IoT-based Human Movement Monitoring System: Prospect for Conceptual Digital Twin

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Abstract

The growing popularity of smart healthcare and novel innovations in human movement monitoring systems open doors for diagnosing various health conditions, including neurological disorders, musculoskeletal system problems, mobility limitations associated with aging, and the oversight of rehabilitation programs. This paper discusses the technical challenges, potential applications, and prospects for conceptual Digital Twin (DT) Technology in IoT-based human monitoring systems, underscoring its role in revolutionizing rehabilitation strategies. Current studies emphasize the possibilities of the Internet of Things (IoT) and Digital Twin technologies across various sectors, including healthcare. However, given its use in real-time monitoring and follow-up of end-to-end rehabilitation programs, it is still emerging. Integrating Digital Twin into the existing IoT-based human movement monitoring system facilitates the handling of large amounts of data, supports analytics, and provides a platform for integrating additional services. This proposed framework incorporates inertia or wearable sensors to collect data on human activities during rehabilitation, utilizes Fast Fourier Transform (FFT) for feature extraction, and employs advanced Machine Learning (ML) algorithms for activity recognition along with Artificial Intelligence (AI) for predictive analytics. Furthermore, it implements a data-driven virtual model at the cloud services that mirrors the physical behaviors of IoT systems for enhanced real-time monitoring and tuning of the system based on personal requirements.

Keywords: IoT, Wearable Sensors, Digital Twin, Rehabilitation

1 Background and Motivation

The integration of Digital Twin technology with the IoT has created new opportunities in various sectors, including healthcare [1, 2, 3]. This has opened new horizons in the field of human movement monitoring systems (HMMS). As the healthcare field increasingly relies on data, continuous real-time monitoring, evaluation, and enhancement of healthcare monitoring are essential for effectively managing and treating diverse health conditions [4, 5]. Tracking human movement extends beyond mere fitness tracking and is crucial for rehabilitation as well as for the early identification of health problems [6]. While IoT-based HMMS is well-suited to meet these demands, the integration of DT technology is necessary to fully unlock their capabilities.

It is crucial to recognize the increasing challenges facing the healthcare sector to understand the importance of human movement monitoring systems and the possibilities of application of Digital Twin parallel to existing IoT systems for rehabilitation or prehabilitation. The major global concern is the rising cost of healthcare, driven by three significant factors, such as an aging population, limited hospital resources, and geographical remoteness as shown in Figure 1. Firstly, the aging population has led to increased demand for healthcare services. According to the 2023 Census (New Zealand statistics), more than 15% of New Zealand's population is 65 years or older, a statistic projected to double by 2050 [7]. As this elderly population expands, so does the requirement for ongoing healthcare monitoring, particularly for chronic diseases and rehabilitation, placing considerable strain on the healthcare system. Secondly, limited hospital resources, including financial constraints, workforce shortages, and inadequate infrastructure, hinder the ability of healthcare systems to meet growing demands. Lastly, geographic remoteness poses challenges in delivering timely and effective healthcare to individuals living in rural or isolated areas [8]. The study reflected that 16% of the New Zealand population doesn't avail the timely Emergency Medical Services (EMS) and advanced-level hospital care [9]. The lack of nearby medical facilities, transportation difficulties, and limited access to healthcare professionals exacerbate disparities in care. New Zealand, like many other nations, is experiencing a notable demographic transformation. With financial constraints and a lack of healthcare professionals, many regions struggle to deliver consistent care to those in greatest need. This situation underscores the urgent need for scalable, technology-driven solutions to ease the pressure on healthcare systems. Geographic isolation further complicates the situation due to resource limitations, leaving many without sufficient care and monitoring, particularly among the elderly population. All these three factors have led to the growing need for a personalized, proactive, and continuous monitoring healthcare system [10, 8, 11]. Human movement monitoring systems are emerging as essential tools to tackle these issues by facilitating the real-time data collection, analysis, and interpretation of physical activity data [12, 13] for its application in various domains including healthcare, sports science, and workplace safety. However, traditional methods for evaluating human movement typically necessitate clinical visits and

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complex laboratory setups, restricting the ability to obtain timely, contextualized data.

