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3D Visualization of Gait Analysis Using Unity Program

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Abstract: This article includes a study on 3D visualization of gait analysis using Unity program to determine the reason for gait disorders. Here, the movements of the right tibia and the force generated in determined areas of the sole of the foot for the 20-second gait of a person were monitored with 3D visualized data. MPU-6050 module, which includes gyroscope and acceleration sensors to detect right foot movements, was used to perform gait analyses. We took force data from six areas determined on the sole by FSR sensors. These sensor data were transferred to the computer using wireless communication with the help of NodeMCU Wi-Fi modules working as server and client. After the sensors' data were normalized, we compared the signals of these data using different filtering methods. As a result of these comparisons, we determined that the low-pass filtering method with an optimized cut-off frequency of 5 Hz was more suitable than the other filtering methods. For this reason, we use low-pass filtering on the signals obtained for 3D data visualization. After filtering the signals of angle, acceleration, and force data received in real-time, we animatedly visualize the data of these signals with 3D column chart and heatmap visualization techniques. In our study, the 3D visualization method used for gait analysis can contribute to diagnosing and treating foot disorders that cause gait disorders.

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1. Introduction

The common reason for performing gait analyses is essential health problems in people's feet and legs. For this reason, research on gait analysis has gained momentum with technological developments. These include smart insoles application for Parkinson's disease (Boucharas et al., 2022), artificial intelligence-supported application of center-of-pressure metrics for posture and balance control (Du et al., 2021), gait analysis applications for flatfoot (Martínez-Martí et al., 2014; Mustafaoglu et al., 2022), lower extremity evaluation system application for movement disorders in children (Zheng et al., 2014), and studies for cerebral palsy patients (Khaksar et al., 2021; Rotoni et al., 2020). Today, various sensors such as FSR (Force Sensing Resistor), flex sensors, capacitive sensors, gyroscope, and accelerometer sensors are widely used for such gait analysis applications. FSR sensors are generally used to measure the force values applied to determined areas of the sole. Readers are encouraged to consult the following references for more detailed information on studies related to FSR sensors: Refs. (Chen et al., 2022; Mustafaoglu et al., 2022; Özkan et al., 2018; Martínez-Martí et al., 2014; Kim et al., 2018; Zheng et al., 2014). Here, we determined six sole areas to measure the force values applied to the sole and measured force values from these areas by FSR sensors. In addition to this sensor, the MPU-6050 module, the Inertial Measurement Unit (IMU) module, was used. The movements of the right foot during walking were examined with the help of this module's gyroscope and accelerometer sensors. Gyroscope and accelerometer sensors are widely used for motion detection in gait analysis. We find it useful for readers to refer to the following references about these sensors: Refs. (Żuk et al., 2022; Kim et al., 2018; Patil et al., 2016, Bamberg et al., 2008).

Internet of Things (IoT)-based studies for healthcare applications are increasing in popularity day by day. Patient data can be easily monitored using microcontrollers built in wireless communication modules. The ESP-8266 32-bit NodeMCU module used in our study is one of these modules based on IoT (Sony et al., 2021). This module is widely used because it is very effective in processing sensor data and transferring it to the computer environment. Various filtering methods are used to process and interpret sensor data regularly. Kalman filter (Vullings et al., 2010), low-pass filter (Kristianslund et al., 2012), high-pass filter (Fu et al., 2021), and band-pass filter (Lee et al., 2021) can be given as examples of these filters. These filters were used in our study, compared, and mentioned in the Discussion section.

Today, Unity 3D is a widely used program in game programming and development, as well as a simulation, virtual reality (Pires et al., 2021; Dyulicheva et al., 2021; Moro et al., 2017), and visualization (Tresser et al., 2021; Altural et al., 2019) tool. We first carried out gait analysis to determine the causes of gait disorders and then performed 3D visualization processes using the Unity program. Finally, we used the heatmap (Boucharas et al., 2022) method to visualize the pressure data applied to the sole of the right foot.

The following section presents the placement of sensors for gait analysis, transferring sensors' data to the program interface prepared with the C# programming language, normalizing signals, and low-pass filtering methods. In addition, the visualization of signal data with 3D column charts, mapping, and foot movements with 3D animation in the Unity 3D program is mentioned. The results of comparing the filtering methods mentioned earlier are criticized in the Discussion section.

2. System Design

2.1. Sensors layout and their locations

In our study, the movements of the right tibia and the force generated in determined areas of the sole for the 20-second gait of a person were monitored with 3D visualized data. The gait phases demonstrating for the sensor data acquisition are shown in Figure 1. We used six FSR (Force Sensing Resistor) force sensors to measure the force values applied to the determined areas of the sole of the right foot and an MPU-6050 module consisting of gyroscope and accelerometer sensors to determine the walking position of the foot. This module was attached to the skin over the tibia. The module placement is shown in Figure 2a. The placement of force sensors between insole-shaped layers made of EVA (Ethylene Vinyl Acetate) material is shown in Figure 2b.

