Design of Multi-channel Sensor System for Sitting Posture Analysis

Jiaming Chen

School of Automation Science and Engineering, Faculty of Electronic and Information Engineering, Xi'an Jiaotong University, Xi'an, China.

jiamingchentianjin@stu.xjtu.edu.cn

Abstract. At present, more people need to sit for a long time in daily life. However, bad sitting habits will undercut work efficiency and pose a threat to health. A sitting posture recognition system can help people maintain a correct sitting posture and reduce fatigue. In this paper, an office chair based on the Ardunio development board is designed and implemented with multi-channel sensors, using force sensors (MD 30-60, RP-L-110) as well as gyroscope sensors (MPU6050) mounted on the chair for sitting posture analysis. Then, Ardunio realizes the collection of sensor data and the data transmission with the host computer. Finally, through the experimental data analysis, seven postures of sitting upright, forward leaning, backward leaning, left leaning, right leg cross sitting and left leg cross sitting are investigated, with the results visually analyzed. The system proposed in this study has potential application prospects in health monitoring and disease prevention.

Keywords: Multi-modal Sensor System, Sitting Posture Analysis, Rehabilitation Medicine.

1. Introduction

In modern society, the rapid development of office automation and information technology has triggered the common phenomenon of sitting for a long time. With the changes in people's work and lifestyle, static sitting for a long time has been integral to daily life. However, this long-term sitting habit can significantly reduce work productivity and seriously harm human health. Health problems such as cervical spondylosis, lumbar disc herniation, stiff shoulders, and vision loss are common consequences of long-term poor sitting posture. A good sitting posture can not only improve work efficiency, but also promote work comfort and reduce physical discomfort. Thus, maintaining healthy sitting habits is an important issue. To help people maintain correct sitting posture, the technology of sitting posture analysis has received widespread attention in recent years. By monitoring and analyzing sitting posture data in real-time, the sitting posture analysis system can correct bad sitting posture [1] and provide targeted improvement suggestions.

Since 2013, Leonardo Martins et al. [2] have collected 11 standard formal pressure maps, performed automatic pose classification through neural networks, and exported them into mobile applications. The final real-time classification rate was about 70%, but when the gesture recognition was reduced to 8 postures, the total classification rate increased to 93.4%. In 2016, Sangyong Ma et al. [3] utilized a 3-axis accelerometer for sitting posture classification, and used support vector machine (SVM) and K-Means clustering for sitting posture classification of the transformed feature vectors. As a result, the overall correct rates were 95.33% and 89.35% respectively, which concluded that SVM has more advantages over K-Means in sitting posture classification. In 2019, Emmanouil Fragkiadakis et al. [4] used 13 piezoresistive sensors to obtain sitting pressure distributions to distinguish 5 sitting postures. Finally, the body postures of 12 people with various body mass indexes were evaluated, with an average discrimination accuracy of more than 98%. In the same year, Teruhiro MIZUMOTO et al. [5] installed eight accelerometers on the back of the chair fabric, using three sitting posture recognition algorithms by considering the initial position of the chair and the difference in the reminder of the tester, with an experimental sample of 28 participants. The recognition rates turned out to be 75.4%, 83.7% and 85.6% respectively. In 2021, Miaoyu Li et al. [6] identified 5 habitual sitting postures through the wireless-based non-contact sitting posture recognition system named "Sitsen" using only radio frequency signals, neither revealing privacy nor various specific sensors. The average accuracy rate reached 97.02%. In 2023, Ming-Chih Tsai et al.

[7] developed a sitting posture recognition system named “SPRS”, which identified the key areas on the chair surface that can capture the basic characteristics of sitting posture, and adopted a variety of machine learning techniques to identify 10 common sitting postures. Twenty volunteers performed sitting posture recognition for 10 minutes, with the final accuracy rate of identifying sitting posture as high as 99.1%.

