1. Introduction

Increasing medical expenses and shortage of medical staff due to the onset of an aging society are a few of the most serious problems in the present age [1]. Current medical treatment involves consulting a doctor after a patient remembers subjective symptoms. However, frequently, diseases have already progressed during this period. Even though there are periodic health examinations, they are performed every few years, and this is presently insufficient for the early detection of illnesses. “Home health care” and “preventive medicine” are important for solving this problem.

In other words, it is ideal to constantly monitor human body signals to detect diseases early and to detect abnormalities in the body before subjective symptoms appear. It is important that continuous monitoring of human body signals is safe, accurate, inexpensive, and stress free. To make this possible, the development of smart textiles that incorporate a human body signal detection function in garments that people wear regularly has been widely investigated [2‒5]. Krehel et al. attached a cloth belt sewn with an optical fiber to the body and monitored respiration. Witt et al. reported breath measurements using a belt sewn on a fiber Bragg grating (FBG) sensor. Takagahara et al. developed a conductive fiber composite material using a conductive polymer (PEDOT-PSS), and a T-shirt wearable vital sign sensor (hitoe) is already available for purchase.

As an optical fiber type sensor has a fiber or yarn shape, it is easily adapted to the process of existing textile products [6‒8]. Conventionally, an optical fiber sensor is sewn onto a fabric by hand or by pressing it with a belt. Authors have devised a method of embedding optical fibers into fabrics during textile manufacturing processes using the characteristics of the fiber or yarn shape of optical fibers [9‒11]. Furthermore, our research group was able to detect pulse waves, which are one of the biological signals, using an FBG sensor, which is an optical fiber type sensor has a fiber or yarn shape, it is easily adapted to the process of existing textile products [6‒8]. Conventionally, an optical fiber sensor is sewn onto a fabric by hand or by pressing it with a belt. Authors have devised a method of embedding optical fibers into fabrics during textile manufacturing processes using the characteristics of the fiber or yarn shape of optical fibers [9‒11]. Furthermore, our research group was able to detect pulse waves, which are one of the biological signals, using an FBG sensor, which is an optical fiber type

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sensor. In addition, we reported various vital signs measured from the pulse waves [12-16]. However, the method of covering the optical fiber and the fabric of the wristband have not been verified yet. When the optical fiber is covered with a thick fiber, the frictional force with the fabric increases and it is easy to embed the fiber into the fabric. However, as a thick fiber is inserted between the pulsation point of the wrist and the FBG sensor, it is predicted that the S/N ratio of the pulse wave signal will decrease. Therefore, in this study, we attempt to verify the structure of the covered FBG sensor and the S/N ratio of the measured signal and calculate vital signs from the pulse wave signal. In addition, for the smart textile, the method of embedding the covered FBG sensor into the knitted fabric and the relation between the clothing pressure from the knitted fabric and the measurement signal are verified.

2. Experimental design

2.1 FBG sensor system and optical fiber covering method.

The FBG sensor system is an optical fiber type high sensitivity strain sensor. It has been applied in monitoring infrastructure state variables [17-22]. This system consists of an interrogator (Nagano Keiki co. Ltd., PF 25-S 01) that includes a light source and a detector and an optical fiber that includes a distortion sensor part (Fig. 1). An amplified spontaneous emission (ASE) light source that emits near-infrared light at a wavelength of 1525 to 1575 nm is used as the light source. Broadband near-infrared light from the light source is inserted into the optical fiber. In the sensor part of the optical fiber, a diffraction grating whose refractive index changes periodically is formed in a part of the core, and only a specific wavelength is reflected by this diffraction grating interval. When strain is applied to this part, the wavelength of reflected light shifts, and strain is measured from this shift length [15, 23-25]. A signal synchronized with the pulsation of the artery is detected by attaching the sensor part to the pulsation point on the surface of the human body.