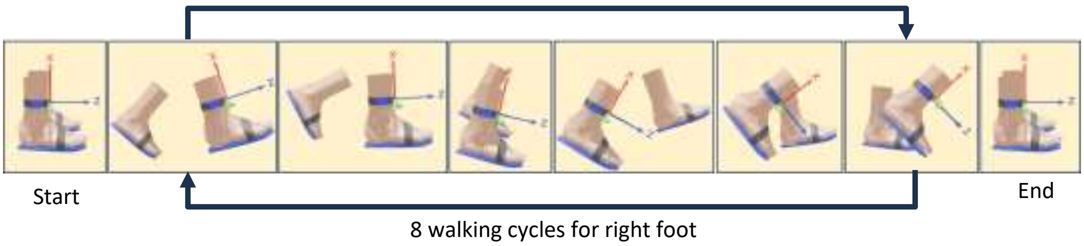


Figure 1: Gait phases while receiving sensor data

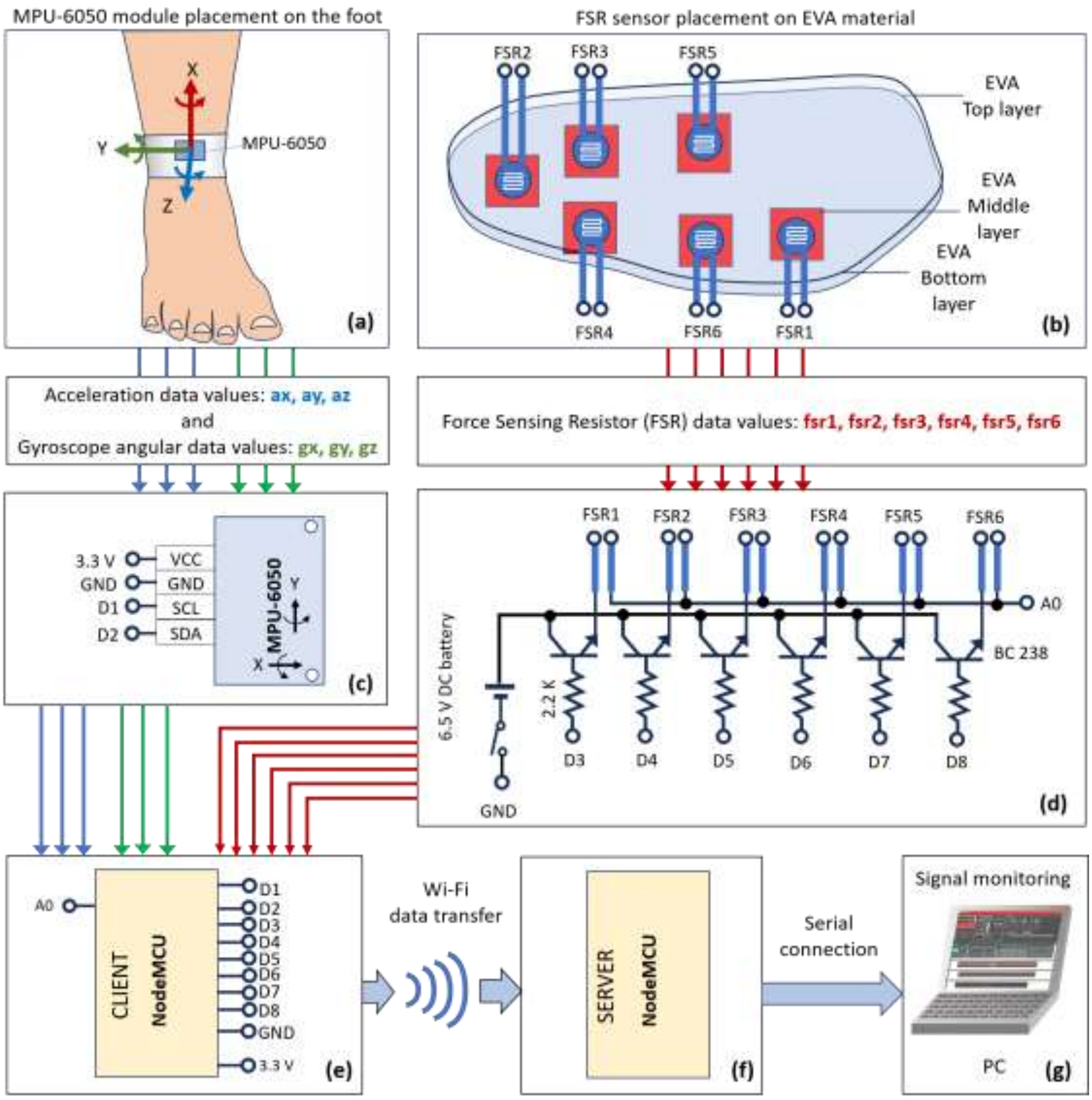


Figure 2: System design for transferring sensor data to the computer

2.2. Transferring force, angle, and acceleration data to the computer environment

As illustrated above, two Wi-Fi modules, known as NodeMCU, were used to transfer acceleration and angle data taken from the tibia area of the right foot and force data taken from the sole of the right foot to the computer environment. One of these Wi-Fi modules was used as a server, and the other was used as a client. All variables defined as gx, gy, and gz were used to transfer the angular data read from the MPU-6050 to the Wi-Fi module working as the client in Figure 2e. In addition to angular data, ax, ay, and az variables were used to transfer acceleration data with the same method. All variables defined as f1, f2, f3, f4, f5 and f6 were used for the data obtained from FSR force sensors.

