Wireless insole sensor system with real-time pressure and shear force measurement

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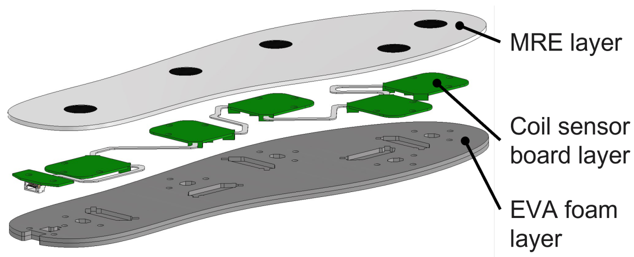
1 Introduction

In the field of sports and rehabilitation, analysis using the information on the tri-axis force applied to the sole (foot plantar force) is attracting attention [1, 2]. In particular, using a system that can measure foot plantar forces in real time will enable efficient training. By feeding back information from the foot plantar force with other senses, e.g., audition, the user can infer from the foot plantar force information what kind of movement the user is performing. Such feedback instruction could accelerate rehabilitation and sports training.

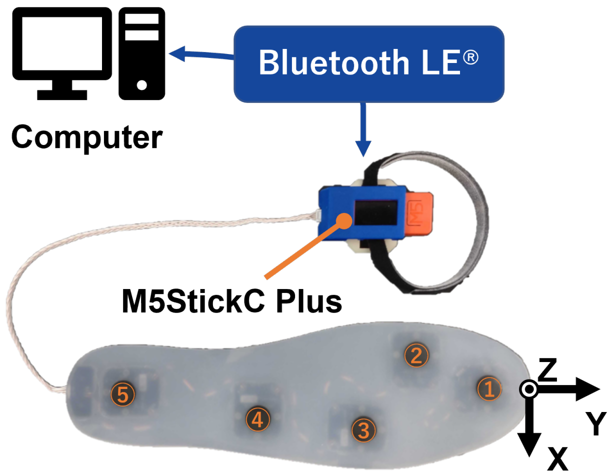
In feedback instruction, it is important to get real-time feedback without feeling any delay. The time that humans perceive a delay varies depending on their senses. For example, in the case of a gap between video and audio, if the delay of the audio signal is less than 70-100 ms, the user perceives the video and audio to be in sync [3]. In web page display, if a new web page is displayed within a few hundred milliseconds after clicking a link, the user perceives it to be real-time [3]. These are subjective real-time sensations, and the degree of delay that is appropriate for feedback instruction must be considered separately. However, in the case of auditory feedback, if feedback is provided within 70 to 100 ms, it may be considered to be real-time feedback. Moreover, for motions with an interval of several hundred milliseconds or more between each motion, feedback within several hundred milliseconds after the motion can be recognized as real-time feedback for the motion, and the user can make use of the feedback for the next motion.

By using a thin and robust tri-axial sensor [4, 5], it is possible to implement insoles that can measure pressure and shear forces on the sole independent of the measurement location. The insole sensor developed by Wang *et al.* is equipped with many of these sensors and can measure tri-axis forces on the sole [6]. However, the number of sensors built into the insoles is so large that it is difficult to transfer data wirelessly in real-time, and the system is used only as a logger.

In this study, we developed an insole sensor system that can acquire pressure and shear force in real-time by using five flexible magnetic tri-axial force sensors with MRE (Figure 1). This paper presents the performance of the insole sensor system. We measured the delay between the time the sensor senses a change in the situation and the time the PC receives the data. We found that the delay time due to the rate of the radio and the system is an average of about 130 ms with a standard deviation of about 17 ms.



(a) Structure of Insole sensor.



(b) Insole sensor wireless communication system.

Figure 1: Proposed insole sensor system.

