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Smart Lower Limb Prosthesis Monitoring System Using Mechatronic Sensors Integrated with a Smartphone Application

M. Munawir Lasiyono[1*]
[1]Department of Mechatronics Engineering, Faculty of Science and Technology, Universitas Bima Sakapenta, Indonesia

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ABSTRACT

The development of mechatronics and Internet of Things (IoT) technologies provides opportunities to develop smart lower limb prostheses capable of monitoring user activities in real time. This study aims to develop a smart prosthesis monitoring system using mechatronic sensors integrated with a smartphone application. The system employs an Inertial Measurement Unit (IMU) sensor to detect prosthetic movement and a pressure sensor to measure changes in prosthetic loading. Sensor data are processed using an ESP32 microcontroller and transmitted to a smartphone via Bluetooth Low Energy (BLE). The test results show that the system detects steps with an average error of 3.09% and achieves a communication success rate of 96.8%, with an average delay of 74 ms at a distance of 5 meters. The application displays step count, pressure, movement angle, activity status, sensor graphs, and usage history. The system provides a foundation for continuous activity monitoring in smart lower limb prostheses.

*Corresponding Author
M. Munawir Lasiyono
E-mail: mmunawirlasiyono@gmail.com

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INTRODUCTION

Lower limb amputation causes changes in mobility capability, balance, walking patterns, and daily activities. Prosthetic legs are developed to help users regain these mobility functions. However, the use of prostheses is not only related to the mechanical capabilities of the device, but also how the device interacts with the user during walking, standing, climbing inclined surfaces, or performing other activities.

The development of modern prostheses has led to the concept of smart prosthesis, which is a prosthesis equipped with sensors, electronic systems, data processing algorithms, and control mechanisms. Sensors can be used to obtain information regarding the user's movement, pressure, position, or gait pattern.

One of the widely used sensors is the Inertial Measurement Unit (IMU) because it is capable of measuring acceleration and angular velocity, allowing it to be used to detect walking phases and movement characteristics. Systematic reviews indicate that IMU is one of the most widely used wearable sensors in real-time gait analysis, while pressure sensors on the sole or insole can be used as a comparison in identifying walking phases [1].

Research by Gouda and Andrysek [2] shows that inertial sensors can be used to detect gait events in real time for lower limb prosthesis users, including during level ground and ramp walking conditions. These results demonstrate that real-time sensor signal processing has the potential to be applied in smart prosthesis systems.

In addition to the IMU, pressure sensors also play an important role. Hopkins et al. [3] developed a relatively low-cost pressure measurement system combined with an IMU to map load distribution on the prosthetic socket. The system uses 12 pressure sensor elements and is capable of transmitting data at 200 Hz sampling to a smartphone application. The results show that the sensors are able to provide information regarding the load distribution pattern during walking activities.

Other research developed portable sensors to monitor the position and activities of transtibial prosthesis users. These sensors can distinguish activities such as sitting, standing, walking, position changes, and non-use conditions of the prosthesis. This indicates that the sensor system can be used not only to count steps, but also to obtain a more comprehensive overview of prosthesis usage [4].

Sensor integration with smartphone devices is also an important opportunity. Research on wireless sensor systems on the prosthetic skin interface shows that pressure and temperature data can be transmitted wirelessly to devices such as smartphones or tablets so that users can obtain information in real time. The system uses NFC and Bluetooth Low Energy (BLE) communication [5].

In the Indonesian context, research on prosthesis development has also been conducted [6], [7], [8]. Sutawika et al. [9] developed a redesign of a robotic ankle prosthesis using gait data from the Indonesian population. This research emphasized the importance of adapting the prosthesis design to the gait characteristics and anthropometry of Indonesian users. Research conducted by Prabowo et al. [10] also developed and tested a lower limb prosthetic prototype and performed static testing based on ISO 10328.

However, most previous studies have focused more on the development of mechanical components, laboratory gait measurements, or the development of specific sensors. The integration of multiple sensors on prostheses with a monitoring system accessible directly via a smartphone still has room for development, especially to produce a system that is simple, portable, relatively inexpensive, and usable for daily activity monitoring.

