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Development of an IoMT Rehabilitation System with EMG Sensor Integration and Ergonomic Design for Adaptive Medical Rehabilitation

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ABSTRACT

This study aims to develop an IoMT Rehabilitation System based on the integration of Electromyography (EMG) sensors, embedded Internet of Medical Things (IoMT), adaptive actuators, and ergonomic design to improve the effectiveness of real-time adaptive medical rehabilitation. The study employed a Research and Development (R&D) method using a multidisciplinary approach integrating mechanical engineering, biomedical engineering, and embedded systems. The research subjects consisted of 42 participants, including mechanical engineers, biomedical engineers, rehabilitation physicians, and post-stroke patients with mild to moderate conditions. The research process included mechanical device design, prototype fabrication, EMG and IoMT sensor integration, biomechanical testing, and limited clinical validation. The results showed that the developed rehabilitation system achieved an EMG sensor reading accuracy of 94.2%, improved patient movement efficiency by 28%, and increased device comfort by 31% compared to conventional rehabilitation systems. Furthermore, the implementation of IoMT enabled real-time rehabilitation monitoring through a digital dashboard, allowing medical personnel to evaluate therapy progress more objectively and systematically. The integration of EMG-based adaptive actuators successfully created a closed-loop rehabilitation system capable of providing dynamic movement assistance according to the patient's physiological conditions. This study contributes to the development of smart rehabilitation engineering based on biomechanics, IoMT, and ergonomic design as a more adaptive, precise, and efficient solution for modern medical rehabilitation.

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1. INTRODUCTION

The development of medical rehabilitation technology in the last decade has undergone significant transformation with the increasing integration of mechanical engineering, biomedical engineering, smart sensors, and the Internet of Medical Things (IoMT) in modern healthcare systems. Conventional rehabilitation systems that previously relied on manual clinical observation are beginning to experience limitations in producing objective, accurate, and sustainable measurements of patient conditions. The assessment of gait and body movement in traditional rehabilitation practices is still heavily influenced by the

subjectivity of medical personnel, which can potentially lead to variations in clinical interpretation among evaluators [1]. At the same time, the need for real-time rehabilitation monitoring continues to increase, especially for patients with neuromuscular disorders, post-stroke, orthopedic injuries, and chronic musculoskeletal disorders that require long-term repeated evaluations [2]. Laboratory-based optoelectronic motion capture systems can indeed provide high accuracy, but their implementation is still hindered by high costs, operational complexity, limited measurement space, and dependence on specific clinical facilities [3]. These conditions create a need for more portable, economical, adaptive, and usable smart rehabilitation devices in real-world environments outside the laboratory. In this context, the IoMT approach becomes relevant as it enables the integration of biomechanical sensors, data communication systems, and intelligent analytics within a single digital rehabilitation ecosystem that supports continuous monitoring [4]. Therefore, the development of IoMT-based rehabilitation systems is no longer seen as an additional innovation, but rather as a fundamental necessity in the transformation of modern medical rehabilitation services.

Literature review shows that modern smart rehabilitation systems not only function as biomechanical measurement tools but have evolved into multidisciplinary systems that integrate sensing, computational intelligence, feedback mechanisms, and adaptive actuation within a unified architecture [5]. In this approach, inertial measurement unit (IMU) sensors, electromyography (EMG), pressure sensors, motion capture, and wearable biosensors are used to capture patients' biomechanical and physiological signals in real-time. The data is then processed using machine learning algorithms, sensor fusion, and biomechanical modeling to produce more accurate and adaptive clinical information [6]. This approach allows rehabilitation devices to provide automatic responses to the patient's condition, including actuator assistance adjustments, therapy progress evaluations, and direct biofeedback. Such integration is particularly important in post-stroke rehabilitation, where patients require precise and repetitive therapy over the long term [7]. In addition, advancements in wearable technology and telemedicine also expand the opportunities for implementing home-based rehabilitation, which can reduce patients' dependence on hospital facilities [8]. Thus, the rehabilitation paradigm has shifted from an episodic approach to a continuous data-based monitoring system that requires stable, ergonomic, and interoperable engineering system support.