1.1 IoT and Real-Time Monitoring

The global landscape is undergoing an unprecedented technological transformation, transitioning from discrete to interconnected, Internet-enabled devices capable of generating and disseminating substantial quantities of valuable data. The Internet of Things is the name given to this new paradigm [8, 11, 14]. One critical area where IoT is set to bring about substantial changes is in healthcare systems [8, 11]. IoT's interconnectivity allows real-time data transmission and processing, providing healthcare professionals with insights that support timely interventions, data-driven decisions, and personalized patient care. In the field of movement monitoring, IoT-based systems employ wearable and mobile devices equipped with accelerometers, gyroscopes, and GPS, which collectively enable the continuous tracking of human movements [12, 13, 15, 16, 17, 18, 19]. The integration of these devices with wireless communication protocols facilitates the monitoring of patients across various settings, including clinical, residential, and remote environments. As healthcare continues to prioritize efficiency and prevention, IoT-enabled human movement monitoring has gained considerable interest for its utility in assessing physical activity, tracking rehabilitation progress [13], prehabilitation [12], and sports science. Recent research has shown how wearable IoT devices, such as smartwatches and fitness trackers, enable remote movement tracking that provides meaningful data for medical analysis. Researchers have utilized a range of analytical techniques to derive significant insights from the large volumes of movement data gathered through sensors. Methods for feature extraction, including time-domain analysis, frequency-domain analysis (using Fast Fourier Transform), and machine learning algorithms, have shown success in processing accelerometer data and differentiating between movement patterns such as walking, running, and sitting. The research conducted by [6, 15] along with [16, 17, 18] emphasizes the significance of sensors for gathering data from IMU sensors, wearables, and smart mobile devices. Furthermore, it discusses data processing methods such as data segmentation and the optimal window size of 3sec to 5sec for feature detection and classification. These improvements are essential for enhancing the precision of movement detection, which is vital for both patient rehabilitation and timely emergency responses. Akash et al [13] implement MQTT (Message Queuing Telemetry Transport) messaging through ThingSpeak to create a feedback loop for the system in case of IoT-based rehabilitation programs for hip fracture patients. While IoT-based movement monitoring systems provide significant advantages, there are notable challenges related to data quality, data storage, data integration, and real-time intervention. Moreover, heterogeneous sensor networks and proprietary communication protocols limit the seamless integration of data, which restricts the scalability and interoperability of IoT-based health monitoring solutions. Especially its application in rehabilitation needs optimal follow-up and management of the system for personalized needs. The significance of the Internet of Things is rooted in its capacity to link systems to the Internet, enabling communication, data

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analysis, and well-informed decision-making. However, overseeing and enhancing IoT-based human monitoring systems pose substantial challenges, especially because of the enormous amount of data produced and the intricacy of interactions among interconnected devices. The continuous flow of real-time data requires advanced data processing capabilities, robust infrastructure, and efficient algorithms to ensure accurate analysis and timely decision-making. Given the significant potential of IoT human monitoring systems for personalized care, rehabilitation, and telerehabilitation, this study aims to explore: *How can IoT-based human monitoring systems be optimized for substantial amounts of real-time data and intricate device interactions, data and complex device interactions, ensuring accurate analysis and timely decision-making for enhanced personalized patient outcomes?*

1.2 Digital Twin Integrating IoT, AI, ML

While IoT has proven its effectiveness in gathering movement data, the growing complexity of human movement analysis demands more sophisticated solutions to go beyond simple data collection [20]. This is where Digital Twin technology becomes relevant [21]. The idea of Twins began with NASA's Apollo program, which developed identical spacecraft to replicate mission scenarios. The strength of a Digital Twin is found in its ability to establish a real- time connection between the physical and virtual system, continuously updating virtual models with actual data and facilitating optimization and decision-making for physical systems [22, 23]. This concept aligns with Cyber-Physical Systems (CPS), as noted by researchers, where Digital Twins represent the cyber component within CPS [24]. The Digital Twins focus on virtual modeling, CPS emphasizes computing, communication, and control to achieve real-time monitoring, control, and coordination between physical and virtual spaces. Key elements of CPS include sensors and actuators while models and data remain central to Digital Twins. This study seeks to address: *How can the concepts, components, and functionalities of Digital Twin technology be effectively integrated and deployed in healthcare to enhance rehabilitation processes?*