Based on these problems, this study develops a Smart Lower Limb Prosthesis Monitoring System Using Mechatronic Sensors Integrated with a Smartphone Application. The system is designed to acquire movement and pressure data from the prosthesis, process it using a microcontroller, and then wirelessly transmit the information to a smartphone.

This study aims to: 1. design a sensor system to monitor lower limb prosthesis activities; 2. integrate IMU and pressure sensors with a microcontroller; 3. develop data communication between the prosthesis and the smartphone; 4. display prosthesis activity data in real time via a smartphone application; and 5. evaluate system performance based on sensor accuracy, communication success rate, and activity monitoring capability.

RESEARCH METHODS

The developed system consists of four main parts: 1. sensor system; 2. data processing unit; 3. wireless communication system; and 4. smartphone application. In general, the system architecture can be illustrated as follows:

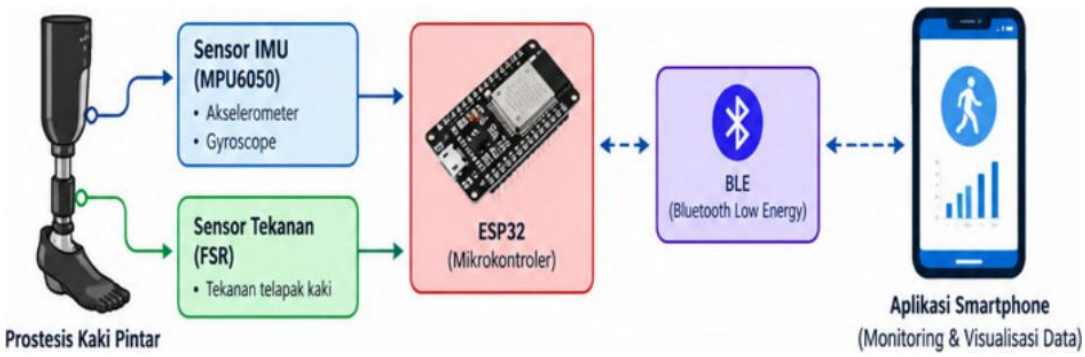


Fig. 1. System Architecture

The selection of the ESP32 is based on the integration of the microcontroller with Bluetooth communication capabilities, thereby reducing the need for additional communication modules. The main components used in the design are shown in Table 1.

Table 1. Main Components

No	Component	Function
1	ESP32	Data processor and system controller
2	MPU6050/IMU	Measures acceleration and movement angle
3	FSR/pressure sensor	Measures pressure on the sole/socket
4	Li-ion battery	Power source
5	Charging module	Battery charging
6	Bluetooth Low Energy	Communication with smartphone
7	Android smartphone	Monitoring and visualization
8	Prosthetic leg	Sensor mounting medium

The IMU sensor is used to obtain acceleration and movement orientation data. The obtained parameters include: X-axis acceleration; Y-axis acceleration; Z-axis acceleration; angular velocity; orientation change; and prosthesis angle estimation. IMU data is used to identify movement changes from a stationary state to walking. The use of IMUs in prostheses has a strong basis from previous research. IMU systems have been used to identify gait events in real time and to obtain kinematic parameters of prosthesis users [2], [11].

The pressure sensor is installed on the sole of the prosthetic foot. The sensor is used to detect pressure changes during: standing; heel strike; mid stance; toe off; and no surface contact. Pressure data can be used as an indicator of activity and load distribution.

Previous research shows that low-profile pressure sensors can be used together with IMUs to obtain load distribution patterns on the prosthetic socket [3].

