoe™ medical electrodes are attached to the dedicated hitoe™ medical leads with a snap. The wearable Holter ECG system is suitable for long-term measurement over the course of days because there is no need for a specialist to place the electrode. The medical electrodes are highly electrically conductive with snap hook buttons, and the medical lead wires are made of silver-plated nylon thread to integrate them with the wear. The system is especially useful for monitoring the occurrence of AF, which often occurs intermittently in the early stages of a disease and is often undetectable with short-term measurements. The AF detection rate can be improved by measuring the ECG over a longer period. In tests comparing the hitoe™ Holter ECG medical system and conventional gel electrode system, the wearable ECG with hitoe™ system showed a slight increase in noise signal episodes with associated deterioration in R-wave amplitudes (Fig. 6). However, this increased noise signal count caused a negligible interruption in a continuous AF episode in a patient with intermittent AF [10]. A clinical study reported that the ECG acquisition rate was higher for gel-type Holter ECG than for the hitoe™ Wearable ECG Measurement System, but the hitoe™ system provided longer total analysis

Fig. 6 Simultaneous tracing from wearable ECG (**a**) and Holter ECG (**b**). Electrodes were positioned to compose a bipolar lead CC5 in both ECG devices. After Ref. [10]

time. Despite its lower ECG acquisition rate, the two-week ECG with the hitoe™ Wearable ECG Measurement System has revealed instances of AF recurrence after ablation in patients who were underdiagnosed by 24-h Holter ECG [11].

Later, the hitoe™ Wearable ECG Measurement System was modified into disposable garments, and the hitoe™ Wearable ECG Measurement System II was released in 2020 in order to avoid hospital laundering (Fig. 3h).

3 New Wearable Biological/Environmental Sensor

Wearable devices equipped with biological sensors have emerged as promising tools for monitoring an individual's lifestyle and providing personalized advice for maintaining a healthful life. These devices have also found applications in managing the physical well-being of workers, particularly during the summer season when temperatures are high. However, for wearable devices to make a meaningful and sustainable contribution to healthful living, they need to be seamlessly integrated into an individual's daily life and exhibit a high degree of naturalness and intuitiveness.

To this end, NTT has collaborated with Toray to develop the conductive textile hitoe™, which takes the form of shirt-type clothing and enables daily biological measurements. In this section, we present a novel wearable sensor that, in conjunction with hitoe™, enables the simultaneous detection of biological and environmental information while featuring a small form factor and low-power consumption.

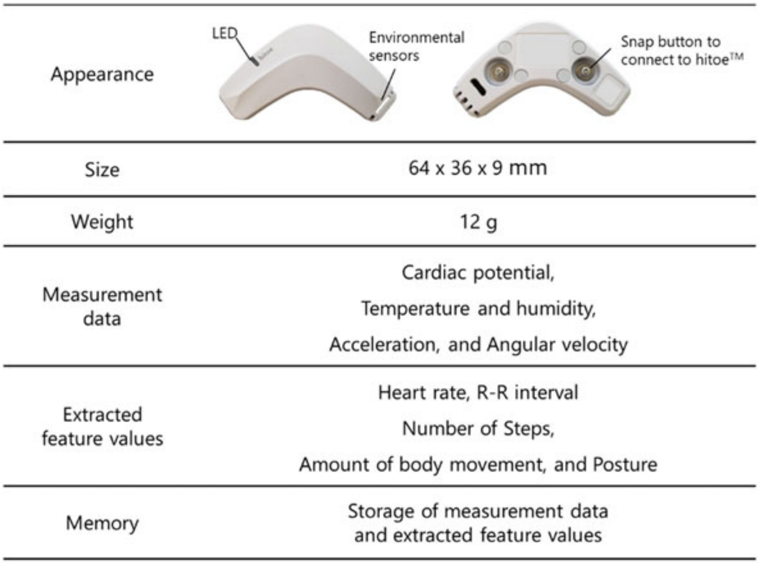
3.1 Wearable Biological/Environmental Sensing with hitoe™

For the purpose of daily biological monitoring, hitoe™ electrodes are incorporated into garments such as innerwear and connected to a sensor comprising analog front-end circuits, an analog–digital converter, accelerometer, central processing unit (CPU), and radio-frequency circuits for Bluetooth Low Energy communication [12]. The measured data are transmitted to a smartphone for visualization and subsequently sent to cloud servers for data storage and further signal processing. To enhance the naturalness of wearable sensing technology in our daily lives, miniaturization and long battery life of the sensor are imperative to minimize interference with user movement and reduce the frequency of battery charging. Moreover, for smart healthcare applications, such as the physical condition management of workers in hot environments, environmental information must also be evaluated to assess the thermal stress on individuals [13].