In the existing research on sitting posture recognition systems, the common problems include the unity of sensors and the lack of data, which significantly affect the perception accuracy of the sitting posture analysis system. Meanwhile, the existing system lacks real-time monitoring pictures, and cannot provide detailed information and feedback on users’ sitting postures in time. To overcome these challenges, this paper proposes a sitting posture analysis system based on Arduino’s multi-channel force sensor and gyroscope sensor [8], which aims to improve the accuracy and real-time performance of sitting posture analysis and provide scientific basis and practical tools for improving sitting posture habits in a modern office environment. Multi-channel force sensors enable accurate measurement of pressure distribution on the cushion and backrest. Gyroscope sensors can provide data on human posture angle and inclination [9]. The combination of these two sensors enables the system to capture sitting posture status from multiple angles, analyze sitting posture data in real-time, and classify specific types of bad sitting postures. The design of the system includes four main links: sensor construction and debugging, data acquisition, data processing and sitting posture analysis. The sensor data is processed by the built-in circuit and converted into pressure information related to the sitting posture. Besides, LED light displays corresponding to the sitting posture state are generated. The brightness of these lights represents the data measured by the pressure sensor. Based on these data, personalized sitting posture correction suggestions can be provided [10], such as adjusting chair height, changing sitting angle, etc., so as to help users improve their sitting habits.

2. Design of Sitting Posture Analysis System

2.1 Hardware Selection and Design

In this design, Arduino Mega 2560 is selected as the microcontroller board (in Figure 1) with ATmega2560 as the model number and 101.6 mm x 53.3 mm as the size. In this controller, ATmega16U2 serves as the main control chip. With 54 digital input/output pins (15 of which can be used as PWM outputs), 16 analog inputs, 4 UART (hardware serial ports), one 16 MHz crystal oscillator, one USB connection, one power jack, one ICSP header and one reset button, it is suitable for handling complex control tasks and a large number of sensor inputs. In addition, the controller is powered by a USB and AC-DC adapter. The biggest difference from Ardunio’s previous series of boards is that it uses ATmega16U2 programming as the USB-to-serial transmitter, instead of the FTDI USB-to-serial driver chip. In this study, the serial port is used to connect to the upper computer, and program burning and data transmission are carried out. The gyroscope and pressure sensor are connected to the analog input pins of the Ardunio development board, and the LED is connected to the digital output pins of the Ardunio development board, all of which are connected using DuPont wires.

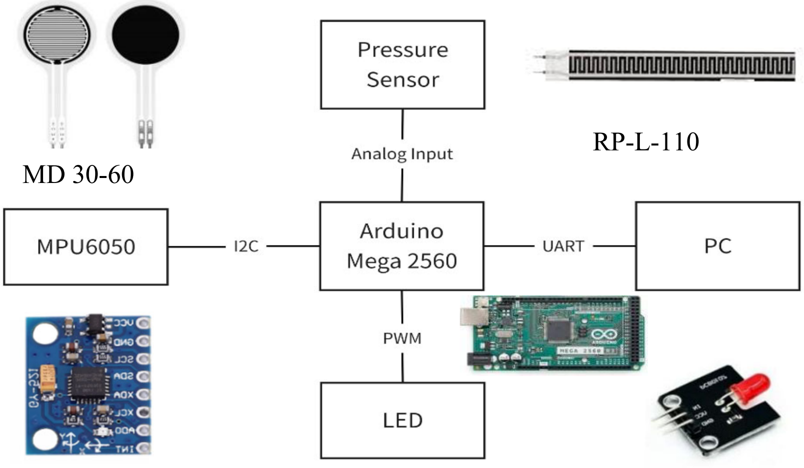


Figure 1. Control Block Diagram of Sitting Posture Recognition System

The model of the circular membrane pressure sensor used in this study is MD 30-60 (as shown in Figure 1), with a sensor range of 150 g-20 kg, a sensor diameter of 30 mm, and a sensing area diameter of 23 mm. The sensor response time is less than 1 ms, the response point is less than 200 g, and the recovery time is less than 15 ms. The model of the long strip membrane pressure sensor is RP-L-110, with a length of 110 mm, a width of 15 mm and a thickness of 0.4 mm (in Figure 1). The pressure sensing range is 20 g~10 kg, the response time is less than 10ms, and the trigger force is less than 20 g. They have the advantages of fast response speed, high sensitivity and wide detection range. As a 6-axis attitude sensor (3-axis accelerometer and 3-axis gyroscope sensor), MPU6050 can measure the acceleration and angle parameters of the X, Y, and Z axes of the chip itself. Through data fusion, the attitude angle can be obtained (in Figure 1). The sensor has a 16-bit ADC with a quantization range of -32768~32767. Meanwhile, the accelerometer has multiple full-scale range choices: ±2, ±4, ±8, ±16 (g). As for the gyroscope full-scale choices, there are ±250, ±500, ±1000, and ±2000 (°/sec). The LED lamp is a 5 mm red LED light-emitting module with an operating voltage of 3.3 V-5 V and an input digital level in Figure 1.