Sensor data entering the microcontroller is filtered to reduce noise. For the IMU sensor, acceleration data can be calculated using:

$$a = \sqrt{(a_x^2 + a_y^2 + a_z^2)} \quad (1)$$

where:

a = resultant acceleration (g)

a_x, a_y, a_z = acceleration on the X, Y, and Z axes (g)

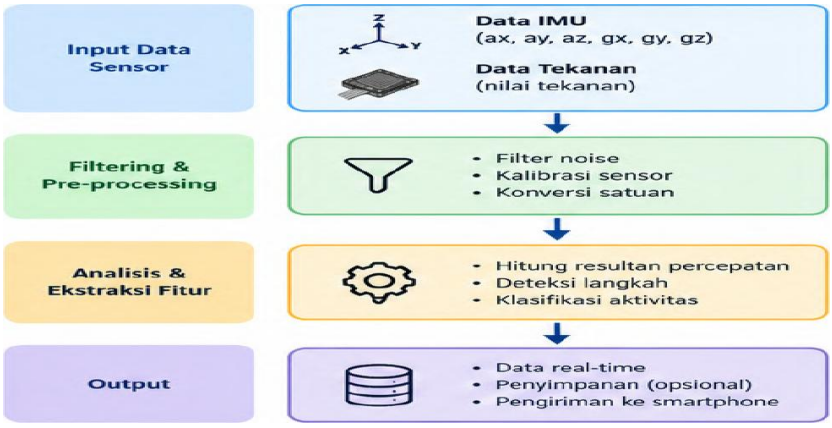


Fig. 2. Data Processing

Changes in the resultant acceleration value are used to help identify walking activities. Meanwhile, the sensor pressure value is converted into a pressure value based on calibration results.

Data from the ESP32 is transmitted using Bluetooth Low Energy. The smartphone receives the data and then displays: 1. step count; 2. pressure; 3. prosthesis angle; 4. activity status; 5. movement graph; and 6. usage history.

This concept is in line with previous research using smartphones as a receiving and visualization device for prosthesis sensor data [5]. The smartphone application is designed with a simple dashboard layout.



Fig. 3. Application Design

The application can also be developed to store data based on date so that it can be used to compare user activity over time.

RESULTS

1. System Design Results

This research produced a smart lower limb prosthesis monitoring system prototype consisting of an Inertial Measurement Unit (IMU) sensor, a pressure sensor, an ESP32 microcontroller, Bluetooth Low Energy (BLE) communication, and a smartphone application. The IMU sensor is used to obtain information regarding changes in prosthesis movement, while the pressure sensor is used to detect loading changes on the sole of the foot. The acquired data is then processed by the ESP32 and transmitted wirelessly to the smartphone application.

The use of inertial sensors in prosthesis systems has the potential to obtain motion parameters objectively. Han et al. [11] developed a measurement system based on multiple inertial sensors to evaluate gait parameters in amputees using prostheses. The system was validated against an optical motion capture system and showed that inertial data can be used to obtain kinematic information during walking.

In addition to the IMU sensor, this research system uses a pressure sensor to obtain loading information. Park et al. [12] showed that Velostat-based flexible pressure sensors can be developed to obtain pressure information on the prosthetic socket and support the identification process of prosthesis usage conditions.

Thus, the integration of motion sensors and pressure sensors in this research is designed to produce a monitoring system that not only counts walking activities, but also provides information regarding movement and pressure changes while the prosthesis is in use.

2. Sensor Reading Results

Sensor reading testing was conducted under several activity conditions, namely stationary, standing, slow walking, normal walking, fast walking, and walking on an inclined surface. The test results are as follows.

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Table 2. Sensor Reading Results Based on Activity

Activity	IMU Acceleration (g)	Pressure (kPa)	Status
Stationary	0.98	2.1	Stationary
Standing	1.04	31.5	Standing
Slow walking	1.21	37.8	Walking
Normal walking	1.35	42.6	Walking
Fast walking	1.57	48.9	Walking
Ramp climbing	1.64	51.2	High activity

Based on Table 2, changes in acceleration and pressure values are observed based on user activity. In the stationary condition, the acceleration value is relatively stable and the pressure is at its lowest level. When the prosthesis is used for standing and walking, the pressure value increases. Fast walking and ramp climbing activities produce higher acceleration and pressure values compared to slow walking activities.

These changes indicate that IMU data can be used to distinguish prosthesis movement conditions. This finding is consistent with Han et al. [11], which showed that inertial sensors can be used to obtain gait parameters in prosthesis users and evaluate movement characteristics during walking.

The use of pressure sensors also provides additional information regarding loading conditions. Park et al. [12] developed a flexible pressure sensor for prosthetic sockets and showed that the sensor can be used to measure pressure under various loading conditions.