In a previous study, the sensor part was attached to the pulsation point using medical tape [12-16]. For this system to be used as a smart textile, it is desirable to install it as a textile product. However, as the surface of the optical fiber is coated with plastic, it is considerably thinner than the thread used for ordinary textile and lacks flexibility and friction. As a result, the fiber falls off when it is introduced into the knitted fabric. In a previous study, an FBG sensor was introduced into knitted fabric by providing friction by covering the FBG sensor [9-11]. In this study, vital signs are measured using a covered FBG sensor. A 16 round braiding machine (Kokubun Limited, 101-C) is used for covering the sensor. In this braiding machine, each eight carriers is used clockwise rotation and counterclockwise rotation. The optical fiber is covered like a braid by silk yarns. In this covering method, the optical fiber is wound around the silk thread, and which is not exposed to the outside [10]. Silk filament yarn is used as the covered yarn. Silk yarn is excellent in biocompatibility as used for underwear. The thickness of covered yarn is not constant, because the fluff occurs in spun yarn. In addition, if fluff is caught, the covered yarn comes off and the optical fiber may be exposed. For the above reasons silk yarn is selected. Optical fibers are used for the core, and silk yarns (14 × 2 tex) are used as the covering yarn. The number of teeth of the change gear in the braiding machine is 90 in the upper row and 20 in the lower row, and the winding pitch is 2.5 mm.

2.2 Vital sign measurement with covered FBG sensor.

The S/N ratio of the pulse wave signal measured using the covered FBG sensor is verified. The pulse wave signals measured by the covered and non-covered FBG sensors are compared. The subject is a male in his 20's, and the measurement posture is the supine position. As shown in Fig. 2, the covered FBG sensor is attached to the right wrist using medical tape, and the pulse wave signal is measured. Reference blood pressure is simultaneously measured.
using a cuff type electronic blood pressure monitor (Nihon koden co. Ltd., PVM-2701) on the upper left arm \[15‒16\]. The pulse wave signal and reference blood pressure are measured 100 times under these conditions. In addition, they are measured under the same condition using a non-covered FBG sensor.

The measured pulse wave signal is subjected to bandpass filter processing from 0.5 to 5 Hz (bandpass processing signal) and first differentiation processing. The pulse wave signal is divided for each peak. They are superimposed and averaged to obtain 1 pulse waveform per measurement (approximately 20 seconds). For the wavelength shift on the vertical axis, the first point is set to 1 and the minimum value is set to 0. Furthermore, the measurement time on the horizontal axis is unified with the pulse wave signal with the shortest measurement time per pulse. A calibration curve for blood pressure calculation is constructed through partial least squares regression (PLSR) analysis with 80 data for the signal processing pulse wave as explanatory variables and reference blood pressure as an objective variable \[26‒29\]. The remaining 20 data are assigned to the calibration curve, and blood pressure is calculated. The influence of covering is verified from the measurement error in calculated blood pressure (standard error prediction, SEP).

2.3 Clothing pressure measurement using the tubular knitted fabric.

A tubular knitted fabric, which was similar to a wristband, was fabricated as a textile product in which the FBG sensor was embedded. Elastic polyurethane/nylon double covered yarn (840 d/110 d) was used as the material of the knitted fabric. A manual punch card type knitting machine (Kashiwazaki U.S. Tech Ltd., SK 280) with a standard rib knitter (SRP 60 N) for the tubular knitted fabric was used. The knitting density of the produced fabric was 25 wales/inch and 13 courses/inch.

To verify the appropriate tubular knitted fabric size, the knitted fabric was produced through trial by changing the number of wales to 80, 90, 100, and 110, and clothing pressure was measured while the fabric was worn. The wrist girth of the subject was 160 mm. Therefore, the ratio of the girth of the tubular knitted fabric to the girth of the wrist corresponded to 51, 57, 64, and 70%, respectively. A contact pressure measuring device (AMI Tech Ltd., AMI 3037-10-II) was used for measuring clothing pressure. The diameter of the air pack of the pressure sensor was 20 mm. As shown in Fig. 3 (a), the air pack is installed on the wrist and covered externally with the tubular knitted fabric, and clothing pressure is measured. In this state, the air pack and the covered FBG sensor are exchanged (Fig. 3 (b)) and the pulse wave signal is measured. The number of measurements is 5 times for each number of wales. From the measured clothing pressure, it is verified that the dimension of the tubular knitted fabric is favorable for the detection of the pulse wave signal.