The transistor switching circuit in Figure 2d prevents bus conflict from transmitting sensor data from FSR sensors to the client over a specific line. Angle, acceleration, and force data from the sensors were transferred to the NodeMCU module working as a server, shown in Figure 2f, via a wireless communication network. The connection to the server Wi-Fi module is provided with a specific username and password. The data from the server NodeMCU module via wireless communication was transferred to the computer environment with a baud rate of 115200 via the serial port connection. We designed a program interface coded in the C# programming language shown in Figure 3 to instantly monitor the signal shape of angle, acceleration, and force data coming to the computer and save these data to an Excel file. With this designed interface program, weight, height, age, gender, and right or left foot selection information of the person whose measurements will be taken can be recorded. However, this personal information involved is outside the scope of this paper. Here, the study mainly focused on sensors' data and their 3D visualization.

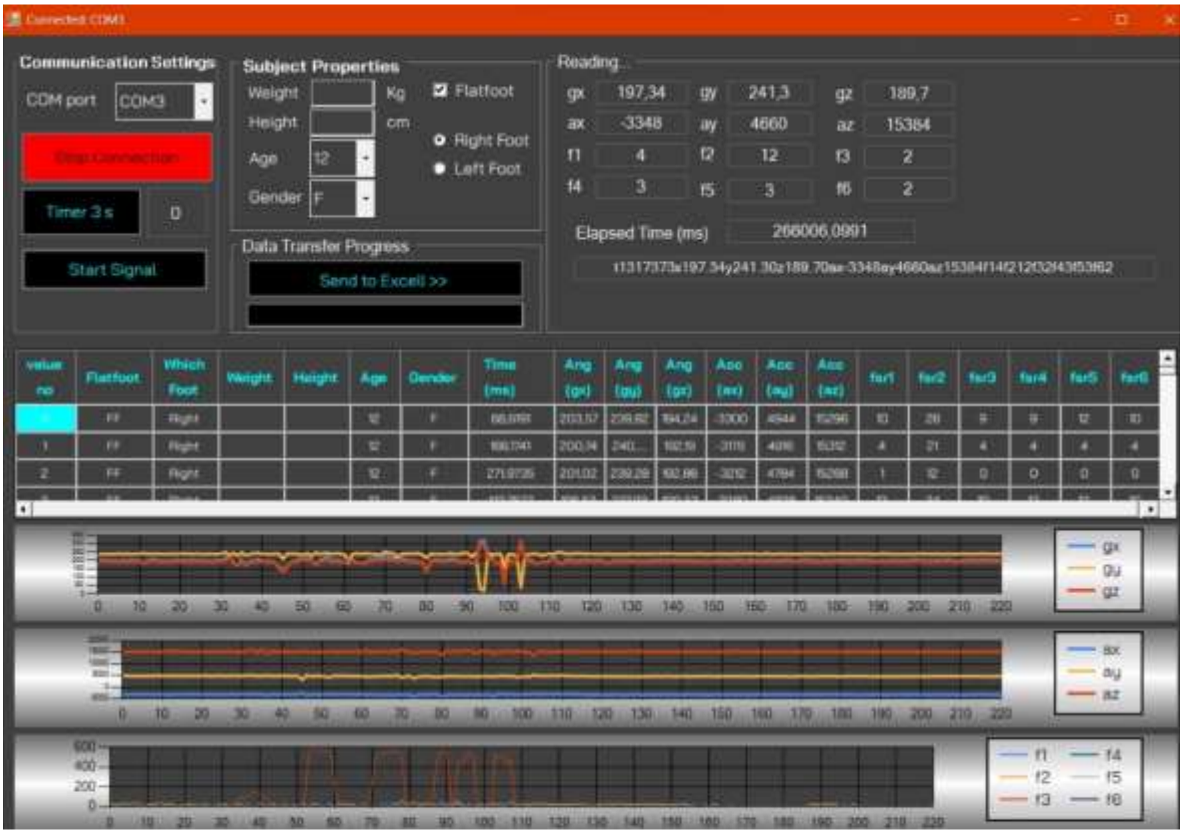


Figure 3: Our interface program is designed in C# language.

2.3. Normalization and filtering of angle, acceleration, and force signals

After generating data from a time-dependent angle, acceleration, and force signals through the program interface shown in Figure 3, we normalized these data using the Python programming language. While angle and force values are normalized between 0 and 1, acceleration values are normalized between -1 and 1. Figure 4 shows the normalized signals. In the next step, we used low-pass filter, high-pass filter, band-pass filter, and Kalman filter methods for the noise reduction of the normalized signals and compared the results of these filtering methods in the Discussion section. As a result of these comparisons, we use low-pass filtering with a cut-off frequency (f_c) of 5 Hz.

