**Design and Development of a Wearable Device to Monitor Knee Joint Health**

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**Abstrac**t. Knee joint disorders have become quite common in today's world because of several reasons like the ageing population, limited physical activities, decline in immunity, unhealthy lifestyle and mainly due to delayed intervention and diagnosis. Early detection of Knee Health is necessary so that immediate treatment could be provided, and further complications could be reduced. To slow down the progression of the disorder and to facilitate appropriate treatments at the right time, Real-time monitoring would be suitable and efficient. This paper proposes a Wearable Knee Brace device for Real-time monitoring of the Knee joint that is designed using miniaturized sensors namely IMU sensors, FSR pressure sensor, Temperature sensor and Oximeter sensor. All these sensors are interfaced with Raspberry Pi 4B microcontroller which can help in real time data collection. 3D modelling of the Knee joint was performed for optimal sensor placement. Data collection was performed on 12 individuals (24 knees) of different age groups and genders. The collected sensor data is then processed to extract key Knee parameters like ROM, cadence, Muscle Pressure Distribution, inflammation and blood flow trends to assess Knee Health.

# Introduction

Wearable technologies have become a popular area of study and research as they present several advantages over the traditional, in-lab diagnostic methods in terms of their lower cost, not requiring a sophisticated and expensive clinical setup for diagnosis, accessible to many and Real-time monitoring [1-2]. Knee joints are a vital structure in the human body. It is a hinge joint that is present between two bones to allow movement in a single plane, like back-and-forth movement and sideways movement. Like all the other hinge joints in the human body such as human fingers, elbow and ankle, the Knee joint facilitates critical movements [3]. Also, the Knee joint bears the entire body weight due to its anatomical location, which makes it susceptible to injuries like osteoarthritis and cartilage wear and tear [4]. Knee Disorders can occur due to various reasons like old age, reduced mobility and unhealthy lifestyle. Other reasons include neuromuscular diseases which have resulted in over 276 million people suffering all over the world. The mobility of patients suffering from this disease is highly affected as the muscles become weak and incapable of supporting movement [5]. People involved in rigorous physical activities like construction workers also have a high risk of developing Knee joint disorders [6].

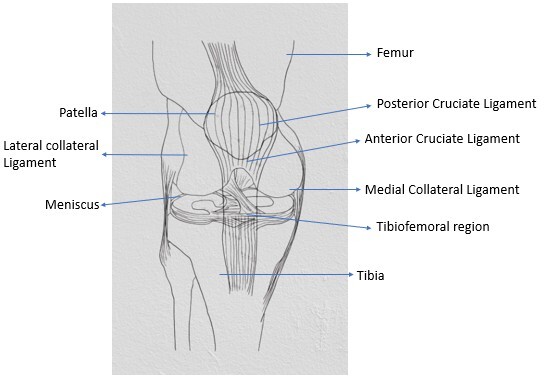
A lot of research has been conducted over time in the field of Wearable Technologies to improve the efficiency of diagnosis. Shelby Critcher et al. have proposed a Wearable Knee Bioimpedance Sensing system to monitor the symptoms of Osteoarthritis by using localized tissue bioimpedance as a biomarker. MLM predictor model was used to evaluate the proportionality between knee pain and 2 factors, namely per-length resistance and per-length reactance of the tissue impedance [7]. Here, Bioimpedance is the only key parameter which has been used to assess abnormality. There is no utilization of motion sensors to isolate movement artifacts in the collected data. G M Salim et al. have proposed a wearable optical based knee monitoring device, mainly to evaluate the knee ROM (Range of Motion). This proposed model has a larger range of motion, with 160 degrees detection angle, compared to optical-type devices [8].

This device seems to have high ROM capturing capabilities but seems to miss out on signal processing for noise removal. M Fatima Domingues et al. has proposed a Wearable e-Health device for monitoring knee angular movement using optical fiber Bragg sensors. With this solution, they found the exponential relationship between the knee angle increase and the reflected Bragg Wavelength shift of the OFS [9]. This is an energy efficient and accurate system but seems to be expensive in design and has been tested on a single individual. This paper presents the development of a low cost, multi sensor-based Wearable Device prototype, embedded with motion sensors like Inertial Measurement Unit (IMU) and FSR pressure sensor, temperature, and a pulse Oximeter sensor, interfaced with Raspberry Pi 4b micro-controller. 56 datasets (left and right knee of 28 individuals) have been collected from individuals of various age groups, and this raw data has been processed for noise removal. This processed data was utilized to extract key Knee parameters like Cadence and ROM, which can be useful for initial assessment of the Knee condition by analyzing the movement rate and flexion and extension angles (flexibility) of the knee. Pressure trends, temperature fluctuations and blood flow trends were plotted for visual analysis.

# SYSTEM DESIGN AND METHODOLOGY

## Anatomy of the Knee

Understanding Knee anatomy is essential to develop the device. Knee Joint is a synovial joint that is found in the human body. As shown in Figure 1, the main structures that make a Knee joint are Femur, Tibia and Patella. The Fibula, also known as the calf bone, is not directly involved in forming the Knee Joint but helps in stability during movement. The femur and Tibia form the upper and lower part of the joint respectively. The patella or the kneecap is located at the center of the Joint and plays a crucial role in providing structural stability. The knee joint is supported by ligaments such as the Anterior Cruciate and Posterior Cruciate ligaments (ACL and PCL) as well as the Medial Collateral and Lateral Collateral Ligaments (MCL and LCL) to control movements. The meniscus is another cartilage-like structure present between the Femur and Tibia and acts as a shock absorber and evenly distributes the load.