2.4 Pulse wave measurement using the covered FBG sensor embedded into knitted fabric.

The thread knitting method was used for the covered FBG sensor embedded into the tubular knitted fabric. Thread knitting is also referred to as inlay knitting, and it is a technique of horizontally inserting a thread that is different from the knitted fabric in the course direction of the knitted fabric. Thread knitting cannot be performed using the punch card type knitting machine with a standard rib knitter. However, thread knitting can be performed using the following method: First, the tubular knitted
fabric is knitted up to the course where the covered FBG sensor is introduced. Next, the knitting needle is pulled out to the front. As shown in Fig. 4, in this needle operation, the covered FBG sensor is passed over the needle in the portion where the sensor is exposed on the surface of the knitted fabric. Similarly, the covered FBG sensor is passed under the needle in the portion where the sensor is exposed on the back side of the knitted fabric. Finally, when one course is knitted using the carriage of the knitting machine, the covered FBG sensor appears on the front and back of the knitted fabric through the specified needle operation. Thus, the covered FBG sensor is introduced into the knitted fabric as shown in Fig. 5.

The pattern of introduction of the covered FBG sensor into the knitted fabric can be set arbitrarily. Both ends of the knitted fabric were connected so that the diffraction grating part in the FBG sensor was on the inside of the knitted fabric. Two knitted fabrics with 90 and 100 wales, which provided good experimental results, are produced.

The covered FBG sensor embedded into knitted fabric is installed at the pulsation point of the right wrist. To verify the influence of the clothing pressure from the knitted fabric, as shown in Fig. 6, the covered FBG sensor is attached to the pulsation point of the left wrist with medical tape, and the pulse wave signals of both wrists are measured simultaneously.

3. Results and discussion

3.1 Vital sign measurement by covered FBG sensor.

The cross section of the covered FBG sensor fabricated by the braiding machine was observed with a scanning electron microscope (Keyence Corporation, VE 9800). A cross-sectional image of the covered FBG sensor is shown in Fig. 7. As seen in the figure, the optical fiber is covered with silk thread without being exposed to the outside. The diameter of the covered FBG sensor was measured at three arbitrary cross sections and averaged; it was approximately 550 μm. As the diameter of the optical fiber is approximately 250 μm, it is approximately twice as thick as the covered FBG sensor.

The bandpass processed pulse wave signals measured using the covered and non-covered FBG sensors are shown in Fig. 8. Pulse wave peaks with slight noise were confirmed in both signals. However, the numerical value of the wavelength displacement on the vertical axis slightly decreases for the covered FBG sensor. As silk thread was inserted between the surface of the skin and the covered FBG sensor, the measurement sensitivity of strain was reduced.

Next, blood pressure was calculated from these pulse wave signals. The data sets used for the calibration and verification of the calibration curve.
Table 1  Calibration and validation data set for blood pressure (BP) calculation.

|          | Non-covered FBG | Covered FBG |
|----------|-----------------|-------------|
|          | Cal. | Val. | Cal. | Val. |
| Number   | 80   | 20   | 80   | 20   |
| Max. BP [mmHg] | 136  | 135  | 135  | 139  |
| Min. BP [mmHg]  | 105  | 108  | 102  | 106  |
| Ave. BP [mmHg]  | 119.4| 123.6| 117.8| 119.2|

Table 2  Results of the calibration and validation of systolic blood pressure calculation.

|          | Calibration | Validation |
|----------|-------------|------------|
| Factor   | R           | Accuracy [mmHg] | SEP [mmHg] |
| Non-covered FBG | 4 | 0.88 | 3 | 2 |
| Covered FBG     | 4 | 0.73 | 5 | 6 |

3.2 Effect of clothing pressure on measured pulse wave signal.

The clothing pressure and the pulse wave signal with the covered FBG sensor were measured in the measurement state of Fig. 3. Table 3 and Fig. 10 show the number of wales of the covered FBG sensor introduced into the knitted fabric and the average clothing pressure when it is worn on the wrist. As the commercially available sphygmomanometer is 3-10 mmHg. Thus, blood pressure can be calculated using the FBG sensor covered with silk thread.
number of wales increases, the circumferential dimension of the knitted fabric becomes longer and relatively larger with respect to the circumferential length of the wrist; thus, clothing pressure decreases.