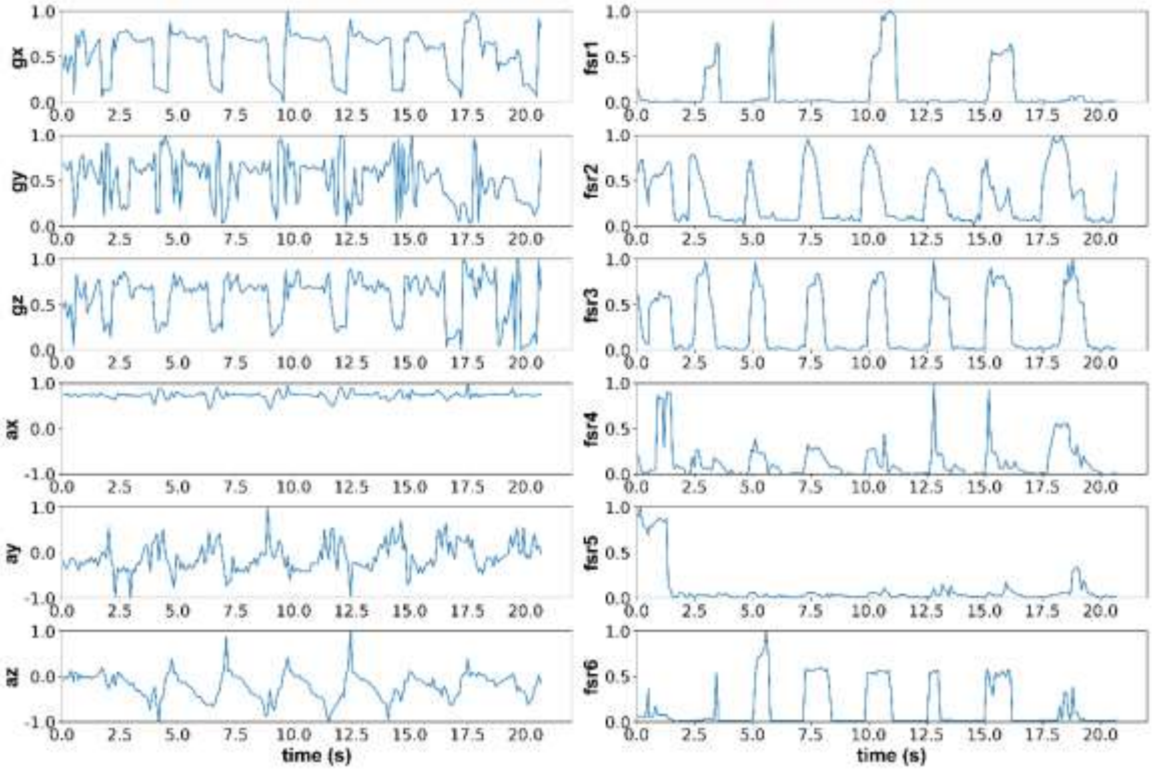


Figure 4: Normalized graphs for angle, acceleration, and force data signals

2.3.1. Low-Pass Filtering

Low-pass filter results of normalized gx angle and fsr1 force data with cut-off frequencies of 5 Hz, 10 Hz and 20 Hz are given in Figure 5. The sampling rate is used as 100.

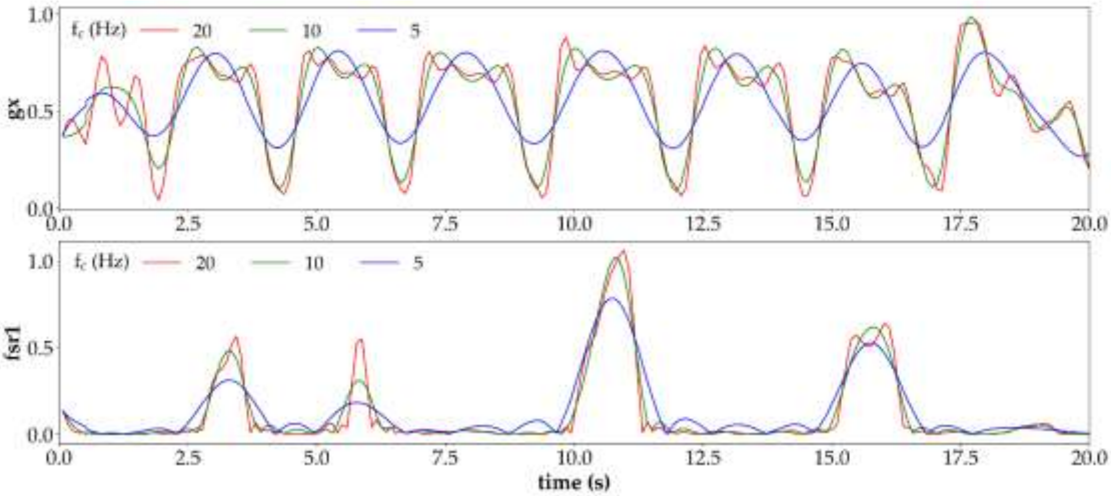


Figure 5: Low-pass filtered signals for gx angle and fsr1 force data for cut-off frequencies of 20 Hz, 10 Hz and 5 Hz.

2.4. 3D modeling with Blender program

We used the Unity 3D game engine for 3D visualization operations and the Blender program for designing 3D models with the FBX file extension. System features used for 3D visualization processes: The GPU hardware property is NVIDIA GeForce RTX 3050 Ti 4GB, and the CPU hardware property is 2.5 GHz. Figure 6a shows the design of the 3D insole model. In Figure 6b, all cylinders namely “fsr1…fsr6” have been added for visualization as a 3D column chart according to the FSR sensor values. Figure 6c shows the 3D foot model designed for 3D visualization of the walking movements of the foot.