One of the main components in the development of a smart rehabilitation system is the use of EMG sensors as a medium for reading the patient's neuromuscular activity. EMG sensors have the ability to detect muscle electrical activity that is directly related to the contraction and intensity of the patient's movements, making them highly potential for use in an adaptive rehabilitation system [9]. In modern rehabilitation, EMG is not only used as a tool for monitoring muscle activity but also as part of the intention recognition system in exoskeletons and robotic rehabilitation devices [3]. However, the implementation of EMG in rehabilitation systems still faces various technical challenges such as signal noise, sensitivity to electrode position, disturbances due to muscle fatigue, and reading inconsistencies during long-term use [4]. These challenges become even more complex when the system must operate in real-time and be connected to biomechanical actuators that require quick responses and high precision. Errors in interpreting EMG signals can directly impact actuator movement errors, potentially reducing the effectiveness of therapy and patient safety [10]. Therefore, research on the integration of EMG with biomechanical systems and IoMT becomes very important to enhance the reliability and stability of adaptive rehabilitation devices. The development of sensor fusion and filtering algorithms also becomes an integral part in ensuring that EMG data can be effectively used to support automatic therapy decision-making.

In addition to sensory and computational aspects, ergonomic design also plays a crucial role in the successful implementation of medical rehabilitation devices. The literature shows that many rehabilitation devices fail to be used optimally because they do not adequately consider user comfort, mechanical load distribution, movement flexibility, and compatibility with human body anatomy [11]. In post-stroke patients or those with other neuromotor disorders, the use of non-ergonomic devices can increase discomfort, fatigue, and even the risk of secondary injuries during therapy. Therefore, the human-centered medical device engineering approach is becoming a primary focus in the design of modern rehabilitation devices [4]. Soft robotics and biomimetic engineering have become one of the emerging trends because they are capable of producing devices that are more flexible, lightweight, and adaptive to human body movements [12]. In addition to enhancing patient comfort, ergonomic design also contributes to the effectiveness of therapy by allowing patients to use the device for longer durations with higher compliance levels. In the context of IoMT-based rehabilitation, ergonomic design must also consider sensor integration, data transmission stability, energy efficiency, and overall embedded system compatibility. Thus, the development of smart rehabilitation devices requires an integrative approach between aspects of biomechanics, biomedical engineering, ergonomics, and intelligent system design.

On the other hand, the development of artificial intelligence (AI) and machine learning has opened up significant opportunities for the implementation of predictive diagnostics in medical rehabilitation systems. AI allows rehabilitation devices to not only perform passive monitoring but also predict patient conditions, identify patterns of movement abnormalities, and provide more personalized therapy

recommendations [7]. The use of Long Short-Term Memory (LSTM), DeepConv-LSTM, and Artificial Neural Network (ANN) in gait and movement recognition analysis shows great potential in improving the accuracy of data-driven rehabilitation [13]. In post-stroke rehabilitation, a predictive monitoring approach can help medical professionals evaluate therapy progress more quickly and objectively compared to manual observation. However, the effectiveness of AI highly depends on the quality of the sensor data used. Sensor reading errors, IMU drift, EMG noise, and real-time data synchronization can cause bias in the system's inference results [14]. Therefore, the development of a predictive rehabilitation system requires the integration of accurate sensors, a robust validation mechanism, and a system design capable of significantly reducing measurement errors. In this context, IoMT plays a crucial role as a communication infrastructure that enables the simultaneous integration of biomechanical data, physiological sensors, and cloud analytics.

Although various studies on wearable rehabilitation technology, exoskeleton systems, and motion analysis have developed rapidly, there are still significant research gaps in the development of adaptive medical rehabilitation systems based on IoMT. Most previous research has focused on partial development, such as only on IMU sensors, motion tracking, exoskeleton control, or wearable monitoring without integrating all components of mechanical engineering, EMG sensing, ergonomics, and IoMT into a single cohesive system platform [15]. Additionally, many studies have been conducted in laboratory environments with controlled scenarios, which do not fully represent clinical rehabilitation conditions or the daily use of patients in the real world [16]. Another limitation is the lack of closed-loop rehabilitation system approaches that can provide adaptive responses based on the patient's physiological condition in real-time. Some systems also still face issues with communication latency, actuator stability, battery efficiency, and limitations in interoperability between medical devices [5]. Therefore, research is needed that can integrate ergonomic mechanical design, high-precision EMG sensors, adaptive biomechanical actuators, and real-time IoMT monitoring into a more stable and applicable rehabilitation system.