To address the aforementioned requirements, NTT has developed a wearable sensor (hitoe™ Transmitter TX02), as depicted in Fig. 7, that is compact (weighing 12 g), has low-power consumption, and enables multi-sensing of biological and environmental information. The sensor can be affixed to hitoe™ innerwear to measure biological information, such as HR and ECG. Furthermore, it can measure the environment between clothing layers. When outerwear is worn over hitoe™ innerwear, the sensor can monitor the temperature and humidity of the space between the two garments. These data are instrumental in assessing a wearer’s heat stress and comfort levels. Additionally, acceleration and angular velocity can be measured to track body movements. From these measurement data, the sensor can derive various feature values, including the HR, R-R interval (RRI), number of steps, amount of body movement, and angle. The measurement data and extracted feature values are transmitted to a smartphone or Internet-of-Things gateway via Bluetooth Low Energy. The extracted feature values are stored in the sensor’s internal memory, enabling data collection in cases where the wearer does not possess a smartphone during measurement. Thanks to the ergonomically designed housing, the sensor fits snugly in the gap between the chest and abdomen, allowing it to be worn comfortably without hindering movement, such as bending and lying down.

3.2 Multi-sensing Technique for Low-Power Operation

Continuous measurement, analysis, and transmission of diverse data lead to an increase in CPU load and power consumption, necessitating frequent recharging or the use of a large battery to maintain operational time. This challenge is addressed by the deployment of a novel biological/environmental sensor that employs a multi-sensing technique developed to mitigate power consumption [12]. The circuit configuration and flow of this technique are illustrated in Fig. 8. Through the efficient utilization of a direct memory access controller, the sensor measures and stores



Appearance	
Size	64 x 36 x 9 mm
Weight	12 g
Measurement data	Cardiac potential, Temperature and humidity, Acceleration, and Angular velocity
Extracted feature values	Heart rate, R-R interval Number of Steps, Amount of body movement, and Posture
Memory	Storage of measurement data and extracted feature values

Fig. 7 Specifications of new wearable biological/environmental sensor

diverse data in a buffer while the CPU is in sleep mode. Once a considerable amount of data has been collected, the CPU is briefly activated for waveform processing and feature-value extraction.

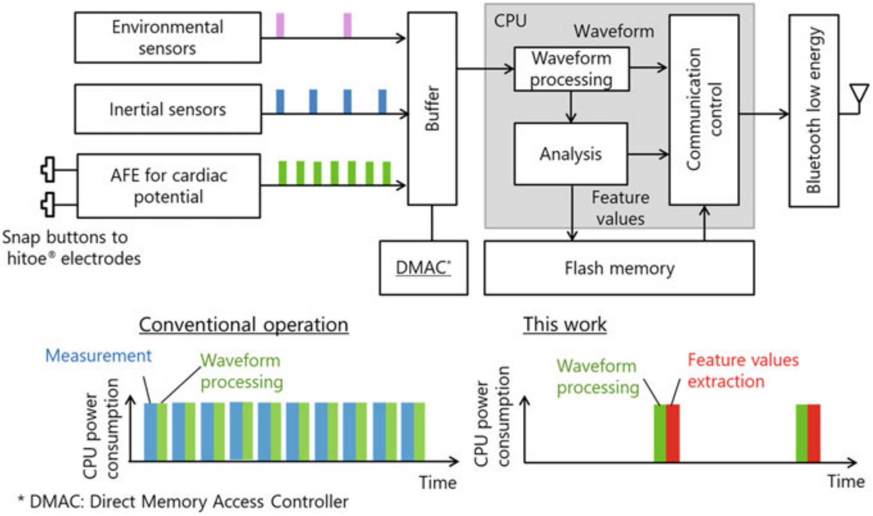


Fig. 8 Low-power multi-sensor processing. After Ref. [12]

The three operating modes of this new biological/environmental sensor are designed to meet different requirements depending on the application. The standard mode allows for the transmission of the cardiac potential waveform at a sampling rate of 200 Hz, acceleration waveform, and extracted feature values. The high-performance mode offers an improved sampling rate of the cardiac potential waveform at 1 kHz and enables angular velocity measurement. The low-power mode extends battery life by stopping the transmission of the waveform. By reducing the CPU load, this sensor is approximately half the size of the conventional one and uses a smaller battery. In the low-power mode, the sensor can operate for more than 100 h. These operating modes provide flexibility in data acquisition and power management to suit different application requirements.

