1. Introduction

The term "stress" was first used by Hans Selye in the 1930's Nature magazine [1]. In his paper, stress was defined as a functional change that occurs in the mind and body when an external stimulus is applied as a burden. There are two types of stress: "good stress," which provides positive motivation, and "bad stress," which causes illness. The term "stress" has negative connotations owing to the increasing sophistication of society and the increasing level of competition in everyday life. The causes of stress include strained interpersonal relationships in the workplace, deadlines, etc. The Ministry of Health, Labor, and Welfare reported that the number of workers that experience stress is increasing [2], and it has also become a leading cause of traffic accidents. Further, stress increases the likelihood of suffering autonomic imbalance and depression. To avoid such situations, it is necessary to constantly measure the degree of stress being experienced in order to determine the likelihood of illness in advance.

Several methods for measuring stress already exist, including the salivary cortisol and salivary amylase methods [3-5]. These methods measure substances secreted from the body because of stress. Although these methods are simple, their implementation is cumbersome when continuous measurements are required. In order to achieve continuous measurement, a wearable sensor that can be used in day-to-day life is desirable.

Conventional wearable pulse wave measurement methods include using a photoelectric pulse wave sensor, piezoelectric sensor, polyvinylidene fluoride (PVDF) film sensor, metal foil strain gauge, nanomaterial-based strain sensor. A fiber Bragg grating (FBG) sensor is an excellent potential candidate for wearable pulse wave measurement [6-10]. The FBG sensor system has the following advantages against the existing method:

Abstract: In this paper, we propose a physiological stress measurement method that uses a fiber Bragg grating (FBG) sensor. There are several points on the surface of the human body at which the pulse wave can be measured, and when an FBG sensor can be positioned at any of these points, to measure the pulse wave signal. When a person is under stress, their pulse rate increases and the peak interval in the measured pulse wave signal becomes shorter. This peak interval change can be measured using the FBG sensor and analyzed using a Poincaré plot; the stress load can then be detected based on the shift in the plot position. The points on the Poincaré plot shift toward the lower left direction because of the stress loading. Depending on the amount of applied stress, the length by which the plot shifts changes. When the proposed measurement method is used, it is possible to continuously monitor a subject for stress by simply installing the optical fiber at a pulsation point. When optical fibers are woven into textile products, it becomes possible to detect stress load by wearing a modified garment. Therefore, this measurement method can be applied as a wearable stress sensor in smart textiles.

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It is robust against humidity and water for pulse wave detection compared with photoelectric pulse wave sensors.

It is less susceptible to electromagnetic waves and external noise compared with the piezoelectric or PVDF film sensors [11‒12].

It has superior impedance matching with the body compared with metal foil strain gauges [13].

It is better in terms of the linearity of the sensor output compared with nanomaterial-based strain sensors [14‒15].

Since a FBG sensor is an optical fiber type, fusion with textiles products is easy (excellent wearable property).

A FBG sensor system is extremely safe for humans as current and light are not inserted into the body.

A clothes-type electrocardiographic waveform measurement system (hitoe® of NTT Co., Ltd; COCOMI® of Toyobo Co., Ltd., etc.) measures the change in the surface potential through electrodes that have high affinity with the skin; therefore, this system cannot measure pulse waves directly [16‒18].

The FBG sensor system can be used to measure various vital signs such as pulse rate, respiratory rate, and blood pressure. In our previous papers, we have already reported that these vital signs can be calculated using the same pulse wave signal [6‒10]; only analysis method is different. However, the stress detection method has not been verified with the FBG sensor system. If stress can be detected, it will be added to a multi-vital signs sensor as a calculable vital sign. Therefore, FBG sensor system can be used simultaneously with the multi-vital sensing, and this can enable accurate monitoring of the physical condition of humans. We plan to develop a multi-vital sign sensor using the FBG system.

In this paper, the details of the FBG sensor, pulse wave signal measurement, and the calculation method for measuring the stress load are described.

2. Experimental Design

2.1 Fiber Bragg grating sensor system

The optical fiber used in the FBG sensor is a single-mode fiber made of silica glass with a core diameter of 10 μm, clad diameter of 125 μm, and a total coated diameter with plastic resin of 250 μm. In the sensor, the high and low refractive index parts are alternately arranged in a constant period, and together, they function as a diffraction grating. Broadband near-infrared light is incident on the core of the optical fiber; however only near-infrared light of a specific wavelength is reflected by the period of the diffraction grating. The wavelength of the reflected near-infrared light is called the Bragg wavelength, and it is determined by the diffraction grating period.

When an external force is applied to the sensor, the diffraction grating period changes, which causes the Bragg wavelength to change. An FBG sensor measures the change in the Bragg wavelength, and the strain is calculated based on the Bragg wavelength shift. In our test, an FBG sensor system (PF-25, Nagano Keiki Co., Ltd. Fig. 1) was used; this system consists of an interrogator and an optical fiber. An amplified spontaneous emission (ASE) light source with a wavelength of 1525-1575 nm and an output power of 20 mW was used as the source. The sampling rate was 10 kHz, and the resolution of the Bragg wavelength shift was 0.1 pm.