(a) (b) (c)

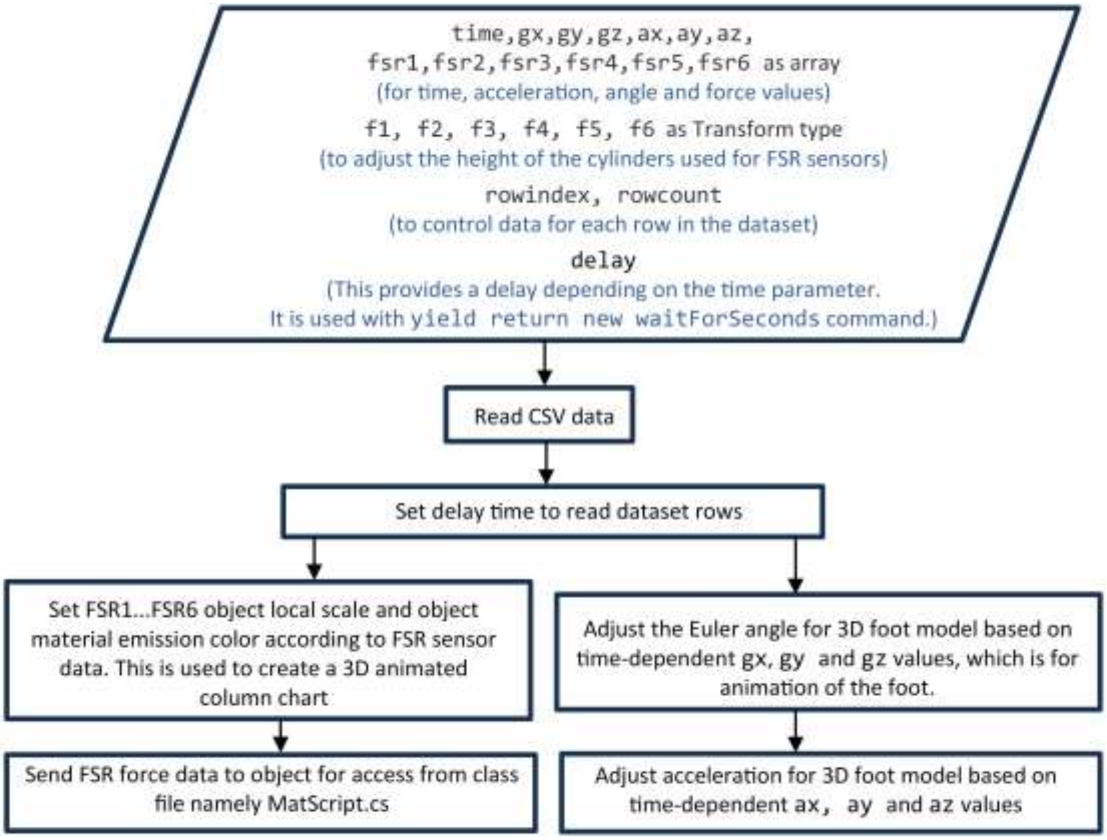
Figure 6: (a) 3D model of the insole (b) Cylinder models for showing the force of the FSR sensors (c) 3D foot model

2.5. Transferring data to the Unity program

We imported filtered sensor data to the Unity program as a CSV extension file for 3D animated visualization of foot movements and the force applied to determined areas of the right sole.

2.5.1. Creating an animated 3D column chart and movement of the 3D foot model

Sensor variables used as "f1…f6" in wireless communication are namely "fsr1…fsr6" in the readexceldata.cs C# file. The algorithm of the codes in this C# file is described in Algorithm 1.