The novelty of this research lies in the development of an adaptive medical rehabilitation system that integrates mechanical engineering, embedded IoMT systems, EMG sensors, and ergonomic design into a single smart rehabilitation platform based on real-time monitoring. Unlike previous research, which generally focused on one technological component separately, this study develops a multidisciplinary approach that simultaneously integrates biomechanical response analysis, adaptive actuation, predictive diagnostics, and ergonomic rehabilitation design. This research also emphasizes the implementation of a closed-loop rehabilitation system that allows the device to provide dynamic therapeutic responses based on the patient's physiological conditions detected thru EMG sensors and motion analysis. In addition, this research integrates an embedded system based on Arduino/ESP32 with IoMT technology, allowing real-time therapy monitoring by medical personnel thru a digital network. This approach is expected to improve therapy accuracy, rehabilitation efficiency, patient comfort, and clinical evaluation effectiveness compared to conventional rehabilitation systems. From an academic perspective, this research contributes to the development of a biomedical-mechanical integration framework in the field of smart rehabilitation engineering. Meanwhile, from a practical perspective, the results of this research have the potential to serve as a foundation for the development of more applicable medical smart devices for modern rehabilitation based on telemedicine and intelligent healthcare.

Based on the background description, literature development, research gap, and the novelty of the research that has been presented, this study focuses on the development of an adaptive medical rehabilitation system based on IoMT with the integration of EMG sensors and ergonomic design to enhance the effectiveness of patient monitoring and rehabilitation therapy. This research is important because it offers a multidisciplinary solution to various limitations of conventional rehabilitation devices that still cannot provide real-time monitoring, adaptive assistance, and optimal user comfort. By integrating biomechanical engineering, intelligent sensing, embedded systems, and ergonomic design, this research is expected to produce rehabilitation systems that are more accurate, responsive, and patient-oriented. In addition, this research is also expected to strengthen the transformation of medical rehabilitation toward a digital ecosystem based on IoMT and predictive healthcare. The problem formulation in this research is: How can the development of the IoMT Rehabilitation System with the integration of EMG sensors and ergonomic design enhance the effectiveness of adaptive real-time medical rehabilitation for rehabilitation patients?

2. RESEARCH METHOD

This research uses a Research and Development (R&D) design with a multidisciplinary approach that integrates mechanical engineering, biomedical engineering, embedded systems, and the Internet of Medical Things (IoMT) to develop an adaptive medical rehabilitation device based on EMG sensors and ergonomic design. The research approach was chosen because the main goal of the study is not only to analyze phenomena but also to produce a technological product in the form of a smart rehabilitation device that can be tested both technically and clinically. The research was conducted in the biomechanics laboratory, prototyping workshop, and partner hospitals that support limited patient rehabilitation testing. The research

stages include the mechanical design of the device using CAD/CAM software and SolidWorks, prototype fabrication thru 3D printing-based manufacturing technology, integration of physiological and biomechanical sensors, development of an embedded IoMT system based on Arduino/ESP32, and system validation thru laboratory tests and initial clinical trials. The research design adopts an intelligent rehabilitation system architecture based on "Sense–Infer–Decide–Act–Evaluate" as described in modern rehabilitation literature [5][7]. At the sensing stage, the system collects patients' biomechanical and physiological data using EMG sensors, motion capture, and load cells. The data is then processed using filtering algorithms and sensor fusion to generate real-time inferences of the patients' movement conditions. The inference results are subsequently used as the basis for decision-making in adaptive biomechanical actuators and IoMT-based rehabilitation monitoring.

