1. Introduction

Due to aging population, the attention is focused on measurement of vital signs during daily life. Blood pressure (BP) is widely used as an index representing the state of the circulatory system. BP can be estimated from electrocardiogram (ECG) and photoplethysmogram (PPG). PPG can be obtained by a combination of a light emitting diode (LED) and a phototransistor (PT). The textile measured PPG has not been realized although there are fabric electrodes for measuring ECG. Therefore, we developed the pulse wave sensing textile for using underwear aiming to continuously BP estimation. By using conductive fibers woven into the textile as wiring, the pulse wave sensing textile is realized. In order to improve the stability of pulse wave measurement, LEDs and PTs were arranged in array on the textile. We showed that arranging LEDs and PTs in an array improve the stability of pulse detection and evaluated that the proposed sensing textile can be measured pulse wave on the wrist even if a person attached the proposed sensing textile is moving. These results suggest that the proposed sensing textile could be built into underwear and used as a part of BP estimation system. Unconscious continuous BP monitoring underwear could be realized by combining the proposed textile with fabric electrodes.

Abstract: This paper describes a pulse wave sensing textile to measure pulse wave continuously without stress. Due to aging population, the attention is focused on measurement of vital signs during daily life. Blood pressure (BP) is widely used as an index representing the state of the circulatory system. BP can be estimated from electrocardiogram (ECG) and photoplethysmogram (PPG). PPG can be obtained by a combination of a light emitting diode (LED) and a phototransistor (PT). The textile measured PPG has not been realized although there are fabric electrodes for measuring ECG. Therefore, we developed the pulse wave sensing textile for using underwear aiming to continuously BP estimation. By using conductive fibers woven into the textile as wiring, the pulse wave sensing textile is realized. In order to improve the stability of pulse wave measurement, LEDs and PTs were arranged in array on the textile. We designed the textile circuit under the consideration that circuit lines on the textile must be straight. We showed that arranging LEDs and PTs in an array improve the stability of pulse detection and evaluated that the proposed sensing textile can be measured pulse wave on the waist even if a person attached the proposed sensing textile is moving. These results suggest that the proposed sensing textile could be built into underwear and used as a part of BP estimation system. Unconscious continuous BP monitoring underwear could be realized by combining the proposed textile with fabric electrodes.

(Received 9 August, 2017; Accepted 13 October, 2017)
can be measured continuously and unconsciously without wearing extra device.

2. Principle of measuring PPG

Fig. 1 shows a diagram of the pulse wave propagation. A pressure wave generated by the contraction of heart ventricle propagates to the periphery along blood vessel. This pressure wave is called a pulse wave. Since blood vessels contracts and expands due to this pressure change, the blood volume changes with pressure change. The volume change measured using near-infrared light is called a photoplethysmogram[10‒11]. Since hemoglobin in the blood absorbs infrared light well, near-infrared light irradiated to the human body is absorbed depending on the blood volume of the artery, as shown in Fig. 2. Therefore, PPG can be obtained by irradiating infrared light from a light emitting diode (LED) and capturing light transmitted and scattered through the human tissue using a phototransistor (PT), as shown in Fig. 1.

3. Pulse wave sensing textile

As shown in Fig. 3, a common PPG sensor is consist of an LED, a PT, and measurement circuit. Since a common PPG sensor is inflexible, it is not suitable for use as a part of underwear. Therefore we propose the pulse wave sensing textile using conductive fibers. A plain weave, in which the warp and weft are aligned in a simple crisscross pattern, as shown in Fig. 4, is used for proposed sensing textile. In order to use as a wiring, conductive fibers are used for part of warp. If both warp and weft are made of conductive fibers, the textile cannot used as a circuit, because all wires are short-circuited. Since warp is used as wiring, the circuit pattern is necessary to be straight lines. Fig. 5 shows the wiring pattern of proposed sensing textile.