2.2 Software Design

The program is burned into the flash memory of the development board, and the original STK500 communication protocol is used to communicate with the computer. In addition, the Arduino ISP programmer can be used to bypass the bootloader and the ICSP (In-Circuit Serial Programming) interface can be used to directly program.

In the program initialization stage, the researcher used the Arduino Mega2560 development board for this research and programmed in the Arduino IDE environment. First, the bootloader booters set the baud rate to 115200 to ensure that they can stably receive the data sent by the Arduino development board. The Arduino development board control block diagram is shown in Figure 7. The connection port number of each sensor and LED lamp is defined in the program to ensure the correct identification and initialization of the sensor. To reduce measurement errors, especially during the initialization of pressure sensors and gyroscope sensors, necessary calibration operations were implemented, with the procedure flow chart shown in Figure 2.

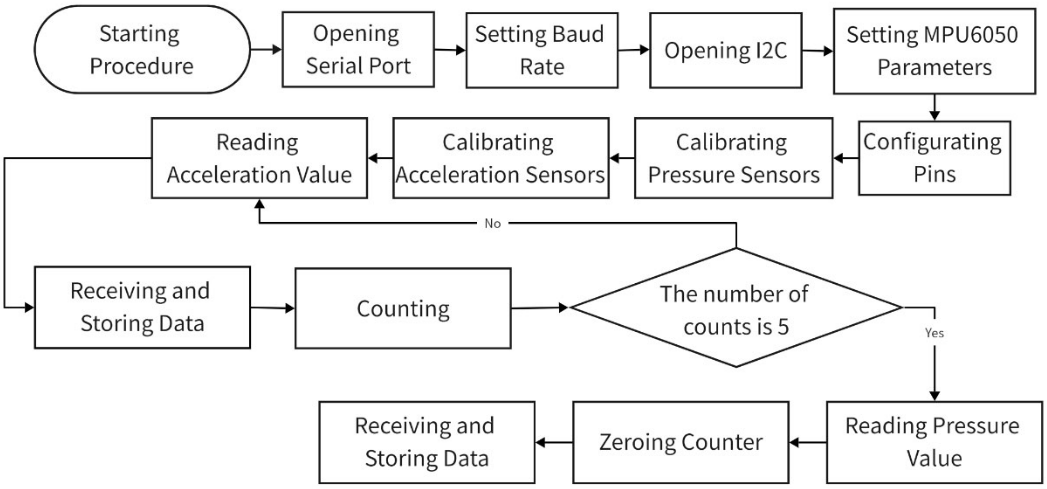


Figure 2. Procedure Flow Chart

2.2.1 Pressure Sensor Calibration

In order to accurately read the value of the pressure sensor, the sensor was calibrated. During the experiment, a weight of known mass was pressed against a pressure sensor to read the corresponding AD value and record the data. From these data, the relationship between pressure values and AD values was constructed.

The specific calibration process is as follows. First, take the 1/AD value as the X-axis and the mass M of the weight as the Y-axis before drawing a scatter plot and adding a trend line. Polynomial fitting is selected and the trend line formula and R-squared values (R^2) are displayed. R^2 indicates the fitting degree of the regression model. When it is close to 1, the fitting effect of the regression model is better and the data correlation is strong. If it is close to 0, the correlation between the data is weak or there is almost no correlation. In this study, the regression model of $R^2 \geq 0.95$ is considered valid. Through this fitting function, the mathematical relationship between 1/AD and mass M can be achieved. By applying this conversion function to the program, the accurate pressure value can be finally calculated according to AD collected by Arduino.