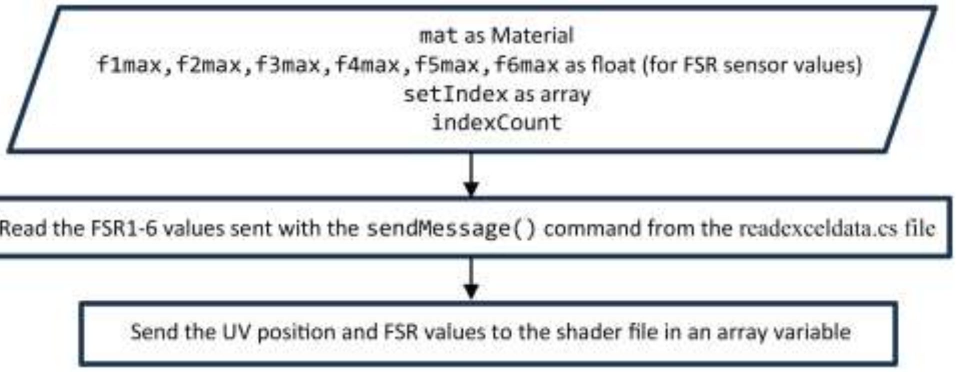


Algorithm 1. Flow chart for readexceldata.cs file

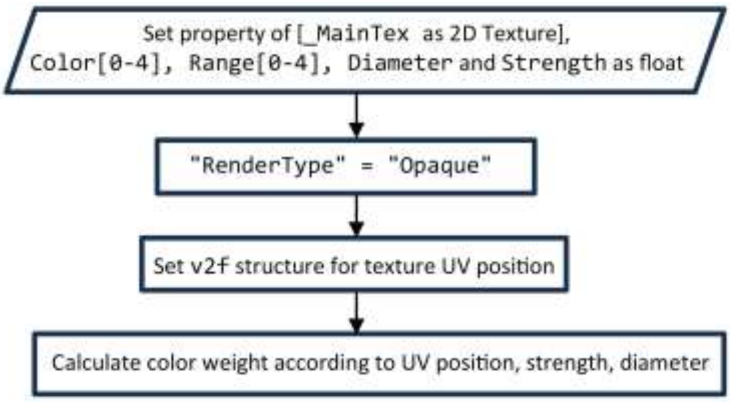
The 3D insole model with FBX extension imported to the Unity program is associated with this C# file. The height scale of the cylinders namely "fsr1…fsr6" in the 3D insole model was adjusted with the force values of the FSR sensors. The "fsr1…fsr6" values for the heatmap are sent to the MatScript.cs file to be transferred to the shader file that enables material editing. We used the variables ax, ay, and az for the movement of the 3D foot model and controlled the rotation movement of this model with the variable data gx, gy, and gz using the Euler angle. In the Unity program, the Euler angle provides the angular rotation of the 3D foot model between 0 and 359 around the X, Y and Z axes. According to the Euler angle, clockwise rotation indicates a positive direction, while anticlockwise rotation indicates a negative one. These angular rotation movements, which are also used in drones and airplanes, are namely "roll", "pitch" and "yaw", respectively, depending on the rotation movement around the X-, Y- and Z-axis. We generated delay time depending on the "time" parameter during the line-by-line reading of time-dependent sensor data. Therefore, we used a variable called "delay" for this delay time. In this way, animation transitions used in visualization can be monitored accurately. This is an essential consideration in visualizing data in real time.

2.5.2. Heatmap visualization based on force data using unlit shader

To show a heatmap visualization of the force values applied on the insoles, we first created a shader file for the material of the 3D insoles, and then we created a C# file namely MatScript.cs associated with the 3D insoles, in which time-dependent force values were sent to this shader file. The algorithms used in the study for the MatScript and shader files are given in Algorithm 2 and 3, respectively.



Algorithm 2. Flow chart for the MatScript.cs file



Algorithm 3. Flow chart for the heatmap shader file

3. Results

The 3D animated time-force column chart applied to the determined six areas on the insoles for the right foot in the Unity program is shown in Figure 7. With this 3D chart, both the force applied to the determined areas of the sole of the right foot and the transmission delays between Wi-Fi modules can be observed.

Figure 7. Animated 3D column chart based on values of force sensors

Figure 8 shows the heatmap on the 3D insole model according to time-dependent force values at about 0.26, 6.06, 10.31, and 18.15 seconds. We set the color bar to the range of 0-1 according to the minimum and maximum force values of the FSR sensor used in the study. Since the strength values are normalized between 0 and 1, the gradient color range is set to 0-1. Blue represents the minimum force value, and red represents the maximum force value. In Figure 9, the movement and rotation direction of the 3D model foot are shown for about 1.83, 10.68, 13.65, and 18.52 seconds synchronously with the heatmap changes depending on the force on the sole of the right foot. Three-axis coordinates and directions in the tibia area of the right foot in Figure 9 show the location and orientation of the MPU-6050 sensor module.