![Fig. 1 FBG sensor system.](image-url)
was 200 kHz. Laser light passed through the onto the phase mask (Ibsen photonics A/S, pitch 1063.3 attenuation and collimator lens, and it was then irradiated nm) by a cylindrical lens with a focal length of 300 mm. The optical fiber, which was a single-mode fiber made of SiO2 glass, was mounted at a distance of ~400 μm from the phase mask. The light irradiation time was ~15 min.

When UV light was irradiated onto the optical fiber, the diffraction grating exhibited an optically induced refractive index change. One end of the optical fiber that was mounted in this fabrication system was connected to the circulator and then the ASE light source. A different optical fiber was used to connect the circulator to a spectrum analyzer. When the diffraction grating was fabricated appropriately, the spectrum analyzer could measure the Bragg reflected light intensity accurately.

2.3 Measurement of the pulse wave signal using the FBG sensor

The FBG sensor installed on the desk (no external strain) is used to measure the calibration signal. The FBG sensor was installed at the pulsation point on the subject’s wrist, and a fixed pressure was applied. The position where the pulse wave signal peak of the subject was the largest was identified, and the installation position of the FBG sensor was determined. As shown in Fig. 3, a medical tape that can ensure constant mounting pressure was used in order to make the output peak intensity of the FBG sensor constant for each experiment (~4 pm in the current experiment). This measurement signal is the shift length (change amount) of the Bragg wavelength when strain is applied from the state without strain. Therefore, in principle, the measurement signal obtained by the FBG sensor system is like the velocity pulse wave, which is the change in the amount of the volume pulse wave. In fact, the primary differential signal (velocity pulse wave) of the photoelectric pulse wave sensor and the measurement signal of the FBG sensor system are similar, and the respective differential signals (acceleration pulse wave).

The pulse wave signal and heart rate were measured simultaneously. Fig.3 shows the pulse wave signal with band pass filtering (0.5-5 Hz) processed to the signal measured with the FBG sensor. The interval between successive peaks in the pulse wave signal was calculated. The heartbeat was measured using an electrocardiogram (PVM-2701, Nihon Kohden Co., Ltd) while the subject was in the supine position. The subjects in this case were two men in their twenties. The relationship between the peak interval of the pulse wave signal as measured by the FBG sensor and independently based on the R-to-R interval (RRI) measured by the electrocardiogram were compared.

2.4 Stress loading methods and measurement pulse wave signal using the FBG sensor

As shown in Fig. 4, a monitor was placed in front
of the subject during the experiment, and the subject was seated. The FBG sensor was placed on the right wrist of the subject, and the reference pulse rate was simultaneously measured using an electronic sphygmomanometer placed on the left upper arm.

Two types of stress detection experiments were conducted. Experiment 1 consisted of placing the subject under stress for a long duration, and then measuring the stress load and pulse rate. A flash mental arithmetic test was used to stress the subject. In this test, a sequence of one-digit numbers are displayed on the monitor, each for a period of 1 s. The subjects were asked to calculate the displayed numbers, based on the operands provided. The need to perform mental arithmetic applies a stress load onto the subjects. The subjects were asked to rest for 6 min and then mentally compute the sums of the displayed numbers for 12 min. The subjects were then allowed to rest for 6 min. The pulse wave signals were measured by the FBG sensor for periods of 30 s at intervals of 90 s.

In Experimental 2, stress detection was performed by placing subjects under stress for a short duration. Stress was applied to the subjects by employing two tests: a flash mental arithmetic test and a color word test. In the color word test, Chinese characters in different colors were displayed on the monitor in a 5×5 matrix. The subjects were then asked to either "pronounce the Chinese characters" or "pronounce the color of the Chinese characters". Because the color and the Chinese characters were different, this applied a stress load onto the subjects. After resting for 3 min, the subjects were asked to perform the color word test for 1 min and the flash mental arithmetic test for 2 min. In the flash mental arithmetic test, five questions with single digit operands and two questions with two digit operands were posed to the subjects, and the stress loads were verified. During Experiment 2, measurements were carried out using the FBG sensor for 30 s periods at intervals of 30 s.

3. Results and discussion

3.1 Fabrication of the FBG sensor using the developed fabrication system

The fiber in the FBG sensor was fabricated in the diffraction grating manufacturing system developed as part of this research. The Bragg wavelength signal that was measured by the spectrum analyzer is shown in Fig. 5. The black line in the figure denotes the signal from the diffraction grating, and the peak is at 1539 nm. The pitch number of the phase mask is 1063.3 nm, and the refractive index of the core of the optical fiber is 1.45. Based on these conditions, it is reasonable that the Bragg wavelength appears at 1539 nm. This peak is the Bragg wavelength of the diffraction grating in the optical fiber fabricated using this system. This optical fiber was used for FBG sensing.