2.2.2 Gyroscope Sensor Calibration

For the gyroscope sensor (MPU6050), the static calibration was used for calibration. First of all, place the sensor on a horizontal plane, so that its X and Y axes are parallel to the horizontal plane and its Z axis is perpendicular to the horizontal plane. At rest, the output （a_x, a_y, a_z）of the accelerometer is read. In an ideal case, the acceleration output of the X and Y axes should be 0, and the output of the Z axis should be the acceleration of gravity g. However, due to the zero bias error and proportional error of the sensor, the actual output will deviate from the ideal value.

To eliminate these errors, the zero offset error of each axis was calculated by averaging multiple measurements, with the calculation formula of zero bias error as follows:

$$Offset_{a_x} = \frac{1}{N}\sum_{i=1}^{N} a_{x_i} \tag{1}$$

$$Offset_{a_y} = \frac{1}{N}\sum_{i=1}^{N} a_{y_i} \tag{2}$$

$$Offset_{a_z} = \frac{1}{N}\sum_{i=1}^{N} a_{z_i} - g \tag{3}$$

Where N is the number of measurements and $a_{x_i}, a_{y_i}, a_{z_i}$ is the accelerometer output of the i-th measurement.

Next, a scale factor correction was performed to eliminate the sensitivity error of the sensor. By rotating the sensor to different postures and using the gravitational acceleration as a reference, the scale factor of each axis is calculated. The formula for calculating the scaling factor is:

$$Scale_{a_x} = \frac{g}{max(a_x) - min(a_x)} \tag{4}$$

$$Scale_{a_y} = \frac{g}{max(a_y) - min(a_y)} \tag{5}$$

$$Scale_{a_z} = \frac{g}{max(a_z) - min(a_z)} \tag{6}$$

Where$max(a_x)$ and $min(a_x)$are the maximum and minimum output of the X axis respectively. Through these scaling factors, the calibration model of the accelerometer with the following formula was derived:

$$a_{x_{calibrated}} = Scale_{a_x} \cdot \left(a_{x_{raw}} - Offset_{a_x}\right) \tag{7}$$

$$a_{y_{calibrated}} = Scale_{a_y} \cdot \left(a_{y_{raw}} - Offset_{a_y}\right) \tag{8}$$

$$a_{z_{calibrated}} = Scale_{a_z} \cdot \left(a_{z_{raw}} - Offset_{a_z}\right) \tag{9}$$

Where $a_{x_{raw}}, a_{y_{raw}}, a_{z_{raw}}$ is the original measured value and $a_{x_{calibrated}}, a_{y_{calibrated}}, a_{z_{calibrated}}$ is the output after calibration.

2.2.3 Data Acquisition and Processing

After completing the sensor calibration, this study measures the acceleration and direction data obtained by MPU6050 during the sitting process of the tester, and the pressure measured by the pressure sensors at various positions to judge the sitting posture of the tester in real-time. According to the data collected by each sensor, it is converted into a PWM wave signal, and the brightness change of the LED lamp reflects the pressure intensity of the corresponding sensor.

In addition, the Data Streamer function in Microsoft Excel was used to transmit real-time pressure and gyro data to the computer through the serial port and store it. These data will be used to plot pressure versus acceleration, thus further analyzing the relationship between changes in sitting posture and pressure distribution.

Because the acceleration changes faster than the pressure, different sampling rates are adopted for acceleration and pressure in this study. The sampling rate of acceleration value designed by the program is 20 Hz, and the sampling rate of pressure value is 4 Hz. Every time the acceleration value is read and stored in the program, it is counted. When the count value is 5, it is cleared and the pressure value is read once. However, since it takes a certain time to transmit data from Arduino to the computer through the serial port, the actual sampling rate is slightly lower than the design sampling rate. The actual sampling rate of the calculated pressure value is about 2.2 Hz, and the sampling rate of the acceleration value is about 11 Hz.

2.2.4 LED Display

In this study, LED brightness aims to display the pressure value of each pressure sensor in real-time. First, the measurement data of the pressure sensor is read and compared to the maximum measurement value of the sensor. Subsequently, the pressure value is mapped to a range of 0 to 255 by proportional conversion, and output as a PWM (pulse width modulation) wave. Finally, the signal is input to the 5mm red LED module on the breadboard, and the pressure value of the corresponding sensor is visually presented through the change of LED brightness, thereby realizing the visual display of pressure information.

