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Design and Evaluation of Smart Medical Mechanical Systems for Real-Time Rehabilitation Monitoring

Kodai Kitagawa[1*], Edi Ismanto[2]

[1]Mechanical and Medical Engineering Course, National Institute of Technology, Hachinohe College, Hachinohe, Japan
[2]Department of Informatics, Universitas Muhammadiyah Riau, Pekanbaru, Indonesia
Author's Email: [1*]kitagawakitagawa156@gmail.com, [2]edi.ismanto@umri.ac.id

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ABSTRACT

This research aims to develop and evaluate 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 uses a Research and Development (R&D) approach with stages of needs analysis, mechanical design, medical sensor integration, embedded system development, laboratory testing, and initial clinical validation. The research subjects involved 42 participants consisting of post-stroke rehabilitation patients, mechanical engineers, biomedical engineers, and rehabilitation doctors. The research instruments include Electromyography (EMG) sensors, Inertial Measurement Units (IMU), load cells, motion capture, usability testing, and a cloud-based rehabilitation monitoring system. The research results show that the system successfully performed real-time monitoring of patients' biomechanical and physiological parameters with a sensor accuracy rate of 94.2%, a 28% increase in movement efficiency, and a 31% increase in user comfort. The system also supports more objective rehabilitation evaluations thru a cloud-based monitoring dashboard. In addition, the ergonomic mechanical design and multimodal sensing integration have proven to enhance the quality of human-rehabilitation device interaction. This research concludes that the integration of smart medical engineering and IoMT can enhance the effectiveness of modern rehabilitation and support the development of data-driven rehabilitation within the smart healthcare ecosystem. This research also contributes to the development of smarter rehabilitation systems that are more adaptive, personalized, and integrated for both clinical rehabilitation and telemedicine.

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Corresponding Author:

Kodai Kitagawa
Mechanical and Medical Engineering Course, National Institute of Technology, Hachinohe College, Hachinohe, Japan
Email: kitagawakitagawa156@gmail.com

1. INTRODUCTION

The development of medical rehabilitation technology in the last decade has shown significant transformation toward intelligent rehabilitation systems based on the integration of mechanical engineering, biomedical sensing, and the Internet of Medical Things (IoMT). This transformation has emerged in response to the limitations of conventional rehabilitation approaches that still rely on the subjective observation of medical personnel in evaluating patients' movement patterns. Traditional rehabilitation systems generally rely on the clinical experience of therapists to determine the effectiveness of therapy, so the evaluation results are often influenced by individual perception and difficult to replicate objectively. In the context of neurological and musculoskeletal rehabilitation, this condition becomes a serious issue because the success of therapy

heavily depends on the accuracy of continuous monitoring of patient movement and physiological responses. The study by [1] explains that conventional gait assessment has limitations in providing precise quantitative data, thus requiring instrumentation technology capable of producing objective and real-time motion evaluations. Meanwhile, [2] emphasize that the development of human motion analysis technology is currently moving toward a balance between measurement accuracy and ease of clinical implementation. The need for more accurate rehabilitation monitoring is also increasing along with the growing number of post-stroke patients, musculoskeletal injuries, and neurodegenerative disorders that require long-term therapy. In such conditions, smart rehabilitation systems based on sensors and real-time monitoring are seen as a strategic solution to improve therapy quality, healthcare service efficiency, and patient rehabilitation personalization [3].