Digital Twin technology has seen extensive application across diverse sectors, each leveraging its distinct capabilities to meet specific goals and enhance operational efficiency [25, 26]. In manufacturing, DTs have been instrumental in achieving significant performance gains by enabling predictive maintenance, minimizing operational downtime, and improving productivity through real-time insights and optimization [23, 27]. Notable examples include General Electric's use of DTs for jet engine monitoring and Siemens' integration in asset management exemplifying its impactful applications. Many Authors explore DT applications in engineering and beyond, offering insights into emerging trends and layered analysis [1, 7, 28, 29, 30]. Meanwhile, Liu et al. [23] and Khan et al. [4] compare DT's advancement in manufacturing and industries. Furthermore, the DT application goes beyond manufacturing and highlights DT's versatile benefits across healthcare [1, 5, 30, 31]. In the healthcare sector, digital transformation is driven by the Internet of Things, Cloud or Edge Computing, Big Data analytics, and AI technologies [2, 3, 14,

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20, 27, 32]. Over the past decade, the application of DT in healthcare has broadened to encompass the virtualization of hospital processes, the modeling of clinical workflows, and the simulation of physiological profiles to support personalized medicine. This raises the research question: *How can Digital Twin technology, when combined with the Internet of Things, Cloud Computing, and Artificial Intelligence/Machine Learning, be effectively utilized to improve the monitoring of human movement and rehabilitation processes in the human movement monitoring System?*

1.3 Exploring Digital Twin and IoT in Rehabilitation

The IoT-based system when integrated with DT, can serve as a synchronized virtual replica of a physical asset that utilizes data collected from sensors and devices to imitate the asset's performance, condition, and behavior [1, 3, 28]. This integration enables immediate tracking, evaluation, simulation, and enhancement of systems, connecting physical and digital environments and aiding better decisions. Driven by real-time data, a digital twin is a real-time virtual replica of a physical system or product. In the context of monitoring human movement, a digital representation of human motion or data model of human movement can be developed, continuously refreshed with real-time sensory information, and utilized for simulating, forecasting, and examining physical activities [29, 31, 33, 34]. Digital Twin technology integrated with IoT has gained prominence in health sectors such as creating human digital twins [20, 29], healthcare monitoring [1, 7, 29, 31], personalized care [29, 31, 33], elderly care [7], rehabilitation [31, 34] but its application in human movement monitoring system remains limited exploration. Some exploratory research suggests the potential for DT to create personalized digital models for tracking movement patterns, especially in rehabilitation and prehabilitation contexts [12]. However, comprehensive DT applications that offer real-time feedback and predictive insights into human movement patterns are rare in existing literature. This study identifies a research gap in the way digital twin technology is being integrated with the IoT framework for monitoring human movement. While IoT systems for activity recognition and tracking are well-established, they lack the predictive- analytics and real-time feedback mechanisms needed to optimize user outcomes in rehabilitation. Furthermore, current IoT systems primarily monitor movement passively without simulating future states or adjusting to individual needs dynamically. Specifically, the existing systems often lack immediate feedback that could guide users in adjusting their data acquisition parameters to optimize performance. There is a need for predictive capabilities that can anticipate rehabilitation progress, detect deviations from expected recovery trajectories, and adapt programs to suit individual needs. Thus, this research aims to bridge these gaps by integrating Digital Twin technology with IoT-based movement monitoring to enable a more holistic, real-time, and adaptive approach to human movement monitoring, particularly for applications in rehabilitation and prehabilitation. *How can the integration of Digital Twin technology with IoT-driven movement monitoring systems improve real-time feedback, predictive analytics, and personalized rehabilitation strategies*

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while addressing the challenges in HMMS?