3. Experimental Platform and Test

In this study, seven postures of sitting upright, leaning forward, leaning backward, leaning left, leaning right, crossing right leg and crossing left leg were analyzed. Pressure sensors and acceleration sensors on chairs were used for measurement, and the data changes of testers from sitting down to standing were recorded to observe differences in various sitting postures.

3.1 Scene Settings

In this study, six membrane pressure sensors (four MD30-60 and two RP-L-110) were arranged on the chair, of which MD30-60 was arranged at the bottom of the chair to measure the pressure state of the tester’s legs when he was seated. It was arranged in four positions: left front, left back, right front and right back, so as to better measure the pressure changes of the tester in different sitting postures. RP-L-110 is arranged on the back of the seat and aims to measure the pressure state of the tester’s back. Two sensors are placed parallel, one left and one right, to measure the pressure data changes on the left and right sides. Both the MPU6050 and Arduino are fixed to the back of the chair (Figure 3 (a)).

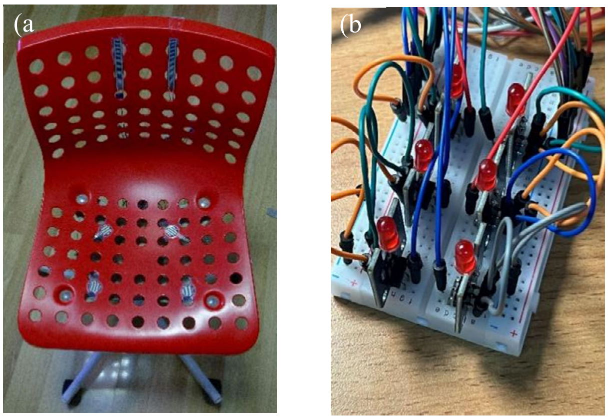


Figure. 3 System Construction Diagram. (a) Physical Drawing of the Chair. (b) LED Arrangement.

Because the thin film pressure sensor is made of flexible material and can be well fitted to the chair, the pressure sensor can be fixed on the chair by using transparent tape. To avoid the inaccurate acceleration measurement data caused by the weak fixation of MPU6050 when the tester sits and stands up, double-sided tape and transparent tape aim to fix MPU6050 in this study. Meanwhile, because the Arduino development board is heavy, double-sided tape and transparent tape are also used to fix it and avoid falling off of the development board in the test.

In order to visualize the LED lamps, six LED lamps were arranged on the breadboard in this study, corresponding to six pressure sensors at different positions, with the LED positions consistent with the pressure sensor positions. Since the output range of the PWM wave is 0 ~ 255, the ratio of the voltage of each pressure sensor to the maximum output voltage is calculated and multiplied by the maximum output of the PWM wave of 255. Moreover, the pressure at each sensor position can be visually displayed through the brightness of the LED lamp (in Figure 3 (b)).

3.2 Experimental Testing

Seven different sitting positions were selected in this study, namely, sitting upright, leaning forward, leaning backward, leaning left, leaning right, crossing right leg and crossing left leg. Through the analysis of pressure sensor data, the results reveal the characteristics and changing law of pressure distribution in each sitting posture.

In upright sitting, forward leaning and backward sitting, the pressure distribution shows left-right symmetry. Specifically, when sitting upright, the readings of the four pressure sensors located at the bottom of the seat are similar, and the values of the two sensors close to the backrest are slightly greater than the readings of the other two sensors. In the forward sitting, the values of the two sensors near the backrest are significantly smaller than the other two sensors at the bottom, and the two pressure sensors located on the backrest are zero. Whether sitting upright or leaning forward, the main stress points are concentrated at the bottom of the seat. The backward sitting shows different characteristics. The readings of the two pressure sensors near the backrest are larger than those of the other two bottom sensors, while the values of the two pressure sensors on the backrest are larger, and the main stress points are located near the backrest and the bottom of the seat. In postures of leaning left, leaning right, and crossing sitting (crossing right leg and left leg), the pressure distribution is asymmetrical, and the pressure sensor readings are usually greater on one side than on the other. Especially in the cross sitting, the reading of the front part of the bottom pressure sensor on the leg-raising side is zero, and the main stress point is still concentrated at the bottom of the seat near the backrest.