2 Insole sensor system

Figure 1a shows the structure of the developed insole sensor, and Figure 1b shows the wireless communication system of the sensor. The length of the insole is 275 mm and its thickness is approximately 8 mm. The insole consists of three layers: 4mm-thick EVA foam, a sensor circuit board, and a 4mm-thick silicone rubber sheet (Ecoflex 00-30; Smooth-on, Inc.), which are bonded in this order. A disk-shaped MRE (15 mm in diameter, 2 mm thick, and 2 mm away from the circuit board) containing iron particles at a volume ratio of 20 percent is placed directly above the sensor circuit board. The placement of the circuit board is determined to follow the COP trajectory during walking [7]. The position of each sensor board is (x, y) = (0,-24), (-20,-66), (24,-98), (18,160), (-3,-240) (unit: mm) from the origin coordinates of Figure 1b, in the order of sensor 1 to 5. The sensor data of each board is measured by a microcontroller (M5StickC Plus; M5Stack Technology Co., Ltd.) with a built-in lithium polymer battery. The measured data are sent to the PC via BLE(Bluetooth Low Energy®). The data transmitted by BLE includes the inductance value of the coil of each sensor and the timestamp (in ms) since the program of the microcontroller was activated. We can obtain the pressure and shear force by simple data processing [4] on the PC that receives the data. We processed the data received by the PC with a Python program.

3 Sensor validation

The performance of the insole sensor system was measured in terms of sensing time interval and system delay time. The sensing time interval was investigated based on each internal timestamp, which is stored in the data sent from the microcontroller by BLE. As for the delay time of the system, we investigated the delay time between when the sensor senses a change in the environment and when it is displayed on the PC. The delay time was measured by capturing the movement of the magnetic object and the change in the value of the data displayed on the PC when the position of the magnetic object placed above the sensor was changed, using two high-speed cameras (HAS-L1; DITECT Co., Ltd.) synchronized. The delay time can be calculated by acquiring the frame at the moment the coin begins to move and the frame at the moment the value on the display begins to change. We conducted a total of 12 measurements and took videos at 1500 fps.

The results are shown in Table 1. The sensing time interval of the insole developed in this study averaged about 23 ms with a standard deviation of about 4.7 ms, and the delay time averaged about 130 ms with a standard deviation of about 17 ms. In the insole of this study, we used the microcontroller to limit its performance so that data could be acquired at the highest period. Therefore, there is a variance in the sensing time interval. To keep the interval constant, we need to use a more powerful microcontroller and improve the program, but we anticipate that these measures will have a trade-off with increased power consumption. With this delay time, it is possible to use this insole sensor system for feedback to senses with a relatively large time resolution. In human hearing, for example, it is known that a telephone conversation is perceived to be real-time when an audio signal is received within 70 - 100 ms [3]. Compared to this finding, the delay time of this insole sensor may cause discomfort to the user, but it is considered to be practicable for low-cycle motion where the delay is acceptable. The delay may be an obstacle for real-time motion feedback in high-period motion such as running but may be able to be used to provide auditory feedback in low-frequency motion such as walking.

	Average [ms]	Standard Deviation [ms]
Data interval	23.06	4.685
Delay time	128.3	17.33

Table 1: Average and standard deviation of data collection interval and delay time.

The current delay time and sensing period may not be practical for implementing force-based posture control and reflex control in robots. To reduce the delay time and sensing period, it is necessary to review the profile used in Bluetooth or the communication method. On the other hand, if the system is used as a teleoperated controller where a certain amount of delay is tolerated, it may be feasible even with the current delay time.

4 Conclusion

In this study, we developed and evaluated the performance of an insole sensor system that can measure pressure and shear force on the sole and acquire data in real-time. The average sensing time interval of the insole developed in this study was about 23 ms with a standard deviation of about 4.7 ms, and the average delay time was about 130 ms with a standard deviation of about 17 ms. We consider that the sensing time interval was sufficient for human motion measurement. The delay time of the sensing was confirmed to have the potential to be used for feedback in which a slight delay can be acceptable, for example, feedback of walking by sounds.

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