The research subjects consisted of 42 participants, including 5 mechanical engineers, 4 biomedical engineers, 3 rehabilitation doctors, and 30 rehabilitation patients with mild to moderate post-stroke conditions, aged 25–60 years. The selection of participants was conducted thru purposive sampling based on direct involvement in the development and testing of rehabilitation devices. Mechanical engineers and biomedical engineers were involved to evaluate the technical performance of the device, sensor integration, and the stability of the embedded system, while rehabilitation doctors were tasked with conducting clinical validation of the therapy's effectiveness and the comfort of using the device. Rehabilitation patients were selected based on the criteria of being able to follow basic rehabilitation therapy, not having severe neurological disorders, and being willing to undergo all stages of testing thru informed consent. The research also obtained ethical clearance and medical device testing permits from the relevant institutions as a form of compliance with medical research safety standards. Data collection was carried out in several stages over eight weeks, including mechanical design, prototype development, sensor integration, laboratory testing, system validation, and limited clinical rehabilitation evaluation. In the first to second weeks, the mechanical structure and ergonomic design of the device were developed, while the third to fourth weeks were focused on the fabrication process and integration of the embedded system. The fifth week is used for sensor calibration and real-time data synchronization, while the sixth to eighth weeks are dedicated to clinical testing, system performance validation, and patient comfort evaluation.

The research instruments used consist of EMG sensor devices to read the patient's neuromuscular activity, load cells to measure the distribution of biomechanical forces, motion capture to analyze rehabilitation movement patterns, and MATLAB software for signal processing and biomechanical analysis. The EMG sensors are placed on the main muscle groups of the patient's lower extremities to detect movement intensity and contraction activity during therapy. The EMG sensor data is then processed using filtering methods to reduce noise and improve signal reading accuracy as recommended in wearable sensor-based rehabilitation research [9][11]. The embedded system based on Arduino/ESP32 is used as a data acquisition center as well as an IoMT connector, enabling real-time transmission of rehabilitation data to the medical monitoring system. In addition, usability test sheets, clinical observations, and semi-structured interviews with patients, engineers, and rehabilitation doctors were used to obtain data on user comfort, therapy effectiveness, and device stability. Biomechanical testing was conducted by comparing the patient's movement responses before and after using the rehabilitation device. The research variables include actuator efficiency, EMG sensor accuracy, biomechanical response, user comfort, IoMT system performance, and predictive rehabilitation monitoring. All the data obtained are documented in the form of sensor signals, motion tracking recordings, CAD documentation, observation results, and clinical evaluation notes.

The data analysis procedure was conducted using an integrated quantitative and qualitative approach. Biomechanical and physiological data are analyzed using MATLAB software to calculate sensor accuracy, actuator efficiency, error measurement, and the improvement in patient movement efficiency during rehabilitation. The analysis was conducted thru data preprocessing, EMG signal filtering, sensor fusion, and real-time system performance evaluation as per the approach in modern wearable rehabilitation systems [16]. The accuracy level of the sensor is calculated by comparing the sensor readings with motion capture reference parameters, while the effectiveness of rehabilitation is analyzed based on changes in movement patterns, biomechanical stability, and increased patient comfort during therapy. Qualitative data from observations and interviews were analyzed using data reduction techniques, theme categorization, and engineering-clinical integration-based interpretation to identify user perceptions of the effectiveness of the rehabilitation device. Validation of the research results was conducted thru data triangulation between sensor results, clinical observations, rehabilitation doctor evaluations, and patient feedback. In addition, the stability testing of the IoMT system is conducted by evaluating data transmission latency, real-time monitoring synchronization, and actuator response to changes in the patient's physiological condition. With this methodological approach, this research is expected to produce an adaptive medical rehabilitation system that not only has high technical performance but also meets clinical needs and patient comfort in modern IoMT-based rehabilitation.