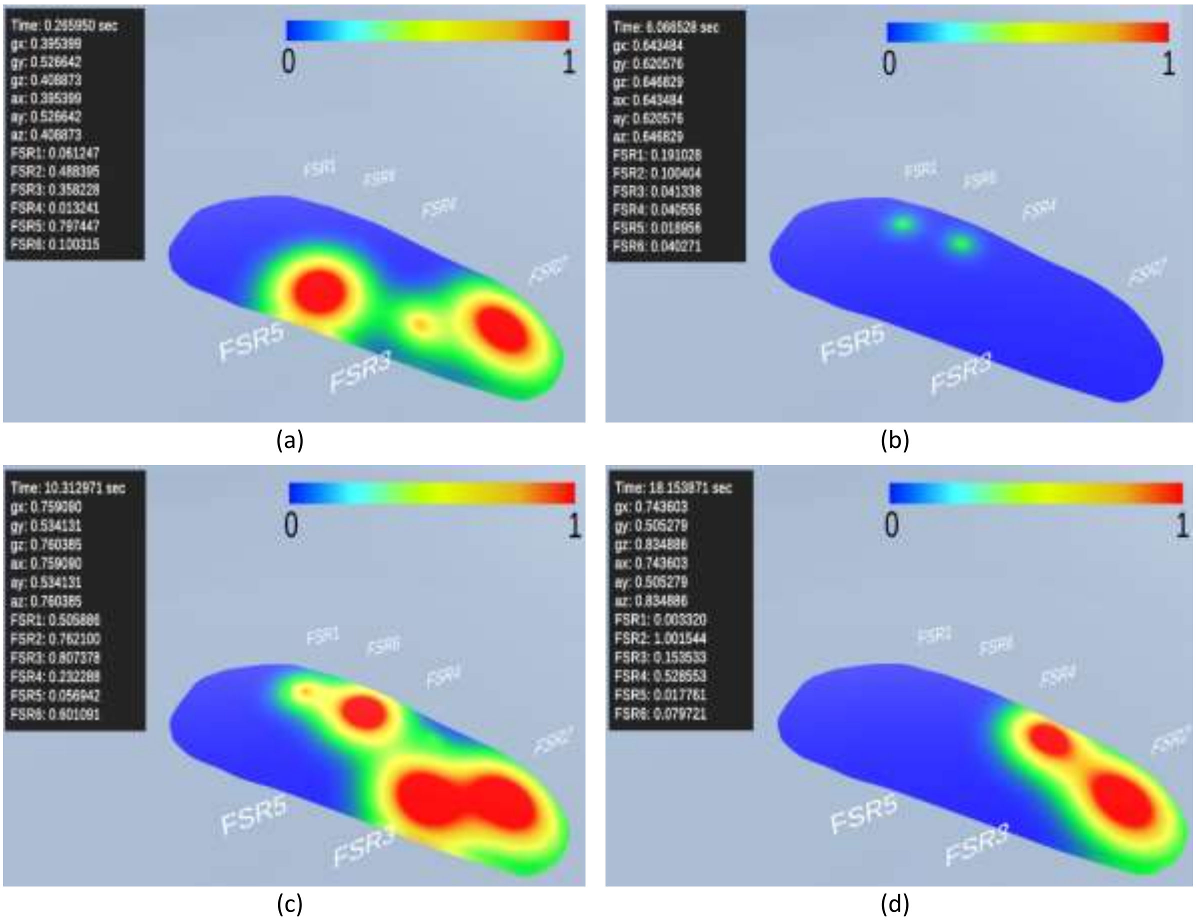


Figure 8: Heatmap visualization based on walking step at (a) 0.265 s, (b) 6.06 s, (c) 10.31 s, and (d) 18.15 s

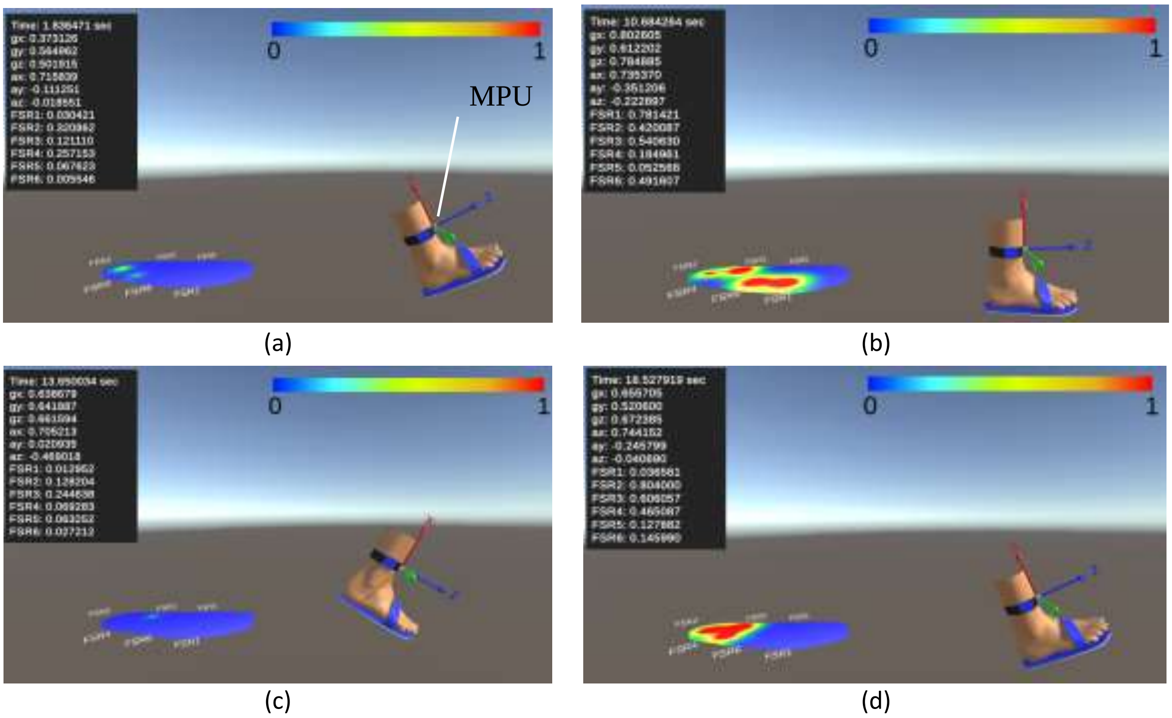


Figure 9: Heatmap based on walking step at (a) 1.83 s, (b) 10.68 s, (c) 13.65 s, and (d) 18.52 s

4.Discussion

Normalization and filtering of angle, acceleration and force signals facilitated the scaling and monitoring of data in the 3D simulation environment. In addition, the data obtained after these normalization and filtering processes can be used as a preprocessing for the use of artificial intelligence algorithms that can be developed in the Unity 3D simulation program.

In order to efficiently read, process, and visualize sensor data based on changing time intervals in 3D programs such as the Unity program, the performance of the hardware components that play an active role in the robust operation of the program must be at a sufficient level. For example, the performance characteristics of the graphics processor and the memory of the graphics card may limit such 3D visualization studies.

Additional signal booster circuits can prevent data loss that may occur when transferring various sensor data, such as force, angle, and acceleration, from one Wi-Fi module to another. These circuits will be very effective in visualizing and monitoring data. We recommend supplying Wi-Fi modules with sufficient voltage and current to prevent data loss.