The results of this study show that the combination of both types of sensors provides complementary information. The IMU sensor provides information regarding movement changes, while the pressure sensor provides information regarding loading changes.

3. Step Detection Results

Step detection testing was conducted by comparing the actual number of steps with the number of steps counted by the system. The test was conducted five times.

Table 3. Step Detection Test Results

Test	Actual Steps	System Steps	Error (%)
1	50	48	4.00
2	100	97	3.00
3	150	146	2.67
4	200	194	3.00
5	250	243	2.80
Average			**3.09**

The test results show that the system is able to detect steps with an average error of 3.09%. The error value is relatively small and indicates that the acceleration signal from the IMU can be used as one of the parameters in the step detection process.

The utilization of inertial sensors to obtain walking parameters is also supported by the research of Han et al. [11]. The inertial sensor-based system they developed was used to obtain gait parameters of prosthesis users and compared with an optical motion capture system. These results indicate that inertial sensors have the potential to be used in objective measurements of prosthesis movement.

In addition, the kinematics dataset of 30 transtibial users developed by Samala et al. [13] shows that IMU data can be used to obtain joint angle and kinematics information during walking. The dataset is also provided openly for research on prosthesis user gait detection and tracking.

Detection errors in this study may be caused by variations in walking speed, changes in step patterns, and differences in signal amplitude when users change activities. Therefore, future development can utilize classification algorithms or machine learning to improve the system's ability to distinguish various activity patterns.

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4. Bluetooth Low Energy Communication Testing Results

Communication testing was conducted to determine the system's ability to transmit sensor data from the ESP32 to the smartphone application using BLE. A total of 1,000 data packets were transmitted at a distance of 5 meters.

Table 4. BLE Communication Test Results

Parameter	Result
Number of packets sent	1,000
Packets received	968
Failed packets	32
Communication success rate	96.8%
Average delay	74 ms
Testing distance	5 m

Communication success percentage is calculated using the equation:

$$P = (N_r / N_s) \times 100\% \quad (2)$$

where:
P = communication success percentage (%)
N_r = number of packets received
N_s = number of packets sent
yielding:

$$P = (968 / 1000) \times 100\% = 96.8\%$$

The test results show that the system is able to maintain communication between the microcontroller and the smartphone with a success rate of 96.8%. An average delay of 74 ms indicates that data transmission takes place with a relatively small lag.

The use of wireless communication in prosthesis systems is also relevant to the development of sensor-based prosthetic devices. Keri et al. [14] developed a low-cost inertial measurement system for lower limb prosthesis users utilizing wireless sensors as part of a movement monitoring system. This research demonstrates that portable sensor systems can be used to obtain user movement information without requiring large laboratory equipment.

The results of this study expand this approach by connecting sensor data directly to a smartphone application so that information can be received and displayed on a more portable device.

5. Smartphone Application Display Results

The smartphone application was developed as a monitoring interface that receives data from the ESP32 via BLE. The application displays several main parameters, namely step count, pressure, prosthesis angle, activity status, and sensor data change graphs.

Table 5. Application Function Test Results

No	Feature	Result
1	Bluetooth connection	Successful
2	IMU data reading	Successful
3	Pressure sensor reading	Successful
4	Step calculation	Successful
5	Prosthesis angle display	Successful
6	Pressure display	Successful
7	Activity status	Successful
8	Sensor data graph	Successful
9	History storage	Successful
10	Disconnection	Successful

The test results show that all main functions of the application can run as designed. Sensor data sent by the ESP32 can be received and displayed in both numerical and graphical forms. The graphical display provides information regarding signal changes during activities so users can view the prosthesis movement and pressure patterns.

The concept of the monitoring application is in line with the development of sensor-based prosthesis systems and digital devices. Systematic reviews on human-prosthesis interaction indicate that sensor subsystems, electronic components, and digital interfaces are important parts in the development of modern prosthetic devices [15]. Sensor systems not only function as a data source, but can also be used to evaluate the performance and interaction of the prosthesis with the user.

In this study, the smartphone application serves as an interface that converts technical sensor data into more easily understandable information. This is an important aspect in the development of monitoring systems intended for use outside the laboratory environment.