This paper seeks to explore the idea of Digital Twins, essential tools and technologies, and their connection with various functional elements such as the IoT, AI, ML, and data analytics. It also aims to establish a conceptual framework for creating Digital Twins specifically for monitoring human movement, particularly in the areas of rehabilitation and prehabilitation programs. Khalid et al. [12] and Akash et al [13] explored an IoT-based activity recognition system designed for prehabilitation and rehabilitation, highlighting that Digital Twin technology could offer an innovative and effective approach for delivering services such as prehabilitation programs to patients preparing for surgery. This technology also has the flexibility to be integrated into environments in the community where the patient is unsupervised by a health professional. Continuous and in-depth monitoring of movements in any environment can provide essential information and feedback on the correct implementation of rehabilitation and prehabilitation programs or other personalized therapies. The goal of this research is to demonstrate and deploy DT technology integrating with IoT sensors to develop a holistic, intelligent human movement monitoring system that provides enhanced real-time monitoring, and personalized, and predictive feedback and can tune the whole system according to personal needs. The outcome of this study could transform how we monitor human movement by providing improved real-time feedback for individuals, resulting in intervention in rehabilitation parameters, optimized performance, and comprehensive tracking of rehabilitation programs.

2 Conceptual Framework

The proposed research is centered on the interplay between IoT sensors, data processing algorithms, and the creation of Digital Twin models to establish an effective system for monitoring human movement in real-time, particularly for rehabilitation and prehabilitation purposes. The proposed framework consists of IoT architecture that includes its key components Sensing devices, IoT gateway, and cloud services. This framework also includes one more software functionality at the cloud services called digital Twin that mirrors the physical system and aspires to establish a seamless connection between the physical world and its digital counterpart "DT model" by leveraging sensor data, advanced data processing algorithms, and integrating AI/ML techniques. Figure 2 shows the key components of the conceptual framework. These include Data Acquisition, Data Transmission, Data Processing, and Virtual systems at the cloud services. IoT sensors are employed to capture real-time data on human movements and exercises involved in rehabilitation and this data is transmitted through wired or wireless communication protocol. The intelligent mobile access point provides connectivity to the cloud via the internet and facilitates data management and processing. The wireless communication includes via Bluetooth, Wi-Fi, or 5G to the cloud where it will be stored for long term, processed, and visualized. Digital Twin functionality is introduced in the cloud parallel to the system so that the system can be made flexible and adapted according to the needs of individuals. Once the sensor data is collected, it goes through various data processing steps to extract meaningful insights. The raw data captured by the IoT sensors is often noisy and requires pre-processing and visualization to identify patterns and features related to different activities. These algorithms utilize techniques such as Fast Fourier Transform for feature extraction and advanced signal processing methods to filter noise and enhance data quality. This processing enables the extraction of relevant movement characteristics that are crucial for effective monitoring and analysis. At the cloud level, there is a greater complexity in data management and processing. This should serve as the core of the entire operation, encompassing fundamental data management and processing along with user and IoT system interactions. The integration of digital twin models creates a virtual version of the physical system, which is continuously updated with real-time data from IoT sensors via the cloud, while also incorporating AI/ML algorithms for predictive analysis. This integration facilitates operational verification and offers a certain level of expert intelligence. These data-driven models can replicate various elements of human movement, delivering valuable insights, and they can employ AI and ML algorithms to provide tailored feedback and predictive analysis, thereby improving the overall efficiency of the comprehensive rehabilitation process and enabling effective telerehabilitation.