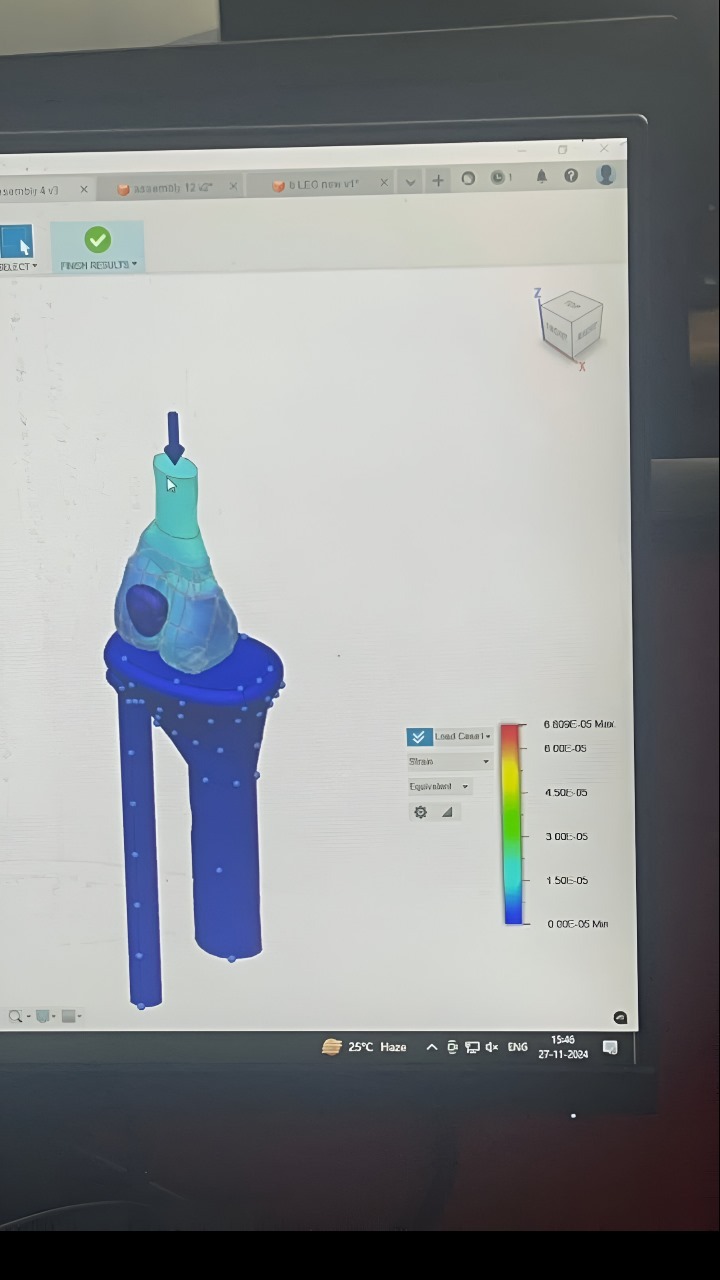
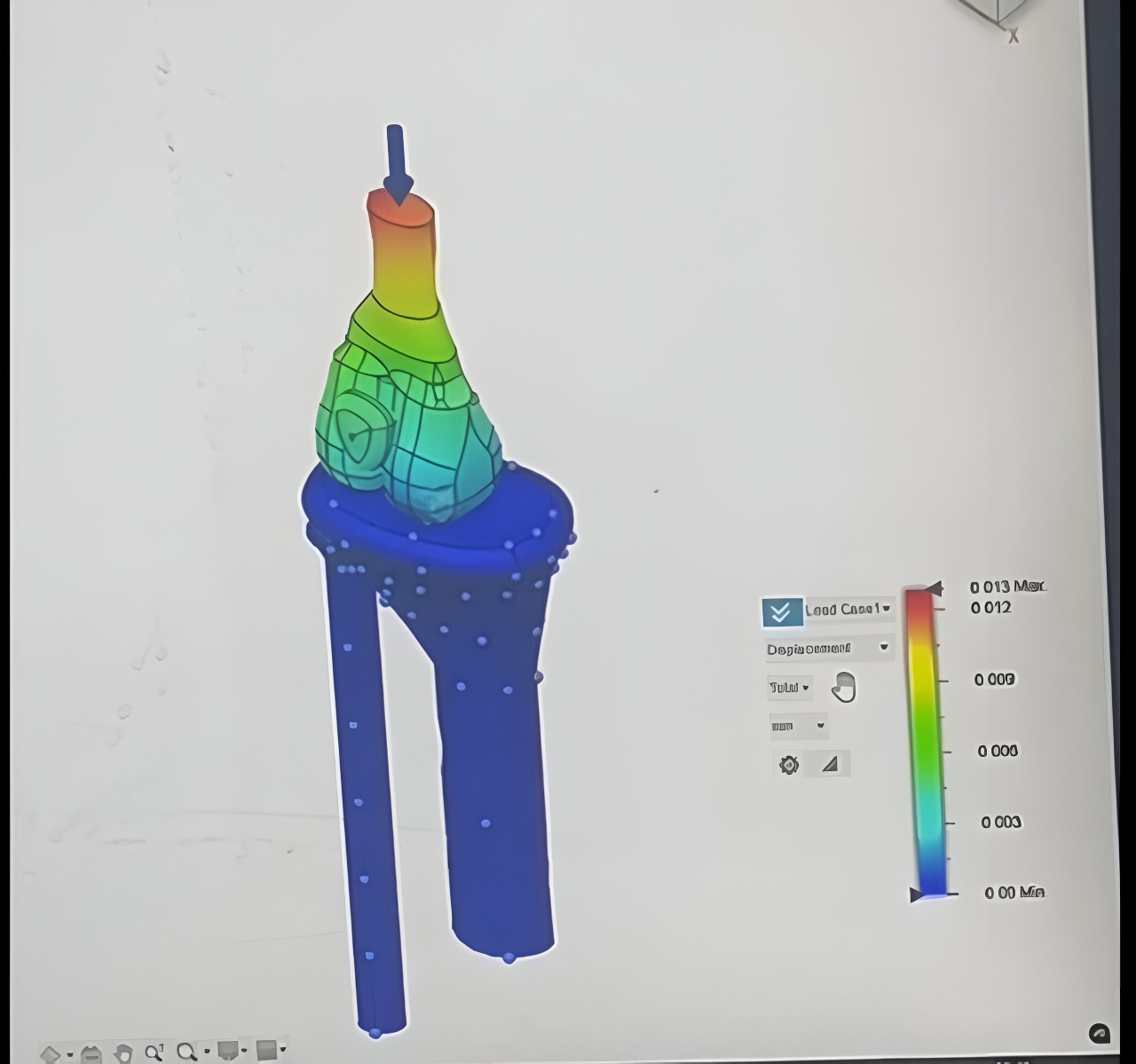