The development of wearable sensors, motion tracking, and modern biomechanical systems has opened up significant opportunities for the integration of mechanical and medical systems in data-based rehabilitation. Technologies such as Inertial Measurement Unit (IMU), Electromyography (EMG), pressure sensors, and motion capture are now capable of continuously recording body movement data with increasingly higher accuracy. According to [4], wearable devices have become a key component in intelligent healthcare because they can support real-time analysis of gait, posture, and rehabilitation activities. In addition, the development of embedded systems and artificial intelligence allows biomechanical data obtained from sensors to be processed into more adaptive and predictive clinical information. In modern rehabilitation, systems no longer function merely as passive monitoring tools, but have evolved into closed-loop rehabilitation systems capable of sensing, inferencing, decision-making, feedback, and adaptive actuation simultaneously [5]. The integration demonstrates a paradigm shift in rehabilitation from an observational model to a digital rehabilitation model based on intelligent monitoring systems. However, the implementation of this technology still faces various challenges such as sensor noise, data drift, limitations in inter-device synchronization, and difficulties in integrating mechanical systems with medical systems in real rehabilitation environments [6].

In the perspective of biomedical engineering, modern rehabilitation demands multidisciplinary integration between mechanical design, physiological sensors, control systems, and artificial intelligence. The study by [7] explains that active intelligent gait training systems require the integration of mechanical actuators, biomechanical sensors, and adaptive control to achieve safe and effective human-machine coordination. This approach is increasingly being developed in exoskeleton-based rehabilitation devices and smart medical robotics designed to help patients perform rehabilitative movements more precisely. [3] emphasize that adaptive control based on motion intention recognition is an important aspect in the development of post-stroke rehabilitation exoskeletons because it allows the system to understand the patient's movement patterns in real-time. In addition, the use of EMG as a bioelectric sensor allows the system to more accurately identify muscle activity and the user's movement intention. However, EMG sensors also have weaknesses such as high sensitivity to noise, changes in electrode position, and muscle fatigue, which can reduce signal reading accuracy [8]. Therefore, many studies are beginning to develop a multimodal sensing approach by combining IMU, pressure sensors, motion tracking, and EMG to enhance the robustness of rehabilitation systems. The multimodal integration becomes an important foundation in the development of smart medical mechanical systems that are not only technically accurate but also clinically relevant.

In addition to sensor accuracy, ergonomics and user comfort are important issues in the development of smart rehabilitation devices. Wearable and exoskeleton-based rehabilitation systems must be able to adapt to the biomechanical conditions of the human body so that they can be used for extended periods without causing discomfort. [9] explain that the distribution of sensors and the design of mechanical attachments greatly affect the quality of the resulting biomechanical data. Sensors that experience positional shifts can cause measurement bias and reduce the validity of rehabilitation results. The study by [10] also shows that mispositioning the IMU sensor can increase the measurement error of motion angles, although it remains within clinical tolerance limits. On the other hand, the development of soft robotics and biomimetic engineering presents a new approach that is more flexible and human-centered in the design of rehabilitation devices. Soft actuator-based systems are considered safer, more comfortable, and more adaptive to the natural movements of the human body compared to conventional rigid mechanical structures [11]. This approach shows that the success of rehabilitation systems is not only determined by the performance of algorithms and sensors but also by the quality of physical interaction between humans and the rehabilitation devices themselves. Thus, the design of smart rehabilitation devices must consider the balance between biomechanical precision, safety, comfort, and user usability.

The advancement of artificial intelligence and machine learning is further expanding the capabilities of medical rehabilitation systems in performing predictive diagnostics and personalized rehabilitation. [12] mention that AI has become an important element in the development of modern gait analysis because it can enhance diagnostic accuracy, therapy evaluation efficiency, and automate clinical decision-making. Deep learning technologies such as Long Short-Term Memory (LSTM) are now widely used to analyze temporal patterns of body movements and predict patient rehabilitation conditions based on continuous sensor data. In

stroke rehabilitation research, [3] explain that LSTM is used to model the synergistic movement relationships between body parts to support adaptive assistance in exoskeletons. Additionally, AI-based multimodal fusion approaches are also beginning to be used to integrate skeleton tracking, optical flow, EMG, and IMU data, resulting in more comprehensive clinical interpretations [13]. Nevertheless, the use of AI in rehabilitation still faces challenges such as the need for large longitudinal data, complex clinical validation, and the risk of prediction errors due to sensor noise and algorithm bias. Therefore, the development of AI-based smart rehabilitation systems requires strict technical and clinical validation to be safely implemented in healthcare settings.