Moreover, NTT proposed a simple method for RRI correction from ECG at a low sampling rate to mitigate the trade-off between high resolution and energy consumption for the calculation of the RRI [14]. The resolution of the RRI is generally dependent on the ECG sampling rate [15]. However, in wearable devices, a high sampling rate like that required for standard ECG testing such as 500 or 1000 sps results in heavy calculation loads, which increase power consumption. The proposed method is suitable for such algorithms and involves combining QRS enhancement using the first derivatives of the filtered ECG signal and QRS detection with adaptive thresholding [16].

Figure 9 shows a schematic of the proposed method. The method uses zero crossing points (Z[n]) in the filtered ECG signal. The points are estimated by $Z[n] = Y[n] - Y[n]\Delta t/(Y[n] - Y[n-1])$, where Y[n] is a sampling point corresponding to the detecting point obtained by adaptive thresholding, Y[n-1] is the previous sampling point of Y[n], and Δt is the sampling interval. Each estimated zero crossing point is used for RRI calculation.

To demonstrate the efficacy of the proposed method, an ideal ECG signal (120 bpm) was generated using an ECG generator (AX-301D, Nihon Kohden). The resulting analog signal was digitized under two sampling conditions: 1 ksps, which

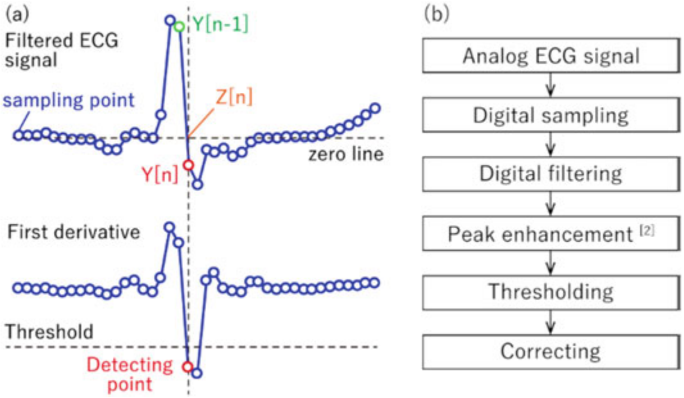
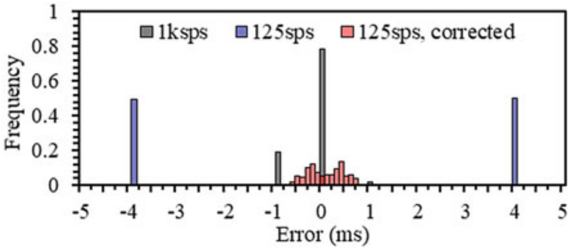


Fig. 9 **a** Schematic of RRI correction. **b** QRS detection and RRI correction flow chart

Fig. 10 Comparison of RRI error histogram



is equivalent to standard ECG testing, and 125 sps. RRI detection was performed based on the flow chart presented in Fig. 9b. Specifically, the digitized ECG signal was filtered using a digital filter appropriate for the sampling rate, and peak enhancement was conducted following QRS detection with adaptive thresholding and RRI calculation. In the case of 125 sps, the raw RRI was corrected using the proposed method.

The resulting RRI error histogram is shown in Fig. 10, which was calculated based on the difference between the calculated RRI for each condition and the reference value (500 ms). The RRI accuracy at the low sampling rate of 125 sps was ±4 ms, which was larger than that at the high sampling rate of 1 ksps (±1 ms). However, the proposed correction method improved the accuracy at the low sampling rate to ±0.8 ms. These results demonstrate the effectiveness of the proposed method in achieving the RRI accuracy required for standard ECG testing under low sampling conditions.