Overall except for the leaning backward, the position with the largest pressure change in the other six sitting postures is the area near the backrest at the bottom of the seat, and the area with the most significant pressure change in the backward posture is the pressure sensor of the backrest.

4. Results and Analysis

In the upright sitting position, the chair rises and falls when sitting down, and the reading of the pressure sensor also changes greatly. When the tester sits completely firmly, the readings of each sensor (especially the bottom of the seat) tend to be balanced, and the pressures on the left and right sides are basically symmetrical. With the passage of time, due to minor body adjustments, the pressure in some areas fluctuates slightly, but the overall distribution remains balanced. After standing up and leaving the seat, the sensor data returns to zero, as shown in Figure 4.

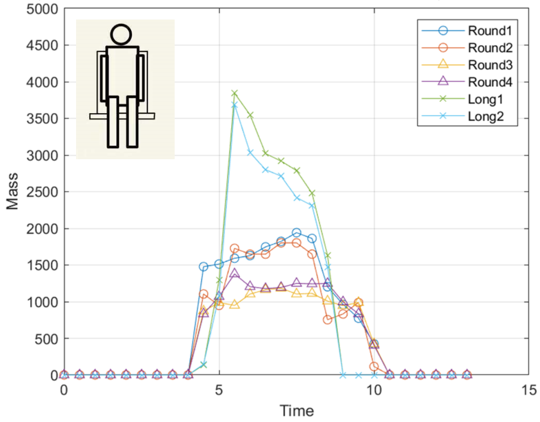


Figure. 4 Analysis of Sitting Posture Data (Mass Unit: g, Time Unit: s)

At the beginning of the learning forward, the sensor reading near the backrest is significantly lower than that in the middle and front areas of the seat cushion, which proves that the force on the front is concentrated. Due to the sitting habits of the tester, the force on the left side of the body is slightly greater than that on the right side. As the sitting posture is stable, the pressure sensor data tends to be stable, and the sensor reading in the front area of the seat cushion is still larger. After standing up and leaving the seat, the sensor data returns to zero, and the pressure sensor reading on the seat back is always zero due to the forward posture, as shown in Figure 5 (a).

The reading of the backrest pressure sensor in the backward leaning is significantly higher than that in the upright sitting, which shows a backward shift of the center of gravity. As the backward tilt state is stable, the pressure of the backrest sensor continues to be high, and the pressure value of the bottom sensor is similar to that of sitting upright. Due to the great pressure on the lumbar and cervical vertebrae in the leaning backward, the tester may adjust his posture from time to time, resulting in short-term fluctuations in back pressure, as shown in Figure 5 (b).

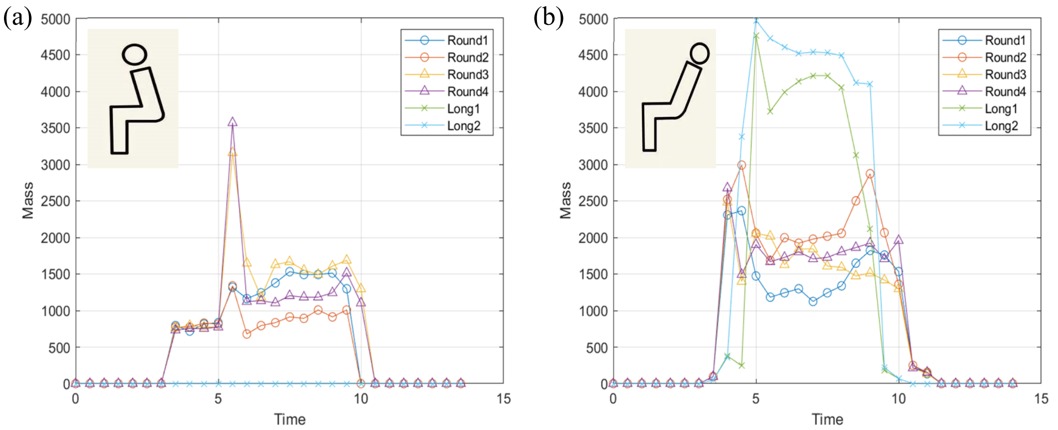


Figure. 5 Diagram of Leaning Posture Data Analysis. (a) Leaning Forward. (b) Leaning Backward. (Mass Unit: g, Time Unit: s)