**FIGURE 1.** Human knee joint anatomy

## 3D Modelling and Stress Analysis

A 3D model of the Knee joint was designed as accurately as possible in Autodesk Fusion 360 modelling software as shown in Figure 2. The material properties of the Titanium Aluminum Alloy (Ti6Al4V), which is a biocompatible material used for orthopedic implants, was chosen as an alternative to bone properties, to perform the strain stress analysis [10]. Table 1 shows the material properties of the Titanium Aluminum Alloy and human bone.

The stress and displacement analysis have been carried out to study the impact area of the force on the Knee Joint when the load is applied from the top. Color coding is used to assess the impact as shown in Figure 2(b) and (c). Red indicates high impact whereas Blue indicates low impact. In stress analysis, impact gradually decreases while moving downwards as the force gets evenly distributed. Also, the displacement is minimal around the joint due to stability.

**(a) (b) (c)**

**FIGURE 2.** (a) 3D model of the Knee Joint designed in Autodesk Fusion 360 using 4 structures: Femur, Tibia, Patella and Fibula. All the structures were designed separately and later combined to form the complete Knee Joint. (b)Mechanical analysis using external force in terms of Newtons (N), the figureshows stress analysis along with an intensity colour chart. (c) Displacement analysis along with intensity colour chart with similar force application.

**TABLE 1.** Comparison table of bone and Ti alloy properties [10]

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Material | Yield Strength (MPa) | Poisson’s ratio | Elastic Modulus (GPa) | Ultimate Tensile Strength (MPa) | Biocompatibility |
| Human Cortical Bone | 30-70 | 0.3 | 5-23 | 194-195 | Natural |
| T i-6Al-4V | 825-895 | 0.33 | 110-113 | 895-930 | Highly  Compatible |