3 Conclusion and Future Work

This paper explores the potential of conceptual Digital Twins in IoT environments for rehabilitation, with a focus on personalized and adaptive human movement monitoring system solutions. While most of the existing literature emphasizes DT applications in industries such as manufacturing and automation, limited research has addressed its transformative role in healthcare. Areas such as healthcare monitoring, personalized medicine, customized treatment planning, healthcare management, elderly care, and diverse health services remain underexplored in the context of DT integration. The review highlights the potential of DTs, particularly when integrated with emerging technologies such as IoT, AI/ML, and cloud/edge computing, to address challenges in cyber-physical convergence and real-time system adaptability. Existing IoT-based systems for human movement monitoring offer significant capabilities for real-time tracking and assessment in both clinical and non-clinical settings. These systems enable healthcare providers to remotely monitor patients' progress and adherence to rehabilitation programs, which is especially beneficial for individuals with limited access to healthcare facilities and curbs healthcare costs. However, these systems often lack the flexibility and adaptability needed to cater to the diverse and evolving requirements of individual patients undergoing rehabilitation. Rehabilitation programs are inherently dynamic, requiring adjustments to intensity, frequency, or type of exercises based on the patient's progress, physical condition, and specific recovery goals. Current IoT solutions do not account for such individualized adaptations. This rigidity not only limits the scope of personalized care but also hinders the accessibility of the rehabilitation process for patients who may be in remote areas, where in-person adjustments by healthcare providers are not feasible. The lack of personalization and adaptability in existing systems can lead to suboptimal recovery outcomes, as patients may not receive interventions tailored to their unique needs. Addressing these limitations through the potential of Digital Twin technology can significantly enhance the adaptability, personalization, and efficacy of the end-to-end rehabilitation process. Future research work will focus on conducting a comprehensive analysis of the end-to-end rehabilitation process, using pre-surgical exercises for abdominal cancer patients in older adults as a use case. The aim is to identify critical parameters that influence the personalization of prehabilitation programs and to optimize IoT system operations using DT technology. This approach will be applied to each stage of IoT-based architecture, specifically targeting the monitoring of elderly populations undergoing rehabilitation or prehabilitation exercises to enhance health outcomes and reduce surgical risks.

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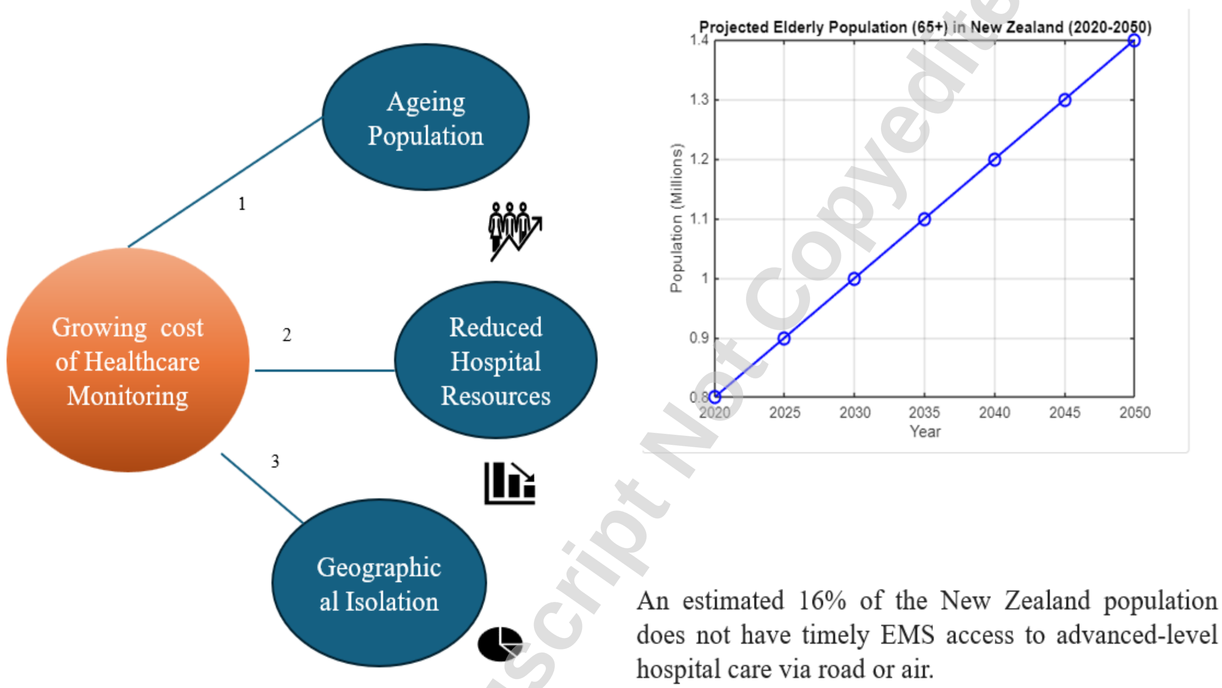

Figure 1: Growing Cost of Healthcare Monitoring System

Legend: It illustrates the key factors responsible for increasing the cost of Healthcare Monitoring System