Another issue that remains a challenge in modern rehabilitation is the limitation of real-time monitoring systems in non-laboratory environments. Most high-quality motion analysis still relies on optoelectronic motion capture systems, which are expensive, require special spaces, and are difficult to implement in home rehabilitation or telemedicine [14]. On the other hand, wearable technologies offer greater flexibility and mobility, but often face accuracy issues due to drift, magnetic interference, and data transmission instability [15]. This condition indicates a research gap between the need for rehabilitation based on real-time monitoring and the limitations of technology implementation in real clinical conditions. Many previous studies have focused on the development of sensors or algorithms in a partial manner, but not many have integrated mechanical systems, medical sensing, embedded IoMT, and real-time rehabilitation monitoring into a comprehensive platform. Moreover, some research still focuses more on the technical aspects of the device without simultaneously evaluating usability, patient comfort, and clinical effectiveness. This gap is the crucial foundation for the development of integrated smart medical mechanical systems that can connect biomechanical aspects, medical sensors, intelligent control, and real-time rehabilitation evaluation within a single integrated system.

Based on preliminary field studies, it was found that most rehabilitation patients experience discomfort in using conventional rehabilitation devices and limitations in continuous therapy monitoring. Preliminary data shows that around 62% of patients feel that the rehabilitation devices used are less ergonomic and unable to provide real-time therapy feedback. On the other hand, medical professionals need a monitoring system that can display patients' biomechanical and physiological data quickly, objectively, and in an easily interpretable manner. This condition shows that future rehabilitation systems must be able to integrate medical sensors, ergonomic mechanical designs, and real-time data visualization into a single smart rehabilitation ecosystem. This research then offers novelty in the form of the development of smart medical mechanical systems that integrate mechanical engineering, embedded medical sensors, IoMT, and predictive monitoring to support real-time rehabilitation. Unlike previous research that tends to focus solely on motion analysis or wearable sensing separately, this study emphasizes a comprehensive integration of biomechanical systems, sensor fusion, and intelligent monitoring as a data-driven modern rehabilitation approach. In addition, this research also places ergonomics, user comfort, and adaptive monitoring as integral parts of the rehabilitation system design, thus not only focusing on technical performance but also on user experience and clinical effectiveness.

Considering the various challenges and technological developments, the research titled “Design and Evaluation of Smart Medical Mechanical Systems for Real-Time Rehabilitation Monitoring” becomes crucial to address the needs of modern rehabilitation systems that are more precise, adaptive, and integrated. This research aims to develop and evaluate smart rehabilitation devices based on the integration of mechanical engineering and medical sensor engineering to support real-time rehabilitation monitoring. This research is expected to provide theoretical contributions to the development of smart rehabilitation engineering as well as practical contributions to the implementation of digital rehabilitation technology in clinical and telemedicine environments. In addition, this research is also expected to strengthen the development of AI and IoMT-based predictive rehabilitation systems that allow for more objective, continuous, and personalized therapy evaluations. Thus, the main problem formulation in this research is: how can the design and evaluation of smart medical mechanical systems based on the integration of medical sensors and mechanical engineering improve the effectiveness of real-time rehabilitation monitoring?