**Table 3** Clothing pressure in each sample.

| Number of wales | Ave. clothing pressure [kPa] | Standard dev. |
|-----------------|------------------------------|---------------|
| 80              | 1.01                         | 0.18          |
| 90              | 0.77                         | 0.20          |
| 100             | 0.44                         | 0.06          |
| 110             | 0.35                         | 0.13          |

![Figure 10](image1.png)

**Fig. 10** Clothing pressure for each number of wales.

The pulse wave signals measured using the covered FBG sensor introduced into the knitted fabric for different number of wales are shown in Fig. 11. From Fig. 11, the periodic pulse waveform corresponding to pulsation is measured. For 0.35 kPa clothing pressure (110 wales) (Fig. 11(d)), the peak of the detected signal is small. In particular the wavelength shift between peak and peak is nearly 0. A signal indicating the motion of the heart is included between these peaks, and this signal part is important for calculating blood pressure. Therefore, the pulse wave signal measured at 0.35 kPa clothing pressure cannot be accurately measured. A clothing pressure ranging from 0.44 to 1.01 kPa (100 to 80 wales) is advantageous for pulse wave detection. However, in the case of 1.01 kPa clothing pressure (80 wales), it was pointed out from the subject that he experienced great pressure while wearing the fabric. In future, it will be undesirable that users experience discomfort while using this sensor as a smart textile. Therefore, when introducing the covered FBG sensor into the knitted fabric through inlay knitting, the number of wales of the knitted fabric is set to 90 and 100.

### 3.3 Measurement of pulse wave signal using covered FBG sensor embedded into knitted fabric.

Fig. 12 shows the pulse wave signals measured using the covered FBG sensor and the pulse wave signals measured using the covered FBG sensor embedded into the knitted fabric for 90 and 100 wales. From Fig. 12, the peak of the periodic Bragg wavelength shift due to the pulse appears in all conditions.

In the pulse wave signals (Fig. 12 (b) and (d)) measured using only the covered FBG, the Bragg wavelength shift at the pulse peak is approximately 1 pm (0.5 pm to–0.5 pm). The noise of these pulse wave signals is higher than in the signals measured using the covered FBG sensor embedded into the knitted fabric. However, the periodic Bragg wavelength shift due to the pulse is more clearly detectable in the signals measured using the covered FBG sensor embedded into the knitted fabric.

![Figure 11](image2.png)

**Fig. 11** Pulse wave signals for each clothing pressure.
wave signals is small. The covered FBG is attached to the wrist with medical tape, and clothing pressure is approximately 0 kPa. In other words, there is absolutely no strain from the exterior of the FBG sensor, such as that from knitted fabric. Only the pulsation from the wrist is measured. Therefore, in the state of no disturbance force, a small pulse wave signal with slight noise is measured. In the pulse wave signal (Fig. 12 (a)) measured using the covered FBG sensor embedded into the fabric with 90 wales, the Bragg wavelength shift at the pulse peak is approximately 1.5 pm (1 pm to -0.5 pm). In addition, the Bragg wavelength shift of the pulse wave signal (Fig. 12 (c)) measured using the covered FBG sensor embedded into the knitted fabric with 100 wales is longer than the Bragg wavelength shift of the pulse wave signal (Fig. 12 (d)) of the covered FBG sensor. However, in the pulse wave signal measured using the covered FBG sensor embedded into the knitted fabric, noise appears between the pulse peaks. In particular, the noise of the pulse wave signal shown in Fig. 12 (c) is large.

Fig. 12 Pulse wave signals for covered FBG sensor embedded into knitted fabric and covered FBG sensor (90 and 100 wales).