In the left or right leaning position, the pressure sensor (corresponding to the tilt direction) shows a higher pressure on one side and a relatively low pressure on the other side. In this case, the pressure distribution gradually stabilizes, but there is always obvious asymmetry. Due to long-term unilateral stress, the subjects may make small adjustments, resulting in slight changes in the corresponding pressure values at some moments. Finally, when the tester stands up and leaves the seat, the readings of each pressure sensor return to zero, as shown in Figure 6 (a)-(b).

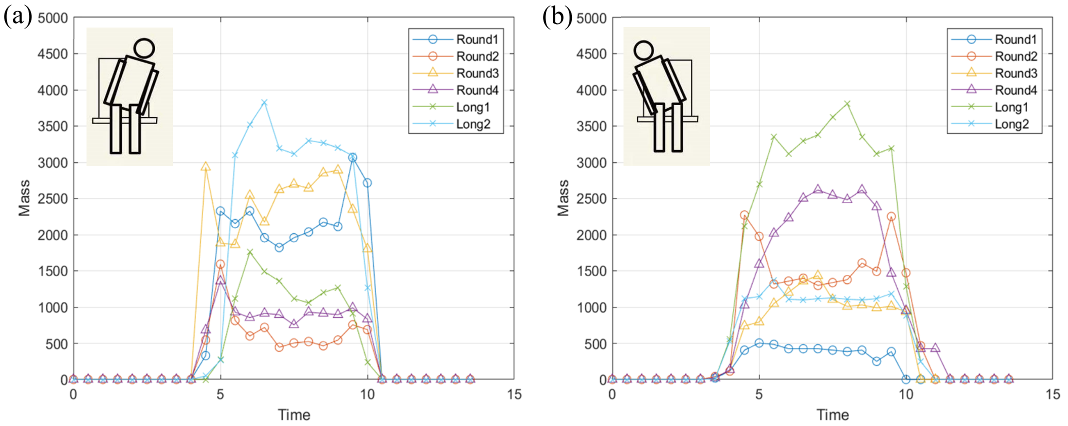


Figure. 6 Diagram of Leaning Posture Data Analysis. (a) Leaning Left. (b) Leaning Right. (Mass Unit: g, Time Unit: s)

Each sensor has a reading at the beginning in the cross sitting position. In the leg leaning position, the sensor at the front of the seat cushion on the crossed side (for example, when the right leg is crossed, the right side) often shows a reading close to zero. Thus, there is almost no force in this area. The other side bears greater pressure. At the same time, the change of the pressure sensor reading on the seat back is similar to that of the seat cushion. Because the upper body deflects when the legs are crossed, the sensor reading on the crossed side is also zero, and the reading on the other side increases. After the final tester leaves the seat, the indication of each sensor returns to zero, as shown in Figure 7 (a)-(b).