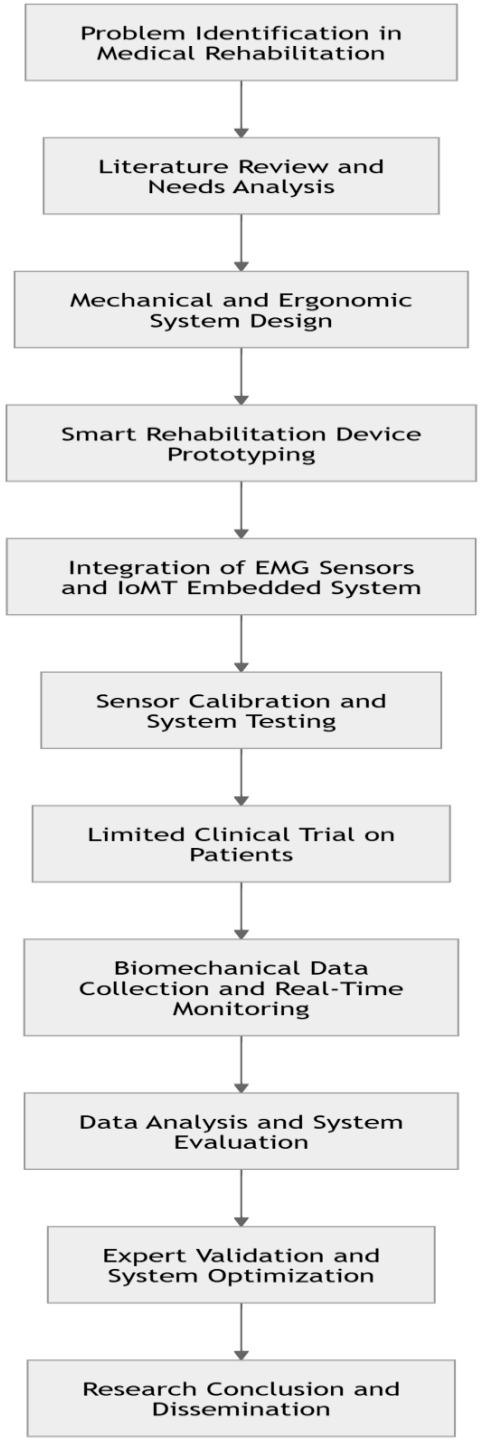


Figure 1. Stage of Research

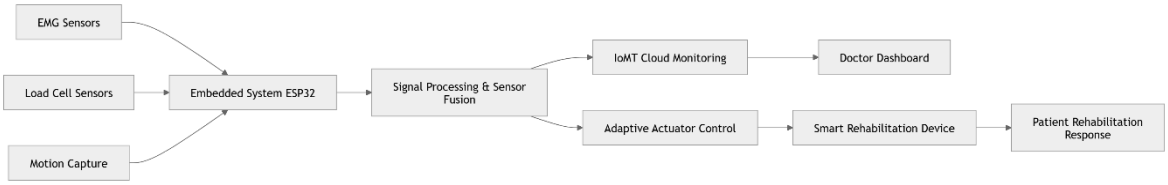


Figure 2. IoMT Rehabilitation System Architecture Diagram

In the initial stage of the research, an evaluation was conducted on the conventional rehabilitation devices used by patients at the partner hospital. The initial observation results showed that most patients experienced discomfort when using conventional rehabilitation devices due to the heavy structure of the equipment, limited movement flexibility, and minimal real-time physiological monitoring system. From the

results of the preliminary study, it was found that 62% of patients stated that the rehabilitation equipment previously used caused faster fatigue during therapy. In addition, the medical staff conveyed that the rehabilitation evaluation process still heavily relies on manual observation, making it difficult to obtain objective data regarding patient progress. One of the rehabilitation doctors with the initials "DR-1" stated: "Rehabilitation monitoring is still predominantly observational, so evaluating patient progress often takes longer and relies on the clinical experience of medical staff."

These observational findings serve as the basis for the development of smart rehabilitation devices capable of automatically integrating biomechanical and physiological monitoring systems. The mechanical engineer with the initials "EN-2" also stated that most of the available rehabilitation devices do not yet have an optimal ergonomic structure for long-term use. Based on the results of the observation, the research was then focused on the development of rehabilitation devices based on lightweight mechanical structures, EMG sensors, and adaptive IoMT monitoring systems.