## Sensors Specifications

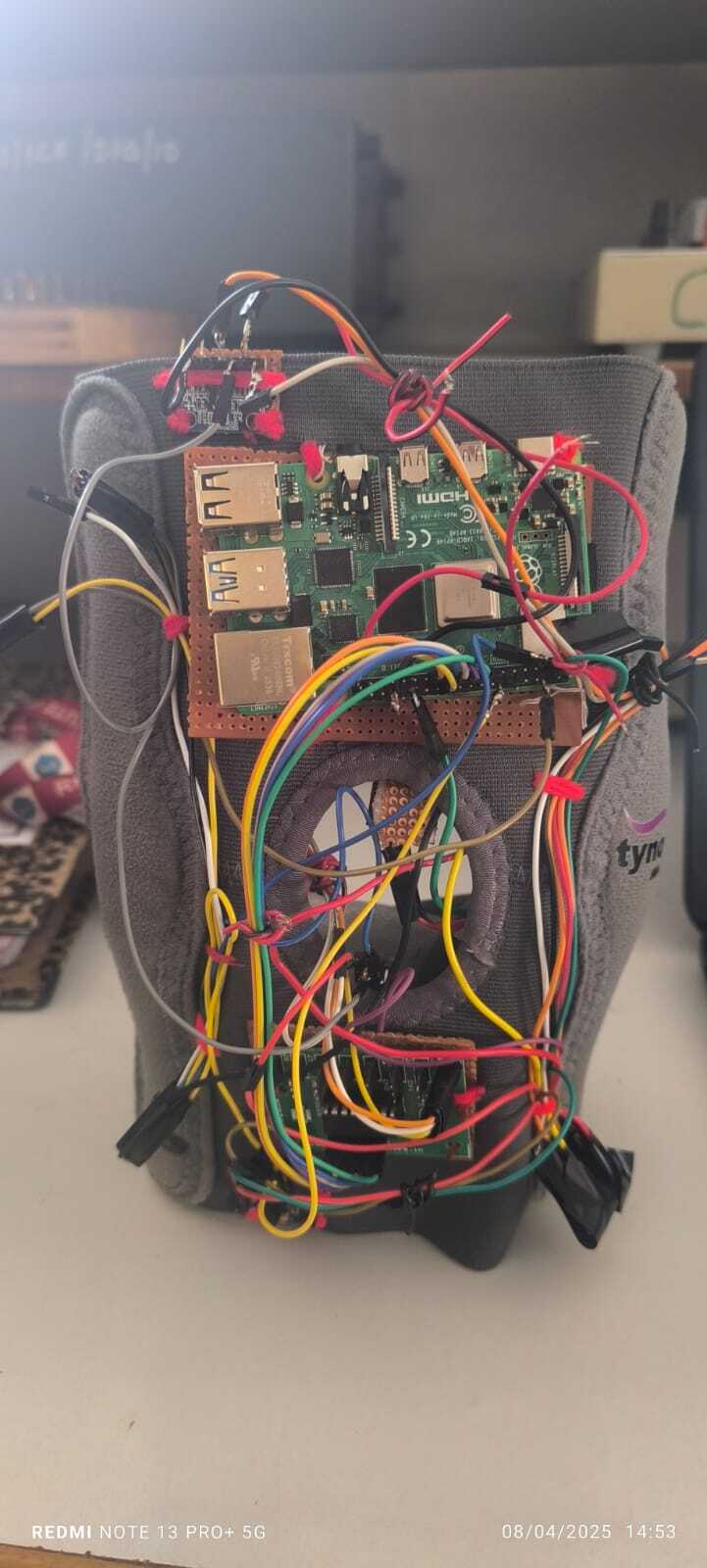
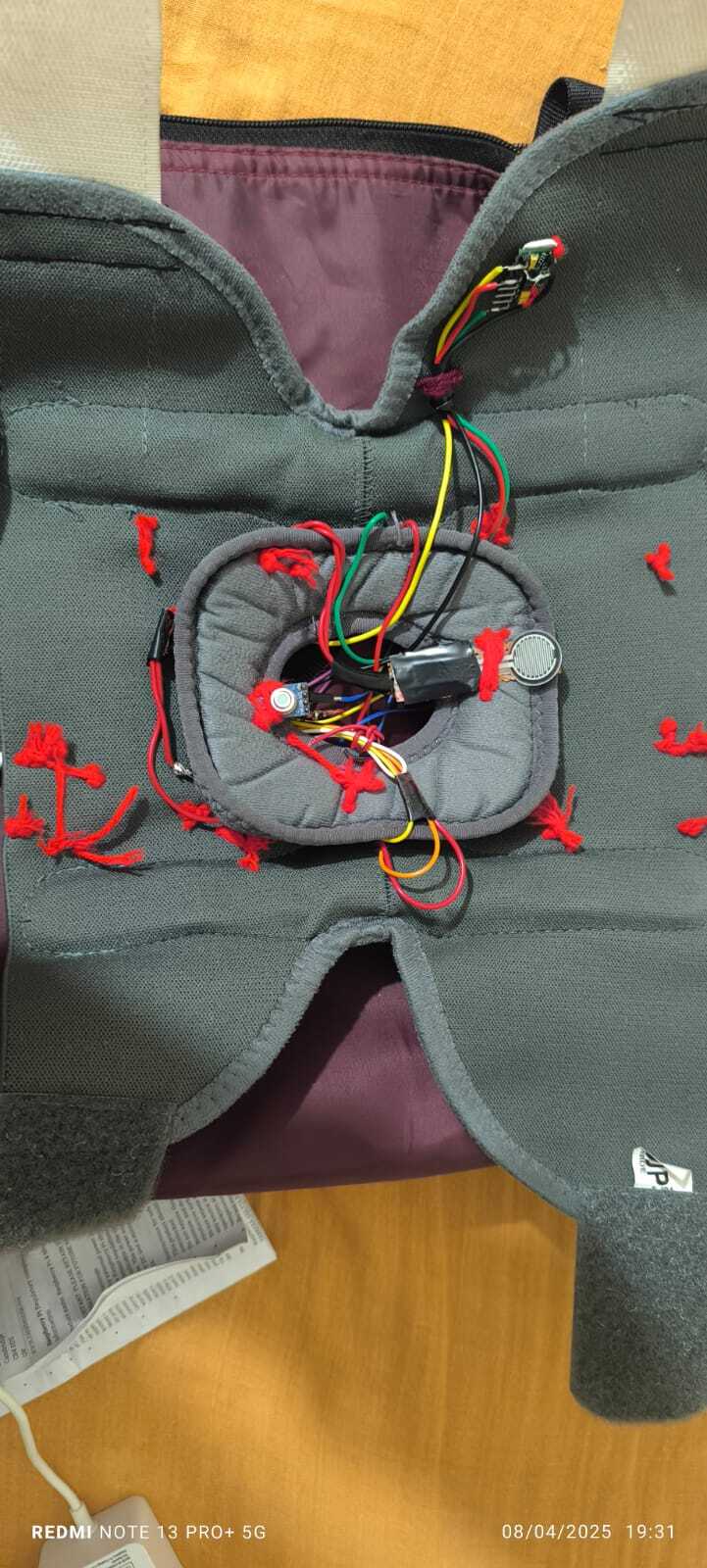
The MPU6050 6-axis Inertial Measurement Unit (IMU) uses I2C communication protocol. The operating voltage is 3-5 volts. The MPU-6050 integrates a 3-axis accelerometer and a 3-axis gyroscope into a single chip, making it ideal for motion tracking applications. A Force sensor resistor (FSR) communicates using SPI (Serial Peripheral Interface) protocol. The operational voltage is 3-5V, when the applied pressure increases, the resistance decreases. The knee skin temperature was measured using an MLX90614 ESF Non-Contact Human Body Infrared Temperature Measurement Module which runs at 3-5 V and has an operational current of 2mA. This sensor is typically factory-calibrated and communicates using the I2C protocol. The MAX30102 Pulse Oximeter Heart Rate Sensor Module is an integrated pulse oximetry and heart rate monitor sensor for monitoring physiological signals like heart rate and blood oxygen saturation (SpO₂) levels. The sensor uses the I2C communication standard. The MAX30102 operates on 1.8V and 3.3V power supplies.