6. Activity Monitoring Results

The system is also designed to distinguish several user activity conditions based on the combination of IMU data and pressure sensors. The initial classification results are shown in Table 6.

Table 6. Activity Identification Based on Sensors

Activity	IMU	Pressure	Identification
Stationary	Relatively stable	Low	Stationary
Standing	Stable with small changes	Stable	Standing
Slow walking	Low periodic changes	Periodic changes	Walking
Normal walking	Moderate periodic changes	Periodic changes	Walking
Fast walking	High periodic changes	Higher pressure	Fast walking
Ramp climbing	Larger angle changes	High pressure	High activity

Changes in signal characteristics indicate that the combination of IMU and pressure sensors can provide more complete information compared to using a single sensor. Multimodal systems in prostheses are also developed by research on robotic prosthetic feet that combine pressure sensors and IMUs to detect heel strike and toe off phases as well as obtain biomechanical parameters [16].

With this approach, the developed monitoring system has the opportunity to be developed from mere step recording into a more detailed user activity identification system.

7. Test Results Recapitulation

Overall system test results are shown in Table 7.

Table 7. System Test Results Recapitulation

Test Parameter	Result
Average step detection error	3.09%
BLE communication success rate	96.8%
Average delay	74 ms
Communication distance	5 m
IMU sensor reading	Successful
Pressure sensor reading	Successful
Application display	Successful
Real-time monitoring	Successful

Overall, the test results indicate that the prototype can perform its main function as a smart lower limb prosthesis monitoring system. The IMU sensor is able to provide information regarding movement changes, while the pressure sensor provides additional information regarding loading. Both data can be processed by the ESP32 and transmitted to the smartphone application using BLE.

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These results are relevant to the research of Han et al. [11], which showed that IMU-based measurement systems can be used to obtain gait parameters objectively in prosthesis users. Meanwhile, Park et al. [12] demonstrated the potential of flexible pressure sensors for use in smart prosthesis systems.

From the perspective of prosthesis development in Indonesia, the research by Wicaksana et al. [17] shows that simulation-based analysis can be used to evaluate the mechanical performance of transtibial prosthetic sockets during the walking cycle. These results demonstrate the importance of obtaining data regarding prosthesis response to loads at various gait phases. Other research in Indonesia also shows that the type of prosthetic foot is related to walking parameters, including the walking speed of transtibial prosthesis users [18].

Thus, the developed monitoring system can complement the mechanical and biomechanical evaluation of prostheses. Data obtained in real time via smartphone has the potential to be used for daily prosthesis usage monitoring and serve as initial data in the development of more complex gait analysis systems.

DISCUSSION

1. Sensor Performance in Prosthesis Monitoring

The results showed that the integration of the IMU sensor and pressure sensor is able to provide information regarding changes in prosthesis condition based on user activity. The IMU acceleration value increased from 0.98 g in the stationary condition to 1.64 g when the user performed ramp climbing activity. At the same time, pressure increased from 2.1 kPa to 51.2 kPa. Changes in these two parameters indicate a relationship between motion activity and the loading received by the prosthesis.

The use of IMUs in prosthesis monitoring systems has the advantage that sensors can acquire movement data without requiring large-scale gait analysis equipment. Han et al. [11] developed a measurement system based on seven wireless inertial sensors in amputees and compared it with an optical motion capture system. The study results showed that IMU data processing can be used to obtain gait parameters and joint angle estimations objectively. Madgwick and zero velocity update algorithms were also used to improve movement data processing.

These results reinforce the use of IMU in this study as a source of prosthesis movement data. Although this study used only one IMU unit, acceleration changes can still be used to identify basic activity patterns. Research on the validity of IMU in transtibial prosthesis users also shows that the kinematics results obtained by IMU have good agreement with optical motion capture, especially for movements in the sagittal plane [19].

Pressure sensors provide different information from IMUs because they directly represent load changes on parts experiencing surface contact. The integration of both sensors is important because movement changes do not always indicate the magnitude of the load received by the prosthesis. Thus, IMU and pressure data can complement each other in providing an overview of prosthesis usage conditions.