3.3 Lightweight Heartbeat Detection Algorithm and Its Implementation

In wearable measurement environments, ECG waveforms are often corrupted by body movement, resulting in significant noise. Therefore, developing a technique that is minimally affected by noise is crucial to improve the accuracy of wearable ECG measurements. Additionally, wearable devices typically have limited computational resources, making it challenging to employ complex or computationally intensive techniques. Thus, a simple yet accurate heartbeat detection algorithm is necessary [17]. The ECG waveform of each heartbeat consists of distinct waves, namely P, Q, R, S, and T waves, with the QRS complex being a region of steep changes in electrical potential. A commonly used method for detecting heartbeats involves capturing QRS complexes [16].

A practical detection procedure for detecting heartbeats was outlined in an application report for an ECG front-end processor [18]. The report presented a reference design for a mass-produced semiconductor chip, and the technique described can be regarded as a general approach. In this algorithm, a threshold-based peak search is applied to the time differential of the ECG signal. A threshold value is set for the time differential values, and the time point at which the value exceeds the threshold is

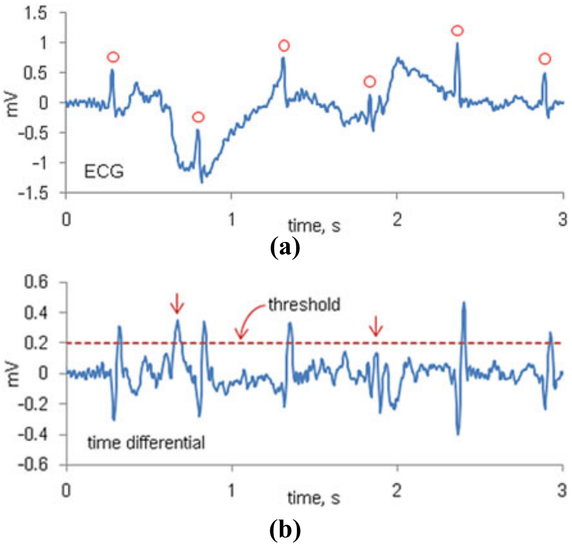


Fig. 11 Example of ECG waveforms and heartbeat detection. **a** Raw ECG. **b** Inverted time differential of ECG. After Ref. [17]

identified as the time of the heartbeat. Figure 11a and b provide an example of ECG waveforms captured by the C3fit IN-pulse and its corresponding time differential waveform. In Fig. 11b, the time differential of the time-series data x(n) is obtained by subtracting x(n − 1) from x(n + 1) for each sampling time. The small circles on the ECG waveform represent the QRS complexes. The time differential value shows slightly shifted peak positions and is inverted.

As shown in Fig. 12, using the time differential instead of the raw ECG signal allows for the cancellation of baseline slopes and swings. It should be noted that depending on the individual's physique, some individuals may have ECG waveforms with a low top R and a deep bottom S, caused by the positional relationship between the electrodes and the heart. However, even in such cases, using the inverted time differential can treat the amount of rapid decrease in electrical potential from R to S as positive amplitude. To adapt to the waveform amplitude trend, which is subject to change with wearable sensing, the threshold value can be set adaptively according to the latest peak values [19]. Nevertheless, during measurements with a wearable device, the electrodes may rub against or peel off the skin, introducing sharp fluctuations in the form of noise that inevitably disturbs the ECG waveform. Consequently, the threshold-based logic described above may lead to errors, such as detecting noise as a QRS unnecessarily (around 0.7 s) or missing a true QRS buried in noise (around 1.9 s), as shown in Fig. 12b.

To address the issues described above, NTT has developed a new lightweight algorithm for detecting heartbeats in wearable ECG measurements [17]. Based on the mechanism of ECG, the QRS complex is generated by a displacement current that occurs during the depolarization of the ventricular muscle propagating from the endocardium to the epicardium. Therefore, the duration of the QRS complex is expected to be almost constant among individuals without cardiorespiratory diseases. Thus,