## Prototype Design and Implementation

The device prototype was developed on a readily available fabric for Knee Brace as shown in Figure 3(a). The 2 MPU6050 IMU sensors namely IMU1 and IMU2 have been placed above and below the knee joint respectively at equal distances and such that it comes on the lateral side of the Knee. The FSR pressure sensor is placed on the back side of the knee brace, near the patellar region, to accurately capture muscle pressure. The MLX90614 temperature sensor is placed on the patella to detect any temperature changes in the skin around the knee joint. Finally, the MAX30102 oximeter sensor has been placed at the back of the knee brace, to detect the blood flow rate in the popliteal artery that runs behind the knee joint as shown in Figure3(b). The developed knee prototype was tested on 28 adults (aged 20 to 80 years). Basic physical and medical information was collected through a questionnaire. Participants were instructed to walk for 6-12 seconds on a flat walkway wearing the brace. Sensor data was stored in CSV format for post-processing.

## Data Processing and Parameter Extraction

Data processing was done using python language, to remove the noise and low frequency drift present in sensor data. Savitzky-Golay filtering was used for smoothing the data before parameter extraction. Range of Motion specifies the bending and extension capabilities of a Knee Joint. Range of motion (ROM) was calculated using Gyroscope data (z-axis orientation) from the two IMU sensors. A high pass Butterworth filter of cutoff frequency 0.05 Hz and order 2 was used to overcome the low-frequency drift of the Gyroscope data. Integration was performed to extract the knee angle from angular velocity, in degrees as shown in Equation (1). Smoothening was performed one more time to avoid any unusual noise. Equation (2) shows ROM calculation using maximum and minimum knee angles.

**(a) (b)**

**FIGURE 3.** (a) A wearable device prototype with all the embedded sensors (b)The back side of the prototype

(1)

(2)

Cadence is the count of the number of steps taken per minute as shown in Equation (3). It is measured by using both FSR data and gyroscope data. The FSR sensor was smoothened by applying a moving average filter during data collection. Savitzky-Golay filter was once again applied for further smoothening of both FSR smoothened data and gyroscope data for extracting angle. Peaks were calculated from gyroscope z-axis data and prominent peaks were calculated from FSR data. The peaks were merged to detect the number of steps.

(3)

Muscle Pressure was captured using an FSR sensor and the pressure distribution over time was graphically visualized. Both the raw FSR data and smoothened FSR data were plotted for graphical visualization. Peak detection was also shown in the same graph. FSR prominence and thresholding were used for detecting significant peaks. Temperature sensor data was used to detect any abnormal skin temperature near the Knee joint. The temperature unit was converted from Kelvin to Celsius. Basic statistical metrics like average temperature, maximum and minimum temperature, temperature range and standard deviation were calculated and displayed on the terminal. It analyses if the temperature is within the normal human body temperature range of 35 degrees to 37 degrees. RED and IR values were collected from the oximeter sensor and used to plot blood flow trends for easier analysis and visualization. Infrared light wavelength is in the range of 880-940nm. The light absorption rate of blood varies with the wavelength and frequency of light. IR light penetrates deeper into the blood vessels and capillaries, as compared to RED light. Hence IR data was used to analyze the blood flow trends at the back of the Knee.

(4)

Savitzky-Golay filtering method was used to preserve important features while removing noise in the data. It is an efficient smoothening technique that fits a polynomial to the sliding window of the data using LSR (least squares regression), instead of mere averaging shown in Equation (4). These extracted parameters help to analyze the condition of the Knee at a basic level.

# RESULTS AND DISCUSSION

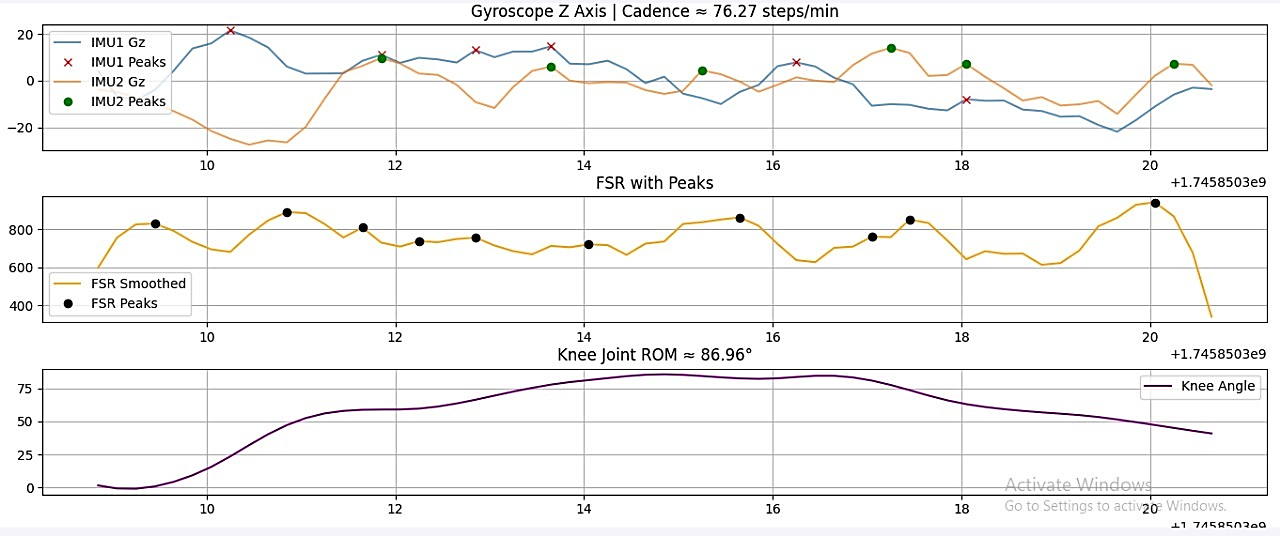
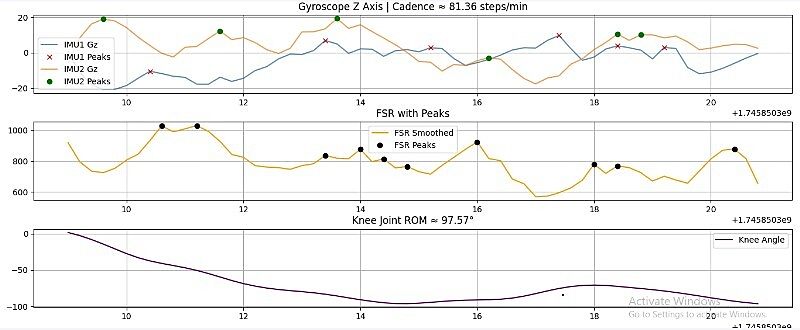
A total of 28 individuals were selected for data collection. Table 2 summarizes the datasets that were collected.