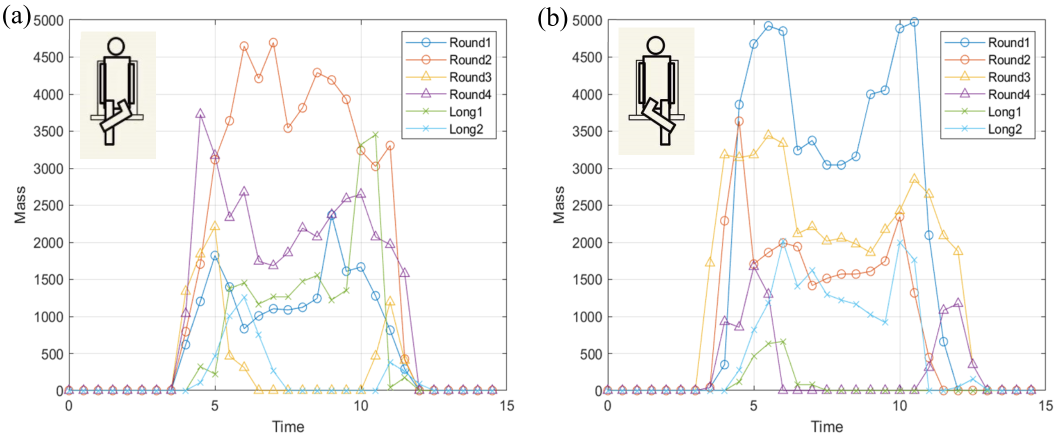


Figure. 7 Diagram of Cross Posture Analysis. (a) Crossing Left Leg. (b) Crossing Right Leg. (Mass Unit: g, Time Unit: s)

Because the acceleration curves of seven different sitting postures are similar in this study, only the image of crossing the right leg is taken as an example. It can be clearly seen that the accelerometer data changes greatly due to the rise and fall of the chair in the sitting and standing positions, and the data is relatively stable for the rest of the time. Moreover, due to the placement angle, the X-axis direction is consistent with the gravity direction, so the acceleration value at stability is similar to the gravity acceleration (as shown in Figure 8).

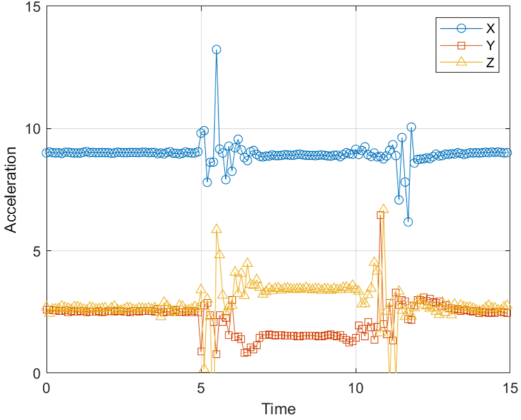
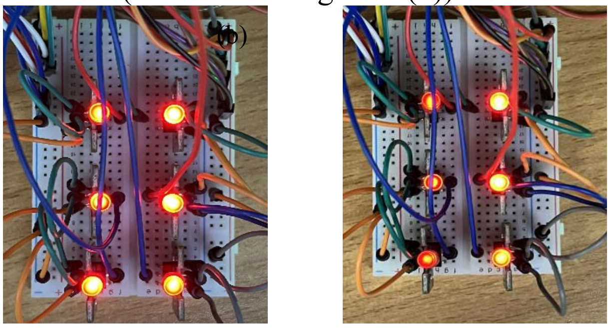


Figure 8. Accelerometer Data. (Acceleration Unit: m/s2, Time Unit: s)

The LED lamp in this study can better display the measured values of pressure sensors at different positions. Taking the upright sitting and leaning right as examples, in the sitting upright position, the brightness of each LED lamp is similar because the force of each sensor is uniform (as shown in Figure 9 (a)). In the right leaning position, the pressure sensor located on the right side of the seat is stressed greatly, so the brightness of the three LED lights located on the right side is brighter, and the LED lights on the left side are dark (as shown in Figure 9 (b)).



(a) (b)

Figure. 9 LED. (a) Sitting Upright. (b) Leaning Left

5. Conclusion and Outlook

In this study, a sitting posture analysis system based on multi-modal sensors is designed and implemented. The system mainly consists of a data acquisition module, a data calculation module and a result feedback module. Among them, the data acquisition module uses (MD 30-60, RP-L-110, MPU6050) to obtain the user's sitting posture information, and the data calculation module transmits the data back to the Arduino to calculate the pressure at different positions of the seat, as well as the acceleration changes of the chair on the X, Y, and Z axes during the whole process from sitting down to standing up. Finally, the results are output in the result feedback module, and the data size on the pressure sensors at different positions is displayed by different LED lights. According to the experimental results, the system can better display the difference in sensor pressure among different sitting postures: upright sitting, leaning forward, leaning backward, leaning left, crossing right leg and crossing left leg. In addition, it is more intuitively displayed on an LED lamp, which shows that the proposed system has good performance in sitting posture analysis tasks with potential application value in health analysis and medical service fields.

In the future, it is necessary to further optimize sensors and data processing, and combine deep learning algorithms to achieve a higher intelligence.

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