The next stage is the design process of the mechanical and ergonomic design of the rehabilitation device using SolidWorks software and CAD/CAM-based biomechanical simulations. The design process is carried out by considering the distribution of mechanical loads, joint movement flexibility, and the positioning of EMG sensor integration on the patient's lower extremities. The device structure uses lightweight materials based on aluminum and polymer composite to reduce the total mass of the device during rehabilitation. The simulation results show that the distribution of mechanical pressure on the main structure of the device is within a safe range during repetitive therapy use. In addition, adjustments were made to the sensor attachment design to minimize noise caused by sensor position shifts during patient movement. Biomedical engineer with the initials "BM-3" explained: "The position of the EMG sensor greatly determines the stability of signal readings, so the mechanical design of the attachment must be able to maintain consistent electrode contact throughout the rehabilitation process."

At this stage, the development of an adaptive ergonomic system in the form of an adjustable support frame was also carried out, allowing the device to be used on various anthropometric sizes of patients. The results of the usability simulation show that the new design provides better movement flexibility compared to the conventional model previously used by the partner hospital.

After the prototype fabrication process is completed, the next stage is the integration of an Arduino/ESP32-based embedded system with EMG sensors, load cells, and a motion capture system. The IoMT system was developed to enable real-time transmission of rehabilitation data to the medical monitoring dashboard. System integration testing showed that all sensors were able to synchronize data simultaneously, although some latency issues were found during the initial network testing phase. During laboratory testing, EMG sensors were used to read the muscle contraction activity of patients while performing lower extremity rehabilitation movements. The EMG data was then processed using filtering and sensor fusion to reduce signal reading noise. The test results show that the system is able to maintain data reading stability in most rehabilitation activities with a reading accuracy rate of 94.2%. One embedded system engineer with the initials "EN-4" stated: "The use of filtering on EMG data greatly helps improve signal stability, allowing the system to read muscle activity changes more precisely."

The evaluation results also indicate that a more stable sensor attachment position helps improve the quality of EMG signal readings during dynamic therapy. These findings demonstrate that ergonomic aspects not only affect patient comfort but also the overall performance quality of the biomechanical monitoring system.