**TABLE 2.** Summary of the dataset collected

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Datasets | Age-group | Number | Gender | History | Remarks |
| 56 (28 Left and 28 Right) for 12 sec walking gait | 20-35  35-45  45-60  60-80 | 6  8  10  4  **28 total** | 13 Male  15 Female | 1 case of Knee surgery and few cases of persistent Knee pain | Observed few participants walking very consciously. Several slow walking observed.  Few calibrations did not take place accurately. |

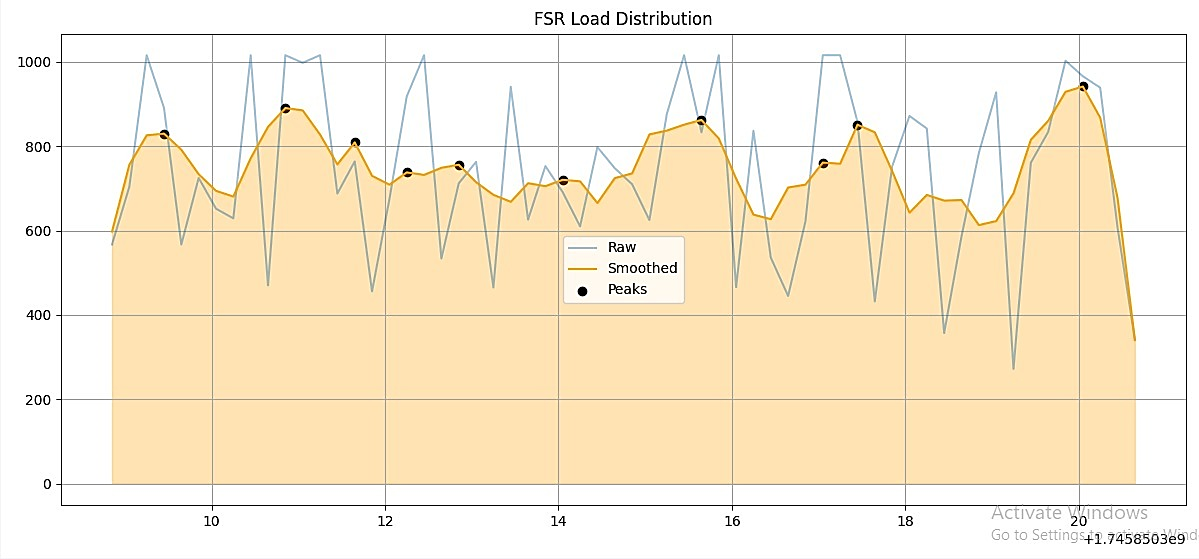
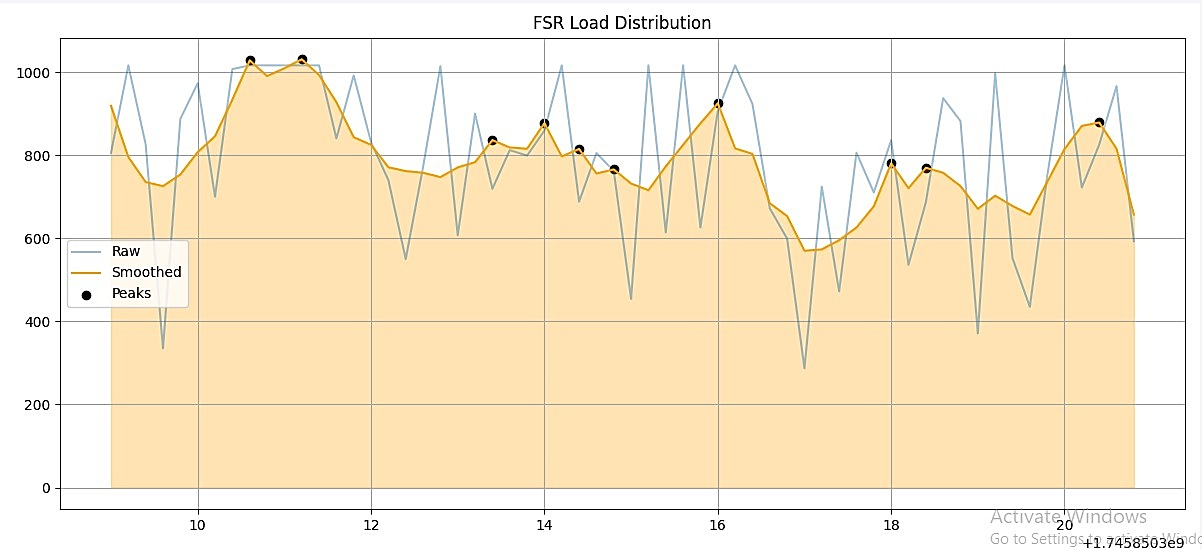
Since participants of various age groups were involved, a comparative analysis of parameters that have been extracted from individuals of 2 extreme age groups (Participant I in 20s and Participant II in 70s) is discussed. Cadence and ROM are two efficient parameters that help decide the condition of the Knee in terms of its flexibility. Higher Cadence value implies faster walking speed and lower ROM indicates limited flexibility. These values provide a basic understanding about the average Knee movement patterns.