The high-pass, band-pass, and Kalman filtering results of the signals regarding angle, acceleration, and force data obtained from the sensors are shown in Figures 10-12, respectively. As mentioned before, we use low-pass filtering with a frequency of 5 Hz. The reason for this is to ensure smooth movement and rotation of the foot in the Unity 3D program and to clearly detect the moment when the sole of the foot contacts the ground. Another reason is that force-value transitions can be monitored regularly when visualizing the heatmap. Although Kalman filtering is close to the actual signal form, we have yet to achieve smooth animation transitions in 3D visualization. The filtering method used in our Unity program visualization study is not only limited to low-pass filtering. We can achieve better results in 3D visualization by more smoothly filtering the periodic changes in the signals showing walking movements. We can achieve better results in 3D visualization by more smoothly filtering the periodic changes in the signals showing walking movements.

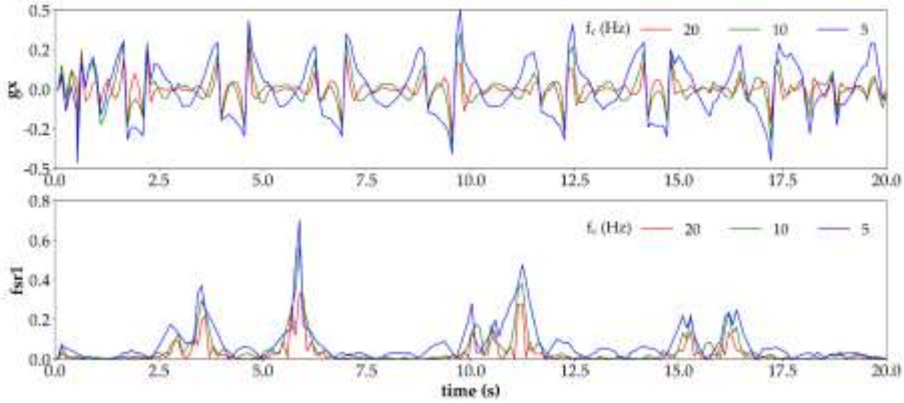


Figure 10: High-pass filter results of normalized gx angle and fsr1 force data are given for 5 Hz, 10 Hz and 20 Hz cut-off frequencies. The sampling rate is set to 100.

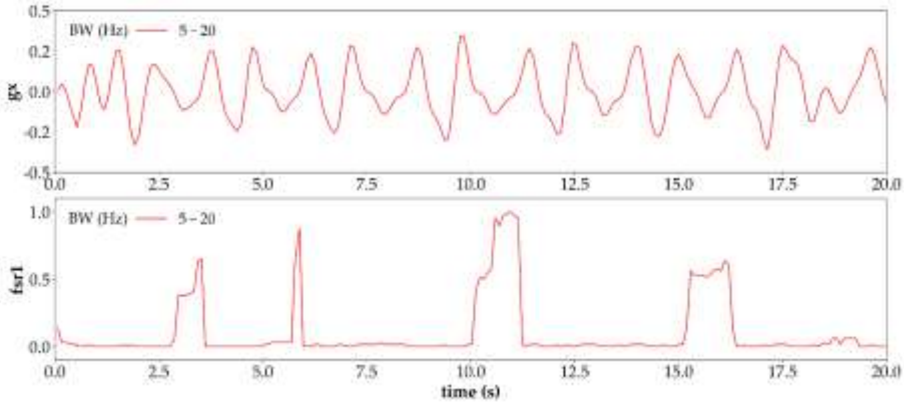


Figure 11: Band-pass filtering results of normalized gx angle and fsr1 force data are given for 5-20 Hz bandwidth (BW). The sampling rate is set to 100.

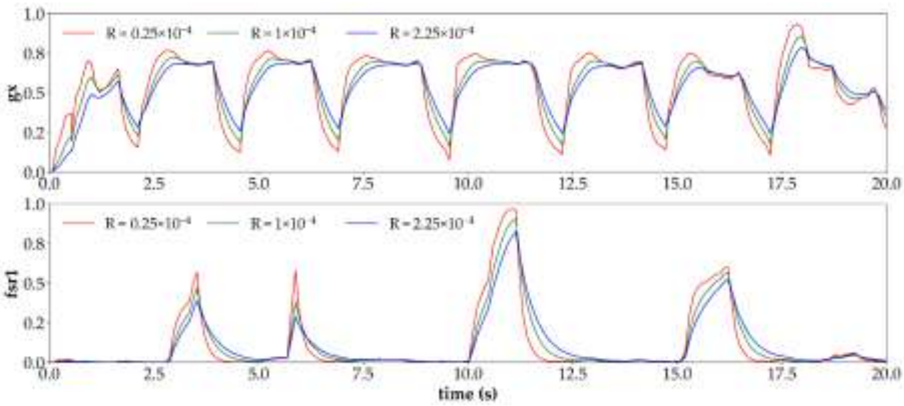


Figure 12: Kalman filtering results of normalized gx angle and fsr1 force data are given for the measurement variance estimation R values of 0.25×10^{-4}, 1×10-4 and 2.25×10^{-4}. Q variance value is used as 1×10^{-4}.

5. Conclusion

We propose a method for 3D visualization of gait analyses. Using our method, real-time 3D visualization of the data obtained from the sensors used for gait analysis in the Unity program can facilitate monitoring the patient's physical movements. In addition, our study will enlighten wireless data communication systems and studies on visualizing and interpreting sensor data in different software-aided programs like the Unity.

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