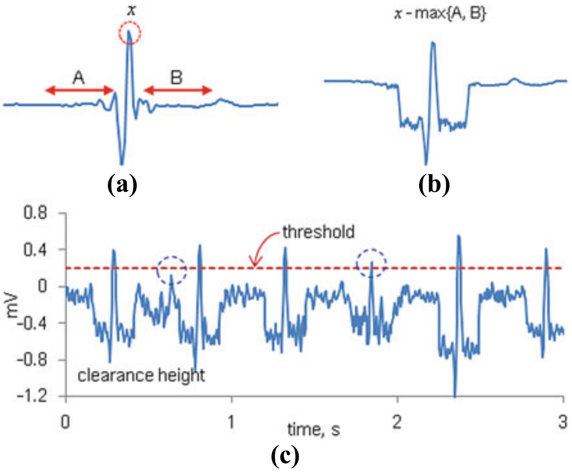


Fig. 12 Schematic of the principle of the algorithm. **a** Inverted time differential of ECG. **b** Calculated clearance height. **c** Heartbeat detection using the proposed algorithm. After Ref. [17]

it is appropriate to consider sensitivity to time width in waveforms. Furthermore, a pinching approach, where a protruding portion is detected from above, is more effective than catching something exceeding a threshold from below. Additionally, it is desirable to consider the area before and after a point, rather than using a one-way scan that focuses only on one point, as in primitive threshold logic.

The concept described above is implemented as an algorithm as follows. First, a peak in the inverted time differential of an ECG, shown in Fig. 12a, is identified. A typical QRS waveform is used to illustrate the principle. If the peak has a certain time width and sufficient clearance around it, it is most likely attributable to QRS. Let x be the value of the inverted time differential at a specific point in time, and calculate ‘x—max {A, B}’, where A and B correspond to specific time ranges before and after x. Max {A, B} corresponds to the floor level in the area surrounding x, A, and B. Figure 12b displays the time sequence of the value ‘x—max {A, B}’ calculated for each time point. This value represents the height of the clearance around each peak and, as a result, selectively enhances QRS-derived peaks. By using the clearance height, a normal threshold-based peak search can be redefined as an accurate heartbeat detection method. The width of time is determined based on the nature of an ECG. For example, the duration of A and B is 100 ms, and the interval between them is 50 ms. Figure 12c displays a case where this method was applied to the ECG in Fig. 11a. The threshold for clearance height can also be set adaptively. The results show that the QRSs that were not handled appropriately by the conventional method are now processed correctly by our algorithm, as indicated by the dotted circles.

4 Application for Smart Healthcare

The feature of the hitoe™ is its ability to acquire and transmit real-time information on HR, ECG, acceleration, temperature, and humidity just by wearing it, and its strength lies in its applications that capture global needs by computing and extracting features from the information. In this section, we will introduce two applications that contribute to smart healthcare with the aim of extending human life toward the realization of a sustainable society.

4.1 Novel Health Risk Alert System for Occupational Safety in Hot Environments

The global increase in temperature over the last century, commonly referred to as global warming, has been recognized as a significant issue by the World Meteorological Organization. This organization has reported that 2020 was one of the warmest years on record, with temperatures about 1.2 °C above preindustrial levels [20]. The adverse effects of global warming on human health are a crucial concern, particularly as extreme heat can lead to health risks [21]. In fact, this warming has been shown to severely limit human activity in tropical and mid-latitude regions [22]. Such warming has also been shown to limit human activity, especially for outdoor and manual workers who are susceptible to increased health risks from exposure to ambient heat during working hours.

To address this issue, workers should pay attention to their own physical conditions and take breaks when they feel uncomfortable. Supervisors must also manage worker conditions and schedule regular breaks. Additionally, a new integrated system has been developed to notify individuals at risk based on their thermal physiology. This method uses wearable sensors to obtain biological and environmental information, and core body temperature is estimated on-ground, as it cannot be measured wirelessly and noninvasively [23]. Overall, it is essential to take measures to mitigate the risks associated with global warming and protect the health and well-being of workers.

The core body temperature, HR, and subjective symptoms of dizziness and nausea are listed as indicators of the risk of poor physical conditions in hot environments [24]. The new method developed in this trial aims to estimate core body temperature variation in real-time using wearable sensors and a calculation model that considers various factors, including heat exchange between the core and skin layers of the human body, heat produced by human activities, the thermoregulatory function due to sweating, and clothing (Fig. 13) [25]. The model takes into account personal information, such as age, height, weight, gender, and clothing, along with heart rate and temperature/humidity inside clothes, to estimate core temperature variation. The calculation model is designed to be simple yet effective and can be performed using limited computation resources, such as smartphones, in real-time. This new method