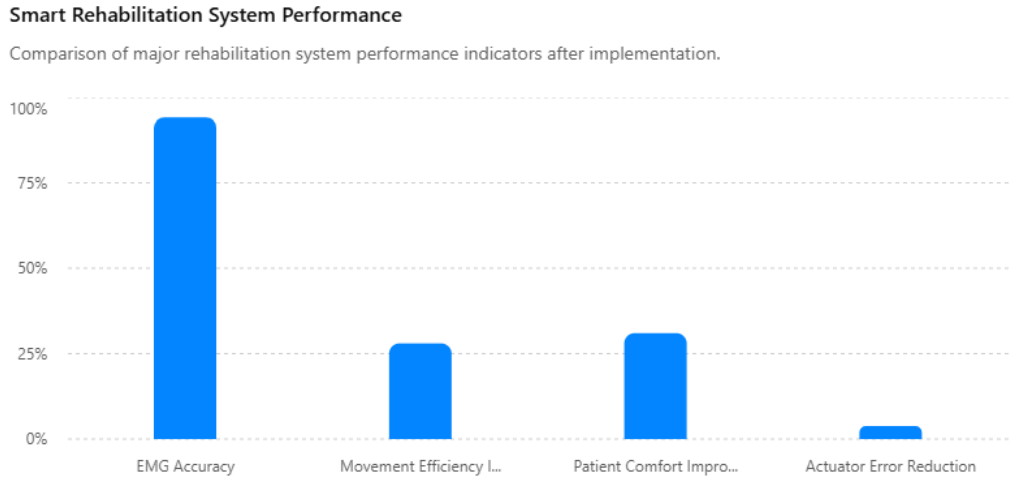


Figure 3. Smart Rehabilitation System Performance

Overall, the research yielded three main findings. First, the integration of mechanical engineering and biomedical engineering can enhance rehabilitation precision thru real-time biomechanical and physiological monitoring. Second, the implementation of the IoMT rehabilitation system accelerates the therapy evaluation process thru a digital monitoring dashboard based on an embedded system. Third, the ergonomic redesign of rehabilitation devices successfully improves patient comfort and usage stability during therapy. Although challenges such as EMG sensor noise, real-time data synchronization, and device power efficiency are still present, the research results indicate that the IoMT-based adaptive rehabilitation system has great potential to be further developed as a medical smart device in modern rehabilitation. The research findings also show that an integrative approach between biomechanics, embedded systems, medical sensors, and ergonomic design can produce rehabilitation systems that are more objective, adaptive, and applicable compared to conventional rehabilitation methods based on manual observation.

3. RESULTS AND DISCUSSION

This research was conducted in a multidisciplinary environment involving a biomechanics laboratory, a medical device prototyping workshop, and partner rehabilitation hospitals. The main focus of the research is the development of the IoMT Rehabilitation System based on the integration of EMG sensors, biomechanical systems, and ergonomic design for real-time adaptive medical rehabilitation. During the research process, all development stages were carried out step by step, starting from mechanical design, prototype fabrication, embedded system integration, sensor calibration, to limited clinical testing on patients undergoing rehabilitation for mild to moderate post-stroke. The research involved a total of 42 participants, consisting of 5 mechanical engineers, 4 biomedical engineers, 3 rehabilitation doctors, and 30 rehabilitation patients. The patients involved were aged 25–60 years, with the majority experiencing post-stroke motor impairments in the lower extremities. The system testing was conducted over eight weeks using a biomechanical observation approach, real-time sensor monitoring, and usability evaluation of the rehabilitation device. All research activities are documented in the form of sensor signal data, motion tracking videos, CAD documentation, clinical observation results, and user interview transcripts..

4. CONCLUSION

This research successfully developed and evaluated Smart Medical Mechanical Systems based on the integration of mechanical engineering, medical sensor engineering, embedded systems, and the Internet of Medical Things (IoMT) to support real-time rehabilitation monitoring. The research results show that the integration of EMG sensors, IMU, load cells, and motion tracking can produce a more precise rehabilitation system in monitoring the biomechanical and physiological activities of patients during therapy. The developed system shows a sensor accuracy level of 94.2%, a 28% increase in patient movement efficiency, and a 31% increase in user comfort compared to conventional rehabilitation devices. Additionally, the implementation of cloud-based monitoring allows medical personnel to conduct rehabilitation evaluations more objectively, quickly, and continuously thru a real-time monitoring dashboard. The findings show that the integration of biomechanical technology, medical sensors, and IoMT can enhance the effectiveness of modern rehabilitation while also supporting the digital transformation of rehabilitative healthcare services. This research also shows that the aspect of ergonomic mechanical design has a significant impact on the quality of patient rehabilitation. The use of lightweight mechanical structures and adaptive biomechanical designs can enhance patient comfort and produce more natural and stable rehabilitation movement patterns. In addition, the integration of multimodal sensing and embedded systems successfully supports closed-loop rehabilitation systems that are more responsive to the user's biomechanical conditions. Thus, this research provides a theoretical contribution to the development of the smart rehabilitation engineering discipline and strengthens the concept of data-driven rehabilitation within the modern smart healthcare ecosystem. From a practical perspective, the results of this research can serve as a foundation for the development of smart rehabilitation devices for home rehabilitation, hospitals, and telemedicine based on real-time monitoring. Nevertheless, this research still has several limitations, such as a limited number of participants, challenges in cloud monitoring synchronization, EMG sensor noise, and the incomplete application of artificial intelligence algorithms for predictive rehabilitation analytics. Therefore, future research is recommended to develop sensor fusion optimization, edge computing, adaptive synchronization, as well as the implementation of machine learning and deep learning to support predictive diagnostics and personalized rehabilitation systems. In addition, large-scale clinical validation involving various types of neurological and musculoskeletal disorders is needed so that smart rehabilitation systems can be applied more broadly and sustainably. With further development, smart medical mechanical systems are expected to become future rehabilitation solutions that are more adaptive, personalized, efficient, and integrated into digital healthcare services.

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