There is a problem in measuring PPG with underwear built the proposed sensing textile. In order to measure PPG stably, it is necessary for a combination of LED and PT to be stably in contact.
with the skin. Due to the elastic properties of the underwear, proposed textile is expected to basically contact with skin, but it is difficult to completely fix on the skin. Therefore, when a gap is generated between skin and either the LED or PT due to body motion or the like, PPG cannot be measured. To overcome this problem, by arranging LEDs and PTs in array, the stability of PPG measurement is improved. Consider the case where five LEDs and four PTs are arranged on textile in a $3 \times 3$ array, as shown in Fig. 6. Under this condition, each PT receive light from three adjacent LEDs. Therefore, even if one combination of LED and PT cannot measure PPG, other combinations can continue to measure PPG.

Based on the above, we fabricate a prototype pulse wave sensing textile. Five LEDs and four PTs were arranged in $3 \times 3$ array on textile, as shown in Fig. 6. Here, the reason for cutting a part of the conductive fiber is to simplify the structure of the
textile by using one fiber as two signal lines. Fig. 7 shows a wiring diagram for textile circuit. This wiring diagram is determined based on Fig. 6, taking into consideration of the limitation that circuit lines on the textile must be straight. The resistance value, related light intensity of LED and sensitivity of PT, is determined so that the PPG can be measured on measurement point. Fig. 8 shows a photo of the prototype pulse wave sensing textile. LEDs and PTs were disassembled from the reflection sensor (CNY 70, VISHAY). The wavelength of the light emitted by the LED is 950 nm. Each LED and PT was fixed to conductive fiber with a solder. The double covered yarn (Core: Polyacrylate fiber of 220 dtex and two tin plating copper wires of diameter 0.06 mm, Sheath: Tin plating copper wire of diameter 0.06 mm, Electric resistance: about 1.2 Ω / m) was used as conductive fiber. Fig. 9 shows this conductive fiber produced by entwining tin plating copper wire around a core bundled with polyacrylate fiber and two tin plating copper wires. In order to easily fix LEDs and PTs to textile with solder, the double covered yarn (Core: glass fiber of 225 dtex, Sheath: Polyester of 56 dtex / 24 f) was used as non-conductive fiber. Polyester can be used as non-conductive fiber if LEDs and PTs can be fixed by swaging. In order to enhance stable connection of electronic components with conductive fiber, two conductive fibers were used for one wiring.

4. Experiment

4.1 Experimental setup

To evaluate the proposed pulse wave sensing textile, we built a measurement circuit. The circuit is composed of an analog band-pass filter circuit (0.3 - 40 Hz) and an amplification circuit. The prototype textile was attached to participant’s left side of the waist, as shown in Fig. 10 (a). In addition, other combinations of LED and PT was held with the forefinger and the thumb of the participant’s right hand, as shown in Fig. 10 (c), and the pulse wave of the forefinger was measured during the experiment. This signal was used as a reference signal to evaluate signals from proposed textile. Output signals from each PTs be obtained by using A/D converter (USB-6008, National Instruments) and the PC. The resolution of A/D conversion was 12 bits and sampling frequency was 1 kHz. In order to verify the stability of the PPG measurement, PPG signals were measured with subjects in a stationary state and in a motion state. The participant was stepping on the spot at 1 second intervals (1 Hz) as a motion. The participant was one healthy adult man. The measurement time was 10 seconds. The same measurement was carried out 10 times in each state.

4.2 Results and discussion

Fig. 11 and Fig. 12 show the typical result of PPG

Fig. 8  Photo of the prototype textile PPG sensor.

Fig. 9  Conductive fiber produced by entwining tin plating copper wire around a core bundled with polyacrylate fiber and two tin plating copper wires.

Fig. 10  Experimental setup. (a) Photo of wearing prototype sensor. (b) Sensor arrangement. (c) LED and PT on finger used as reference signal.
signals from each PT measured in a stationary state and in a motion state. In Fig. 10 and Fig. 11, PT 1, PT 2, PT 3, and PT 4 correspond with PTs which position are showed in Fig. 10 (b). From Fig. 11, all PPG signals were measured stably in all channels in a stationary state. From Fig. 12, in contrast, PPG signals measured by the textile were unstable although PPG signal measured by the finger is stable. This is due to noise caused by the motion. However, it seems that PPG can be measured with anyone of PTs.