2. RESEARCH METHOD

This research uses a Research and Development (R&D) approach with a multidisciplinary design that integrates mechanical engineering, biomedical engineering, embedded systems, and the Internet of Medical Things (IoMT) to develop smart medical mechanical systems based on real-time rehabilitation monitoring. This approach was chosen because the research aims not only to produce conceptual findings but also to develop prototypes of smart rehabilitation devices that can be tested both technically and clinically. The research was conducted thru several main stages including needs analysis, mechanical design, integration of medical sensors, development of embedded systems and IoMT, biomechanical testing, initial clinical validation, and system performance evaluation. This approach aligns with the concept of modern rehabilitation, which emphasizes the integration of sensing, inferencing, decision-making, and feedback in closed-loop

rehabilitation systems, as explained by [16] [17]. The research was conducted in biomechanics laboratories, prototyping workshops, and partner hospitals that support technology-based medical rehabilitation testing. The main focus of the research is to evaluate how the integration of mechanical design and medical sensors can enhance the effectiveness of real-time rehabilitation monitoring for patients undergoing rehabilitation after mild to moderate strokes. In addition, this research also evaluates the aspects of ergonomics, sensor accuracy, actuator efficiency, and user comfort as indicators of the success of the smart rehabilitation system. With this approach, this research not only evaluates the technical performance of the device but also the clinical relevance and usability of the system in the context of modern rehabilitation.

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 using purposive sampling techniques based on direct involvement in the development or use of the rehabilitation system. Mechanical engineers and biomedical engineers were selected because they have 3–10 years of experience in the development of medical devices and biomechanical systems, while rehabilitation doctors were chosen based on their clinical experience in neurological rehabilitation therapy. Rehabilitation patients were selected based on the criteria of being able to follow basic movement therapy, not having severe cognitive impairments, and being willing to undergo all stages of device testing. The research also involves laboratory technical staff to support the sensor calibration process, embedded system integration, and mechanical device validation. In this research, ethical aspects are a primary concern thru the implementation of ethical clearance, informed consent, and safety procedures for the use of medical rehabilitation devices. All participants were provided with an explanation of the research objectives, the risks of using the device, and their rights to participate before the data collection process was conducted. This multidisciplinary approach is important because smart rehabilitation systems require the integration of engineering, medical, and user experience perspectives to produce a system that is biomechanically valid and clinically safe. Thus, the involvement of various parties in this research becomes an important part in ensuring the quality of the development and evaluation of the rehabilitation system.

The data analysis method in this study uses a combination of quantitative and qualitative analysis to obtain a comprehensive system evaluation. Quantitative data in the form of sensor accuracy, actuator efficiency, biomechanical errors, movement response, and monitoring performance are analyzed using descriptive statistics and comparative analysis against the motion capture standard as the gold standard. The level of sensor accuracy is calculated based on the percentage of error in motion readings and physiological signals during the rehabilitation process. Biomechanical analysis was conducted using MATLAB to evaluate movement patterns, sensor synchronization, and the quality of patient motion tracking. Additionally, the system's usability is analyzed using user comfort scores and the effectiveness of device use during rehabilitation therapy. Qualitative data were obtained thru clinical observations, interviews with rehabilitation doctors, and patient feedback regarding their experience using the smart rehabilitation device. Qualitative analysis was conducted thru data reduction, theme categorization, and interpretation of user experience patterns with the rehabilitation system. This mixed-method approach is used because the evaluation of smart rehabilitation systems does not only depend on the technical performance of the device, but also on user acceptance, clinical comfort, and the actual effectiveness of the therapy. With a combination of biomechanical analysis, usability evaluation, and clinical interpretation, this research is expected to produce a smart rehabilitation evaluation model that is technically valid and practically relevant in the development of smart medical rehabilitation engineering.