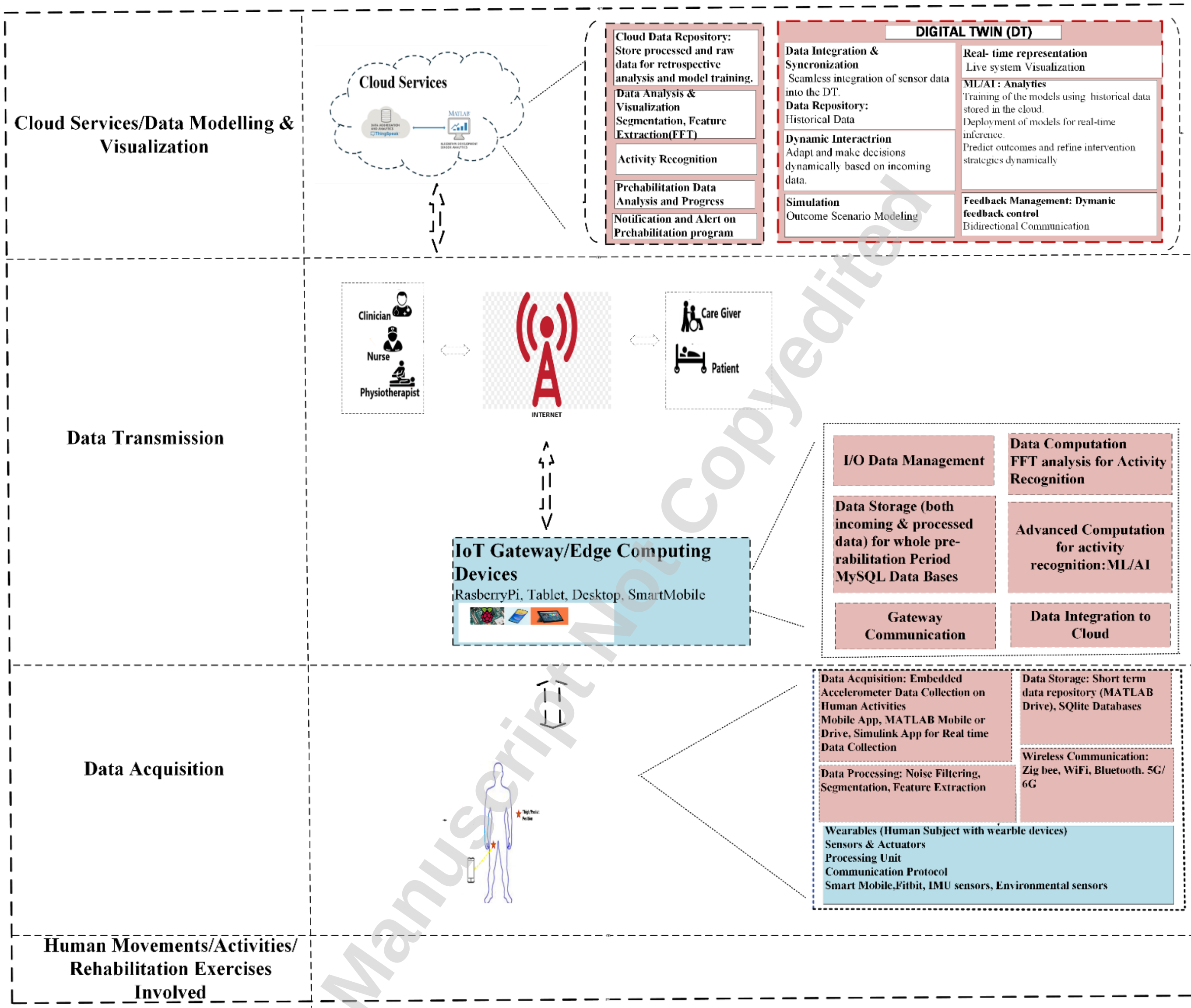

Figure 2: Overview of the Conceptual Framework of the Proposed System

Legend: It shows the overall architecture of the proposed system for IoT-based Human movement Monitoring System - Prospects for a Conceptual Digital Twin and the functionalities of its key components.