In the covered FBG sensor embedded into the knitted fabric, clothing pressure is applied to the wrist by the knitted fabric. The measured pulse wave signal is strongly affected by this pressure. As shown in Table 3, the clothing pressures for 90 and 100 wales are 0.77 kPa and 0.44 kPa, respectively. Clothing pressure is the force applied by the knitted fabric toward the wrist, and it is in the direction opposite to the force applied on the FBG sensor from the pulsation point. That is, in the FBG sensor, as a relatively large force is applied to the sensor from the pulsation point, the peak of the pulse is large. On the contrary, because there is a force unrelated to the pulse wave by clothing pressure, this is detected as noise in the pulse wave signal. This tendency is the same as the result shown in Fig. 11, and it was found that clothing pressure strongly influences the S/N ratio of the pulse wave signal. Since peaks appear in these pulse wave signals, the pulse rate and respiration rate can be calculated from the pulse wave signal of this S/N ratio. However, since the S/N ratio is clearly lower than the pulse wave signal in Fig. 8, it would be difficult to compute blood pressure from the pulse wave signal in Fig. 12. Therefore, improvement of the S/N ratio of the pulse wave signal measured at the covered FBG sensor embedded into knitted fabric is a problem.

4. Conclusion

In this study, an FBG sensor was covered with silk yarn and blood pressure was calculated from the pulse wave signal measured using the covered FBG sensor. In addition, the covered FBG sensor was embedded into knitted fabric, and the relationship between clothing pressure and the S/N ratio of the pulse wave signal was verified. The findings obtained in this study are described below.

- The FBG sensor was covered with silk yarn through the braiding method, and it was confirmed
using cross-sectional images that the silk yarn was around the optical fiber.

- As the FBG sensor was covered with silk yarn, its measurement sensitivity was lower than that of the non-covered FBG sensor. As a result, the measurement accuracy of blood pressure was lower.
- When the covered FBG sensor introduced into the knitted fabric was installed on the wrist, clothing pressure decreased as the number of wales of the knitted fabric increased.
- The noise and peak signal of the pulse wave signal increased with clothing pressure.
- The S/N ratio of the pulse wave signal improved when the covered FBG sensor embedded into the knitted fabric was installed on the wrist, as compared to when only the covered FBG sensor was installed.

According to the abovementioned results, the covered FBG sensor embedded into the knitted fabric is effective for application to smart textiles. However, there are a few problems in the development of wearable vital sign sensors using the covered FBG sensor embedded into the knitted fabric.

The first problem is increasing the number of subjects. The S/N ratio improves as clothing pressure increases; however, when clothing pressure is extremely high, fitting feeling is bad. Therefore, clothing pressure should be optimum. On the other hand, the S/N ratio of the pulse wave signal is largely influenced by the in vivo structure from the blood vessel at the pulsation point to the sensor part on the body surface. In other words, individual differences such as the flexibility of the blood vessel of the subject, the subcutaneous fat tissue and the strength of the pulse rate are affected. In order to clarify the influence of this individual difference, the number of subjects must be increased. In this experiment, a clothing pressure of 0.77 kPa with 90 wales was optimal; however, the number of subjects was small. Increasing the number of subjects and verifying the optimum clothing pressure is a problem.

The second problem is the verification of the method used to cover the FBG sensor. In this study, 14 × 2 tex silk yarn was used. The measurement sensitivity of the pulse wave signal decreased when the FBG sensor was covered with silk yarn. If thinner filament yarns are used, it is predicted that the distance between the surface of the skin and the FBG sensor will reduce and measurement sensitivity will improve. Pulse wave signals should be verified using an FBG sensor covered with 14 tex single yarn silk or thinner silk yarns.

The third problem is the calculation of multiple vital signs from the pulse wave signal measured using the covered FBG sensor embedded into the knitted fabric. It has been reported that multiple vital signs can be calculated from a pulse wave signal measured by attaching a non-covered FBG sensor at a pulsation point with medical tape [12–16]. It should be verified whether this can be achieved using the covered FBG sensor embedded into the knitted fabric.

When these problems are solved, the FBG sensor can be used as a smart textile embedded into clothes. As a result, this measurement system can be used as a wearable vital sign sensor.

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