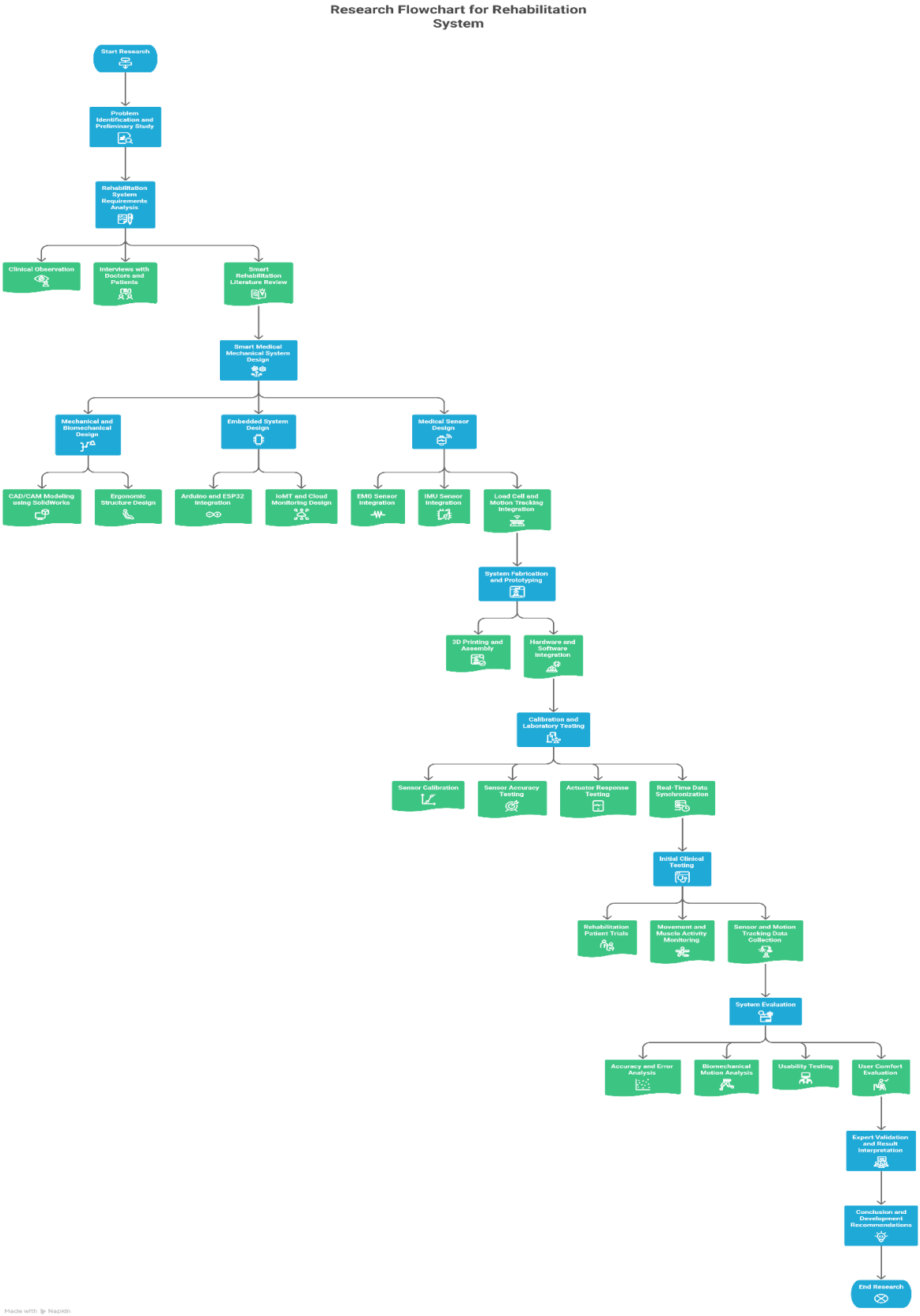


Figure 1. Stage of Research

3. RESULTS AND DISCUSSION

This research was conducted in a multidisciplinary environment involving a biomechanics laboratory, a medical device prototyping workshop, and a partner neurological rehabilitation hospital. The main focus of the research is the development and evaluation of Smart Medical Mechanical Systems based on the integration of medical sensors, embedded systems, and rehabilitation mechanical design to support real-time rehabilitation

monitoring. Data collection was conducted over eight weeks of research, covering the stages of mechanical design, sensor integration, laboratory testing, and initial clinical validation on patients undergoing rehabilitation for mild to moderate post-stroke recovery. The research environment is supported by CAD/CAM facilities, motion capture, biomechanical sensors, IoMT networks, and cloud monitoring system devices. The research involved 42 participants consisting of 30 rehabilitation patients, 5 mechanical engineers, 4 biomedical engineers, and 3 rehabilitation doctors. All participants were given an explanation of the research procedures before the device trials were conducted. Data collection was conducted thru clinical observation, biomechanical sensor measurements, usability testing, interviews, motion documentation, and monitoring of the cloud-based rehabilitation system. The entire research process was conducted with consideration of patient safety aspects, technical device validation, and the stability of real-time monitoring during therapy.