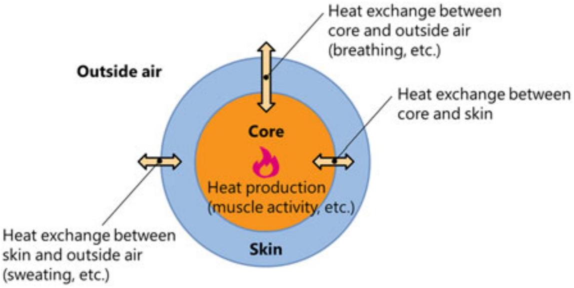


Fig. 13 Calculation human body model with core and skin layer for estimating core body temperature. After Ref. [26]

can be used to notify individuals at risk based on their thermal physiology, allowing them to take proactive measures to prevent health risks associated with extreme heat.

To verify the effectiveness of the proposed technique, a clinical experiment was conducted at Shigakkan University in an artificial weather room to estimate body temperature variations using the model. Rectal thermometer measurements were taken, as illustrated in Fig. 14, and the estimation accuracy was confirmed to be 0.15 °C [26, 27]. Criteria and algorithms were established to determine the high risk of poor physical condition for each worker. Three indicators, including HR, estimated core temperature fluctuation, and subjective information based on joint experiments and thermal physiology, were used to set criteria. An algorithm was also developed to determine the overall risk of poor physical condition, based on the state of the three indicators. The system issues an alert in the case of high risk. The health risk alert system was applied to 49 construction workers employed during the summer of 2020 for the world's largest sports events in Tokyo (a total of 834 person-days from August 5 to September 30), as illustrated in Fig. 15.

The implemented technologies for core temperature variation estimation, poor physical condition risk determination, and workload estimation were integrated into a smartphone app as a health risk alert tool for occupational safety. A system was also built to remotely monitor the physical condition of each worker wearing wearable biological or environmental sensors via the cloud. Alerts were sent to workers, supervisors, and remote monitoring systems for those identified as being at high risk. Comprehensive detection of risk cases was achieved during the construction period by supplementing each case with the three indicators of the poor physical condition risk determination technology, including HR, core temperature increase, and subjective information. Workers who received the alert paid attention to their own physical condition and took proactive measures to rest and avoid heat exposure. Supervisors assessed workers' physical conditions and directed breaks accordingly. No serious cases of poor physical condition, such as heat stroke, were reported during the construction period, indicating the usefulness of this health risk alert system.

The health management of workers and volunteers is crucial for event operations, in addition to athlete safety. The Nippon Telegraph and Telephone East Corporation applied this health risk alert system to construction and maintenance workers for the world's biggest sports events held in Tokyo during the summer of 2021. Future

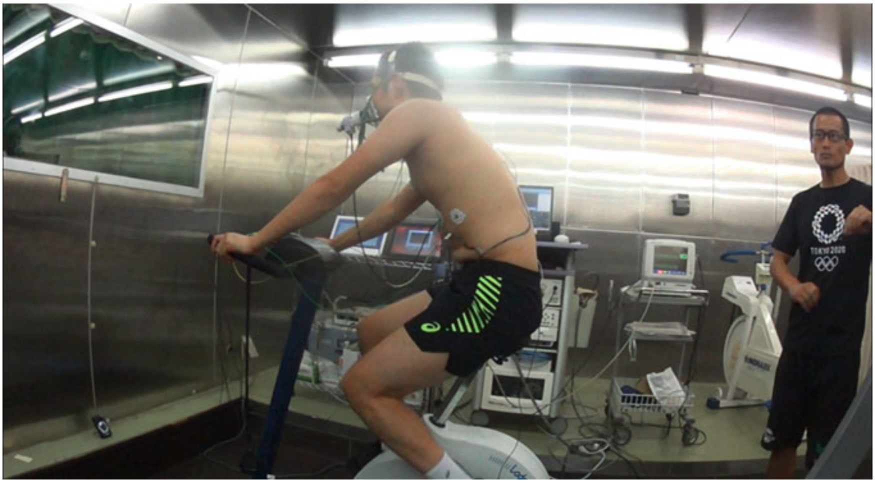


Fig. 14 Experiment in the artificial weather room. Subject is using an exercise bike in a room with temperature control to simulate outdoor activity in hot weather (photo courtesy of Shigakkan University)