2. System Capability in Step Detection

The test results showed an average step detection error of 3.09%. This value indicates that the system is able to provide an estimate of the number of steps with a relatively low error rate in the testing scenario used.

However, the step detection process in prosthesis users has its own challenges because gait patterns are not always the same as those of non-amputee users. Changes in speed, step length, prosthesis type usage, and surface conditions can affect acceleration signal characteristics.

This is demonstrated in research validating various step-counting algorithms in lower limb prosthesis users. The study tested 10 accelerometer-based algorithms on 48 amputee users and showed that step counter accuracy is influenced by user characteristics and the types of activities performed in real environments [20].

Therefore, the 3.09% error value in this study cannot yet be considered a universal accuracy rate. This value only describes the prototype performance under the testing conditions used. Testing with a larger number of users and a wider variety of activities is needed to determine system capabilities under actual usage conditions.

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Subsequent development can utilize machine learning-based algorithms to improve the system's ability to distinguish various activity patterns. Recent research shows that data from wearable sensors can be processed using a combination of CNN and LSTM to recognize multiple locomotion modes for prosthesis applications [21]. This approach shows that sensor signals can be developed from mere step counters into activity and environmental condition recognition systems.

3. Analysis of Pressure and Activity Changes

The results showed that fast walking and ramp climbing activities produce higher pressure compared to stationary and slow walking conditions. This condition can technically be related to changes in load distribution during the gait cycle.

Load changes on the prosthesis are an important parameter because the force received by prosthetic components changes throughout the walking cycle. National research by Wicaksana et al. [17] regarding finite element simulation on transtibial sockets showed that the heel strike phase is one of the critical conditions with stress concentration at the posterior distal part of the socket. PET and ABS materials also showed different mechanical responses to loading during the walking cycle.

These findings provide context for the use of pressure sensors in this study. If the system can record pressure changes continuously, the data can be used to identify loading changes at certain phases during walking. Thus, the monitoring system not only functions to determine step count, but can also be developed as a device for monitoring prosthesis loading conditions.

Another national study on prosthetic foot dorsiflexion testing indicates that foot performance evaluation needs to consider loading conditions and movement characteristics occurring during use. Testing based on ISO 10328 can be used to evaluate the mechanical performance of prosthesis components in a measurable manner [22].

By combining sensor data with mechanical testing, future research can be directed to determine the relationship between measured pressure values and the mechanical response of prosthesis components.

4. BLE Communication Performance and Smartphone Integration

The test results showed that BLE communication has a success rate of 96.8% with an average delay of 74 ms at a distance of 5 meters. These results indicate that wireless communication can be used to transmit sensor data from the prosthesis to the smartphone without cables.

The presence of wireless communication provides advantages in terms of portability. Users do not need to carry large data acquisition devices during activities. The system can be placed on the prosthesis, while the smartphone is used as an interface device to view measurement results.

The concept of intelligent prosthetic devices is currently moving toward the integration of sensors, microcontrollers, and user interfaces. Bai et al. [23] explained that intelligent lower limb prostheses are evolving by utilizing electronic technology, microcontrollers, sensors, and interfaces that enable better interaction between users and devices. Human factors are important because prosthesis technology must not only be able to work technically, but also needs to consider how users interact with the device.

In the context of this study, the smartphone serves as a user interface that converts technical data from sensors into more easily understandable information. Dashboards displaying step count, pressure, angle, and activity status can help users view prosthesis usage conditions without having to understand raw sensor data.

5. Relevance of Monitoring to Prosthesis Usage Evaluation

The developed monitoring system has the potential to support prosthesis usage evaluation because it is capable of generating continuous data. Unlike conventional measurements which are generally performed at specific times and places, wearable systems can be used to collect data when users perform daily activities.

Research on methods for evaluating user adaptation to prostheses shows that prosthetic usage assessment requires a combination of various parameters, including biomechanical aspects, activity, function, and user experience. Sensor-based measurement approaches can be one way to obtain objective data regarding user adaptation to prostheses [24].