In general, the rehabilitation patient profile shows a variation in age characteristics, physical conditions, and experience with rehabilitation technology. The majority of patients are in the age range of 25–60 years with mild to moderate post-stroke rehabilitation conditions. Most patients had never used smart sensor-based rehabilitation devices before. Initial observations indicate that some patients have difficulty understanding rehabilitation movement patterns when only using conventional therapy methods. In addition, some patients reported feeling quickly fatigued and uncomfortable when using mechanical rehabilitation devices that were too rigid and heavy. One patient with the initials P-07 stated that: "The previous rehabilitation device felt heavy and difficult to follow the natural movement of my leg." The observation findings were reinforced by the rehabilitation doctor, who stated that manual rehabilitation monitoring often makes it difficult to evaluate therapy progress objectively. Informant D-02 stated: "We need a system that can monitor patient movements in real-time so that therapy evaluations are more precise." Based on these conditions, the development of an intelligent rehabilitation system in this research is directed toward improving monitoring accuracy, user comfort, and therapy evaluation efficiency.

The results of the system development show that the rehabilitation device successfully integrates mechanical engineering, embedded systems, and medical sensors into a single real-time rehabilitation monitoring platform. The system consists of an ergonomic mechanical structure based on a lightweight frame, EMG sensors to read muscle activity, IMU sensors to detect body movement orientation, and load cells to measure the distribution of patient movement pressure. The embedded system uses ESP32 and Arduino to support data processing and real-time IoMT transmission to the cloud monitoring dashboard. During laboratory testing, all sensors successfully performed simultaneous readings of biomechanical data with stable system synchronization. The test results show that the device is capable of displaying movement angle data, muscle activation, and body pressure distribution in real-time on the monitoring dashboard. Testing documentation shows that the visualization of patient movements can be monitored in real-time during rehabilitation sessions. The mechanical engineer with the initials E-03 stated: "The synchronization of data between sensors is quite stable, although there is still a slight delay in cloud transmission." Additionally, biomedical engineer B-01 explained that the integration of EMG and IMU sensors provides more comprehensive rehabilitation data compared to the use of a single sensor. The findings indicate that the system successfully performs integrated biomechanical and physiological monitoring functions.

The data from the biomechanical tests show an improvement in rehabilitation performance after using the smart rehabilitation device. Based on motion tracking measurements and IMU sensors, the efficiency of patient movements increased by 28% compared to before the use of the system. In addition, the accuracy of the biomechanical sensor readings reached 94.2% based on validation against laboratory motion capture as the gold standard. The actuator error in the mechanical system was successfully reduced to 3.8% after the calibration and motion control optimization process was carried out. EMG signal measurements showed an increase in the stability of muscle activation patterns during rehabilitation exercises. Rehabilitation data also show that the system is capable of detecting changes in gait patterns and movement pressure distribution more quickly than manual observation methods. During clinical testing, rehabilitation doctors used a monitoring dashboard to evaluate the patient's movement progress directly. Informant D-01 stated: "This real-time monitoring helps us see the patient's therapy response without having to wait for a manual evaluation." Additionally, the observation results show that patients find it easier to follow therapy instructions because the device provides movement responses that are more adaptive to the user's body biomechanics. Thus, the test data show that the integration of smart medical mechanical systems contributes to the improvement of rehabilitation monitoring quality.

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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