3.2 Calculation of the pulse rate from the pulse wave signal of the FBG sensor

The RRI signal is important because stress is detected using the Poincaré plot. Therefore, the pulse wave signal measured by the FBG sensor and the RRI must be verified. Fig. 6 shows the result of time fluctuation of PPI obtained from the FBG sensor measured simultaneously with RRI obtained from the
electrocardiogram. As can be seen from the figure, the RRI and PPI signals are very similar, and the PPI signal obtained from the FBG sensor is the same as that for the heartbeat.

Next, the pulse rate is calculated from the pulse wave signal measured by the FBG sensor. If the pulse rate is accurate, it means that the measured PPI is also accurate over a long duration. These experiment results are shown in Fig. 7. As can be seen from the figure, the pulse rate has a high correlation coefficient, and the measurement accuracy is ±2.4 bpm. Although the number of subjects was 34, the pulse rate was accurately calculated from the pulse wave signal using the FBG sensor without being affected by individual differences. Based on these results, the PPI was shown to be accurately measured by the FBG sensor.

3.3 Detection of stress loading by the FBG sensor in long duration (Result of Experiment 1).

Stress load can be detected using the accurate PPI signal measured by the FBG sensor. Fig. 8 shows the transitions in the reference pulse rate for every measurement carried out every 90 s. The pulse rate over 450-1080 s when under stress load increased further than when there was no stress load. The presence of a stress load can be detected based on the change in pulse rate.

Fig. 9 is the Poincaré plot calculated from the pulse wave signal of the FBG sensor at measurement points A-D in Fig. 8. Compared to the measurement points that were plotted before the stress load was applied, the plot points at measurement points B and C that were measured after the stress load was applied have shifted to the lower left. However, in the plot of measurement point D where the stress load is canceled, the plot shifts to the upper right. Fig. 10-A and 10-B show the results of the Poincare plot with and without stress. It is apparent that the plot shifted to the lower left when stress was applied.

Based on these results, it was possible to judge the presence or absence of a stress load based on our analysis using the Poincaré plot of the pulse wave signal measured with the FBG sensor.

3.4 Detection of stress loading by the FBG sensor in short duration (Result of Experiment 2).

Based on the results of Experiment 1, the stress
condition from the Poincaré plot of PPI detected by the FBG sensor can be confirmed. In Experiment 2, the stress load detection is verified in short duration. Fig. 11 shows the results of the short duration stress measurements in two subjects. When both subjects were stress loaded, the plot shifted to the lower left. Fig. 12 shows the median of each Poincaré plot. The results for both subjects shifted to the lower left during the color word test. Subject A who had a high correct answer rate for mental arithmetic shifted to less than that when at rest, and subject B, who has a low correct rate for mental arithmetic, was shifted farther than when at rest. In other words, subject A is in a relaxed state while performed the mental arithmetic test. Subject A had a high correct answer rate for mental arithmetic and subject B had a low correct rate for mental arithmetic. Therefore, it is presumed that subject A was soberly calculated mental arithmetic test, the shift length of plot position is short. As a result, it was possible to measure the presence or absence of a stress load with the FBG sensor.

4. Conclusion

In this paper, we attempted to detect physiological stress using an FBG sensor, which is a type of optical fiber strain sensor. The findings presented in this paper are listed below:

- In the development system, the diffraction grating of the FBG sensor was fabricated in the core of the optical fiber.
- The pulse rate was calculated based on the PPI of the pulse wave signal measured by the FBG sensor.
- When stress was applied, the FBG sensor could be used to detect if the pulse rate had increased.
- The presence or absence of a stress load could be
detected using the FBG sensor.

The above results indicate that the stress load can be detected using the FBG sensor. Therefore, a new sensor that can measure stress and blood pressure simultaneously using the FBG sensor system can be developed. The FBG sensor is flexible and thin, and the sensor part can be installed into textile products [19]. These textile products can be attached to sleeves; a wrist-band type sensor will be developed in the future.

The challenges in order to develop a multi-vital sign sensor based on an FBG sensor system are stated below:

- Miniaturize the size of the FBG interrogator to the extent that it fits into a pocket.
- Reinforce the FBG by covering with silk yarn, as it can break easily.
- Minimize power consumption as FBG is photoelectric.
- Eliminate the effects of noise due to body movement. For example, to use a FBG sensor that senses body movement separately from the FBG sensor for pulse wave measurement and to design a system that detects a pulse wave only when body movement is not detected or when the body is stationary.

Once these challenges have been overcome, then a wearable multi-vital sign sensor that detect pulse rate, respiratory rate, blood pressure and stress load based on an FBG sensor will be realized.

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