As shown in Figure 4 and Figure 5, Participant I has a higher Cadence (81.36) and ROM (97.57), which indicates knee flexibility and stability. The pressure distribution peaks are consistent which indicates stronger foot pressure on the ground while walking. Participant II has lower Cadence and ROM which may indicate instability or slow walking as observed. The temperature variation curves are quite similar for a walking gait with slight increase and decrease in values over time. There is no sharp variations/peaks in temperature as shown in Figure 6, hence there may not be any case of inflammation around the Knee. The raw RED and IR values exhibit fluctuations due to noise as shown in Figure 7, whereas the smoothed signals can be analyzed more easily. Participant I shows more stable perfusion patterns indicating stable blood flow during gait. Participant II has a slight unstable pattern which may indicate weaker blood supply to the Knee. Weaker Blood supply may indicate circulatory problems. This analysis shows the presence of physiological differences in the two participants in terms of 5 distinct parameters. These parameters cannot justify the Knee condition completely but can pave way for further in-depth analysis of the problems.



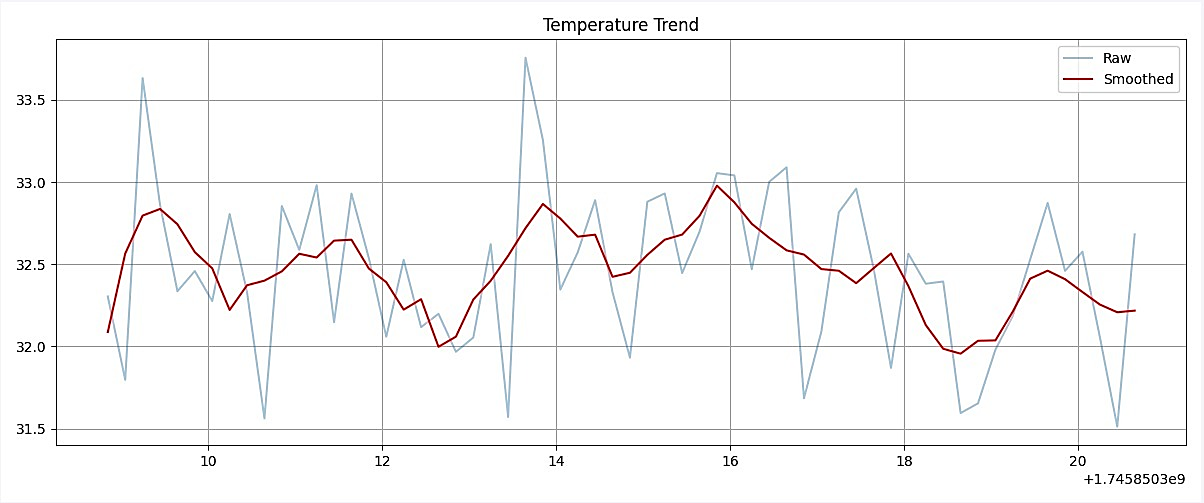
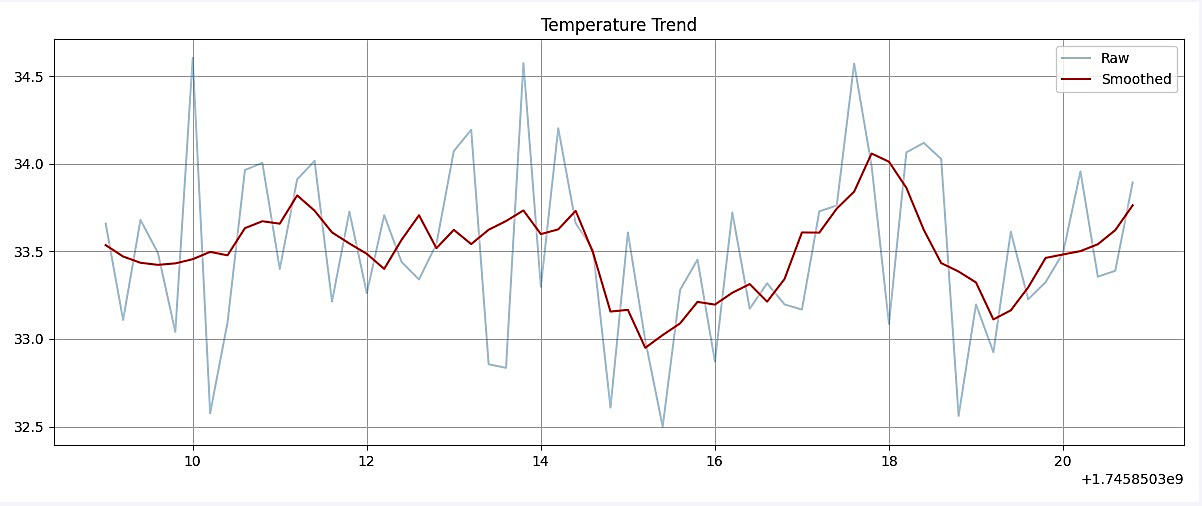
1. (b)