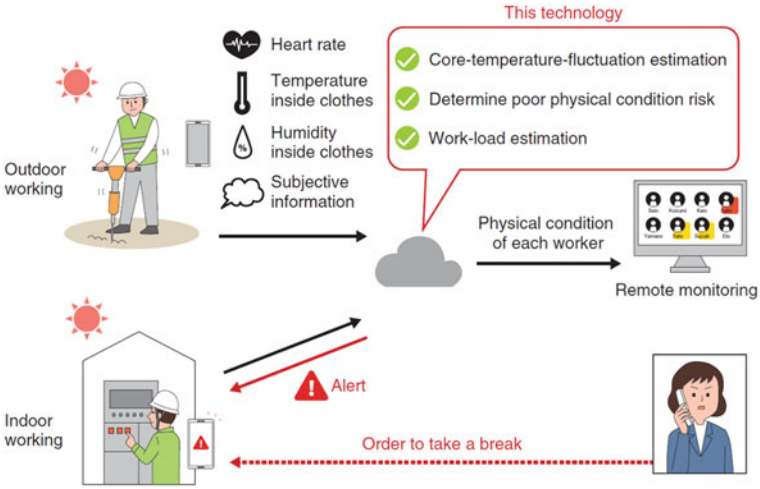


Fig. 15 Schematic diagram of the health risk alert system for workers and their supervisors. After Ref. [26]

studies may involve the application of the system to athletes, as well as other outdoor and manual workers, such as firefighters and outdoor police officers.

4.2 Application for Rehabilitation Medicine

The second application is rehabilitation support using HRs and acceleration data obtained by hitoe™. Since 2017, a joint research project between Fujita Health University and Toray Industries, Inc. has been underway. In stroke rehabilitation, the more training opportunities a patient has after stroke onset, the better progress can be expected [28]. However, in actual rehabilitation settings, patients should be as active as possible in their daily lives through getting out of bed and doing voluntary training, as training opportunities with therapists are limited. However, it is not easy for patients to vigorously load their hemiplegic bodies on their own, and support is needed to achieve a better recovery. As a tool to provide this support, a system that can precisely monitor the activity data of stroke patients on a 24-h scale using a wearable device has been developed (Fig. 16). In this system, a patient wears a garment that even a hemiplegic patient can put on and take off easily, which was introduced in Sect. 2.2, and the data is automatically collected on a server via a relay such as a smartphone or gateway, providing a report for the patient and family and detailed measurement results for the medical team. These reports provide concrete information about the recovery process, allowing the patient to have a conversation with the therapist about progress and the next training session. Detailed measurement results provide information on changes in activities of daily living for each patient, and can be shared with the entire healthcare team for collaboration. The technology that makes this possible is characterized by algorithms that process the data, and it features advanced downsampling that avoids network load at hospital facilities while preserving activity characteristics and compensation processing for partial data loss. Such processing is enabling new clinical approaches, such as using machine learning to predict indicators of recovery in stroke patients [29–31]. The technology that allows patients to move around hospital facilities without having to carry a smartphone features a gateway relay for data collection, handover to reduce data loss between adjacent gateways, and time-stamp correction to match the time difference in data collected at each gateway [32]. Furthermore, as a feature for medical validation, the system supports tests widely used in rehabilitation medicine, such as the six-minute walk test, allowing new comparative studies by easily matching existing testing approaches with the results of 24-h activity monitoring.

5 Improving Performance of Athletes by Using hitoe™ EMG Sensing Data

The hitoe™ electrode can also be used as an electrode for EMG measurements. Although EMG hitoe™ clothing has not yet been commercialized, it has been used for specialized tasks, such as training elite athletes or racing drivers, and have evaluated them [33, 34]. As an example, here we show how top cyclists utilized hitoe™ for monitoring their muscle condition.