In the Indonesian context, research on transtibial prosthesis users shows that prosthesis characteristics can be related to mobility parameters such as walking speed. Research on SACH Foot and

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Single Axis Foot users shows differences in walking speed parameters based on the type of prosthetic foot used [18].

These findings indicate that monitoring walking parameters is important because prosthesis performance can affect user mobility characteristics. The system developed in this study can be a tool to obtain activity data more practically.

6. System Contribution to Smart Prosthesis Development

The main contribution of this research lies in the integration of motion sensors, pressure sensors, microcontrollers, wireless communication, and a smartphone application. Most previous studies focused on one specific aspect, such as kinematic measurement using IMU, socket mechanical testing, or prosthesis component development.

This research system combines several of these functions into a monitoring prototype. IMU data is used to determine movement changes, pressure sensors are used to determine loading changes, ESP32 is used for data processing, BLE is used as a communication medium, and a smartphone is used as a visualization device.

This approach is in line with the development of smart prosthetic limbs, which are increasingly directed toward systems capable of acquiring data from users and responding to usage conditions more adaptively. Studies on smart prosthesis development indicate that sensor technology and electronic systems are important parts in the development of new generation prostheses [25].

Thus, the developed system can serve as a basis for subsequent development, such as adding sensors at multiple points on the sole of the foot, developing activity classification algorithms, cloud-based data storage, and providing notifications when abnormal loading conditions occur.

7. Limitations of the Study

Although the system showed quite good results in initial testing, this study still has several limitations. First, testing still uses limited activity scenarios, thus not yet describing all prosthesis usage conditions in daily environments. Second, the number of sensors is still limited to IMU and pressure sensors, so other biomechanical parameters cannot be observed directly.

Third, step detection testing has not been directly compared with gold standards such as motion capture or force plates. In fact, previous research shows that comparing IMUs with motion capture systems can be used to determine the validity level of kinematic measurements in prosthesis users [11], [19].

Fourth, the smartphone system still functions as a monitoring device and has not been used to perform complex gait analyses. Therefore, further research can add machine learning-based classification algorithms to recognize activities such as walking, standing, sitting, ascending stairs, descending stairs, and walking on inclined surfaces.

8. Development Implications

The research results indicate that sensor and smartphone technologies can be used as a relatively simple approach to build a prosthesis monitoring system. The use of components such as ESP32, IMU, pressure sensors, and BLE allows the system to be designed in a more portable form compared to laboratory-based gait analysis systems.

In further development, the system can be directed into a monitoring platform that periodically stores usage data. This data can be used to determine changes in user activity from day to day and provide additional information for the prosthesis evaluation process.

In addition, the integration of sensor data with smartphone applications opens up opportunities to develop early warning systems. For example, the system can provide notifications if pressure exceeds a certain limit, significant changes in step patterns occur, or a decrease in user activity occurs.

Thus, this study not only produces a measurement device, but also provides a basis for the development of a smart prosthesis ecosystem connecting mechanical devices, mechatronic sensors, data processing, wireless communication, and digital applications into a single integrated system.

CONCLUSION

This study produced a smart lower limb prosthesis monitoring system integrating an Inertial Measurement Unit (IMU) sensor, a pressure sensor, an ESP32 microcontroller, Bluetooth Low Energy

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(BLE) communication, and a smartphone application. The system is capable of reading changes in prosthesis movement and pressure based on user activity and displaying information in real time via smartphone.

The test results show that the system is able to detect steps with an average error of 3.09%, while data communication using BLE has a success rate of 96.8% with an average delay of 74 ms at a distance of 5 meters. All main functions of the application, including sensor reading, step calculation, pressure display, movement angle, activity status, graphs, and history storage, run as designed.

The integration of the IMU sensor and pressure sensor provides complementary information regarding prosthesis movement and loading. With the smartphone application, prosthesis usage data can be monitored more practically without direct cable connections. This system can serve as a basis for smart prosthesis development for continuous user activity monitoring.

Subsequent development needs to be conducted through testing on more prosthesis users, adding variations in activities and surface conditions, and validation using standard devices such as motion capture or force plates. In addition, the implementation of machine learning algorithms and cloud-based data storage can be developed to improve the system's ability in activity classification and gait pattern analysis.

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