**FIGURE 4.** Depicts the Cadence and Range of Motion (ROM) (a) Participant I (b) Participant II



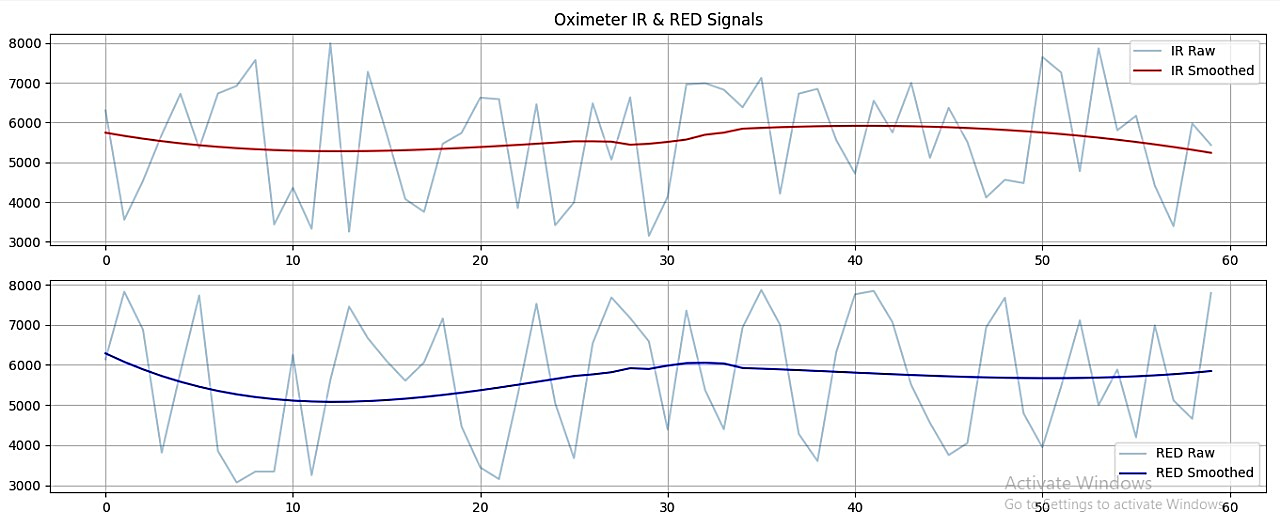
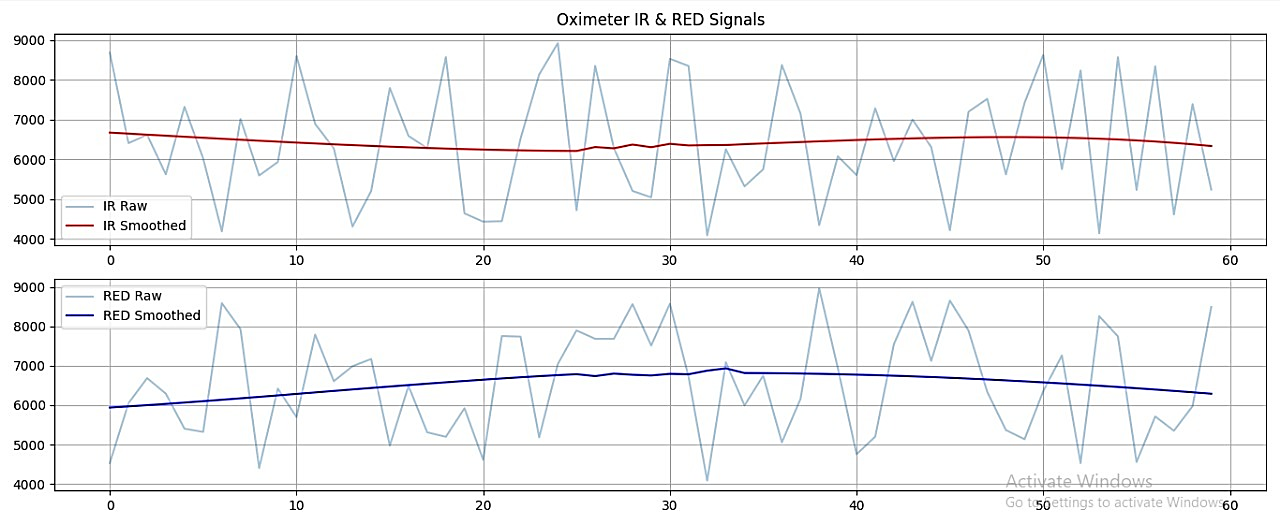
1. (b)

**FIGURE 5.** Depicts the pressure distribution trend (a) Participant I (b)Participant II



(a) (b)

**FIGURE 6.** Temperature variation (a)Participant I (b) Participant II

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1. (b)

**FIGURE 7.** The blood flow trends (a) Participant I (b) Participant II

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**CONCLUSION**

This paper presented the development of a low-cost Wearable Knee prototype for the analysis of the Knee joint conditions. Raw data processing for noise removal was done using butterworth filters and Savitzky-Golay filtering technique, mainly to preserve important signal features. Physiological parameters like Cadence, ROM (Range of Motion), pressure distribution, temperature variations and blood flow trends were calculated and analyzed, by comparing the parameters of 2 individuals with extreme age gaps. The results showed significant differences in parameter values between two individuals. This analysis can be improved further by leveraging extensive real time data collection for different gait patterns like climbing stairs, running, etc to improve the efficiency and scope of the device.

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