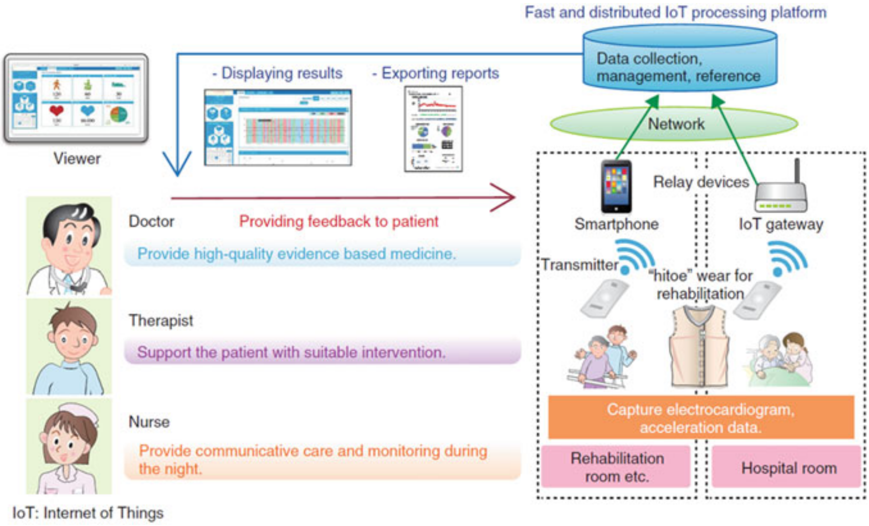


Fig. 16 Rehabilitation support system using hitoe™

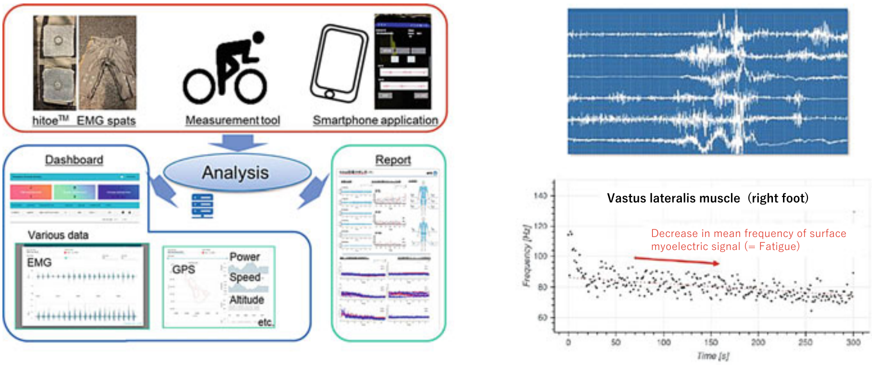
For athletes, knowing the state of their own muscle activities is very important for conditioning and improving performance. Surface EMG is an effective way to ascertain muscle activity with little physical burden.

Conventional EMG sensors had practical problems when utilized in real cycling fields, such as electrodes falling off due to perspiration, problems with preparation time to fix electrodes one by one, and hampering of athletes' movements. In contrast, with the measurement using hitoe™, the electrodes can be easily fixed to the skin by simply putting on the training wear with hitoe™ mounted on the lining, and there is no need to worry about them falling off.

To evaluate their EMG during cycling on a real cycling bank, cyclists wore special spats, with the hitoe™ electrodes attached at the position of the targeted muscles inside (Fig. 17).

Figure 18 shows an overview of the system that the cyclists used for their training. The real field data collected with the hitoe EMG wear and a smartphone were analyzed in the server. The analyzed data combined with other sensor data, such as GPS, cycling power, and speed were presented via the dashboard interface to the analyst. A comprehensive report was returned to the athlete and coach. Figure 18b shows the surface myopotential data acquired during a time trial. It is known that the frequency components of the surface EMG signal change as muscle fatigue progresses. The data shows the reduction of the average frequency component of the surface EMG signal with time. Furthermore, the differences in pedaling styles on the basis of muscle fatigue and muscle activity of cyclists were evaluated from those data. Such data helped the cyclists realize the training issue and improve their performance [33].

Fig. 17 Specially designed spats for cyclists. The hitoe™ electrodes are attached at the position of targeted muscles



(a) System overview for cyclist training

(b) EMG signal (top) and mean frequency of surface EMG on vastus lateralis during the time trial(bottom)

Fig. 18 System using hitoe™ for measuring surface myoelectric potential. After Ref. [33]

6 Summary

As a material for skin electrodes suitable for detecting our biological signals in everyday life, hitoe™ is expanding its applications not only in the medical field but also in the healthcare field, including sports, monitoring of workers, and rehabilitation recovery support. In addition to the material's features of good adhesion to the skin and the ability to obtain clean signals, we believe that new applications will expand in the future as data analysis technologies using transmitters, signal processing, and machine learning, as well as effective intervention methods using these technologies are developed.

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