In order to evaluate whether the proposed sensing textile can be used for estimating BP instead of measuring with finger, pulse intervals calculated from PPG signals of waist and finger were compared. The measurement of the PPG at the finger was done by using a PPG sensor on the circuit board. Fig. 13 and Fig. 14 show the relationship between pulse time (foot to foot) of PPG measured by the proposed sensing textile and one by the finger in a stationary state and in a motion state, respectively. In these figures, the horizontal axis shows the pulse interval measured by the proposed sensing textile, and the vertical axis shows one by the finger. The straight lines are the regression lines, and regression equations are described in each figure. The coefficient of determination was 0.94 in a stationary state, and it
was 0.89 in a motion state. In order to verify the effectiveness of arraying, the acquisition rate was calculated. Fig. 15 shows the acquisition rate calculated as the ratio of the number of pulse time measured by proposed textile to that by the finger in a motion state. The acquisition rate was from 26% to 46% when one PT was used, while the rate calculated from four PTs was 87%.

The results of experiment suggest that PPG can be measured by the proposed sensing textile on the waist. It is necessary to extract the peak or foot of the pulse from PPG to estimate BP. From Fig. 11, it seems that the peak or foot of the pulse can be extract even from one signal in a stationary state. From Fig. 12, forcing on one signal of PTs on the textile, PPG cannot be measured sometimes in a motion state. It means that continuous measurement during daily life cannot be realized by using one PT. However, the foot of the pulse can be measured continuously by using four PTs on the textile, as shown in Fig. 15. In addition, Fig. 15 suggests that the arraying PTs clearly improve the acquisition rate. Furthermore, Fig. 13 and Fig. 14 suggest that the pulse time measured by the proposed sensing textile is almost equivalent to the one by the finger even if in a motion state. From these results, the proposed sensing textile could be used as fabric for underwear and as a part of BP estimation system. If it is possible to estimate BP with the underwear itself worn every day, it is unnecessary to attach and detach sensors. In addition, the textile circuit can be washed. However, since the prototype of sensing textile used solder to bond PTs and LEDs, it is considered that there is a problem in durability against washing. For practical use, further examination is needed to improve durability, for example by swaging PTs and LEDs. Unconscious continuous BP monitoring underwear could be realized by combining the proposed textile with fabric electrode.

5. Conclusion

In this paper, we proposed pulse wave sensing textile for using underwear to measure continuously without stress. We designed the textile circuit under the consideration that circuit lines on the textile must be straight and arranged LEDs and PTs in array for the stability of PPG measurement. We showed that arranging LEDs and PTs in an array improve for the stability. We evaluated that the proposed textile can be used instead of the measuring with fingertip for estimating BP even if a person is moving. In the future, we would like to evaluate the effect of individual variability and construct BP monitoring underwear system using pulse wave sensing textile.

References

1. S. Patel, H. Park, P. Bonato, L. Chan, and M. Rodgers, J. Neuroeng. Rehabil., 9(1), 21 (2012).
2. A. Pantelopoulos and N.G. Bourbakis, IEEE Trans. Syst. Man, Cybern. Part C, 40(1), 1–12 (2010).
3. C.T. Huang, C.L. Shen, C.F. Tang, and S.H. Chang, Sensors Actuators A Phys., 141(2), 396–403 (2008).
4. V. Chandrasekaran, R. Dantu, S. Jonnada, S. Thiyagaraja, and K. P. Subbu, IEEE Trans. Biomed. Eng., 60(4), 1080–1089 (2013).
5. Y. Asakura and Y. Sankai, Int. J. Pharma Med. Biol. Sci., 6(1), 1–6 (2017).
6. H. Gesche, D. Grosskurth, G. Küchler, and A. Patzak, Eur. J. Appl. Physiol., 112(1), 309–15 (2012).
7. S. S. Thomas, V. Nathan, C. Zong, K. Soundarapandian, X. Shi, and R. Jafari, IEEE J. Biomed. Heal. Informatics, 20(5), 1291–1300 (2016).
8. E. S. Winokur, D. Da He, and C. G. Sodini, Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. EMBS, 2724–2727 (2012).
9. J. Coosemans, B. Hermans, and R. Puers, Sensors Actuators A Phys., 130–131, 48–53 (2006).
10. Y. Mendelson and B. D. Ochs, IEEE Trans. Biomed. Eng., 35(10), 798–805 (1988).
11. J. Allen, Physiol. Meas., 28(3), R1–R39 (2007).