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Real-Time Optimization in Knee Rehabilitation: Exploring EMG Signal Classification and IoT-Based Control Systems

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Abstract

Knee rehabilitation is essential for regaining joint range of motion and flexibility following an injury or surgery, and it frequently calls for weeks of physical therapy. Temporal delays that interfere with real-time feedback and lessen synchronization between patient movements and device actions are just two of the major drawbacks of current technologies. Longer recovery times and less than ideal patient care result from these difficulties, which are exacerbated by the absence of sophisticated control systems that can increase accuracy and response times. Knee-related conditions make up a significant percentage of musculoskeletal disorders, which are a major cause of disability worldwide. In order to satisfy the increasing demand for efficient rehabilitation solutions, these technological gaps must be filled. Potential solutions to these problems are offered by developments in machine learning, EMG signal classification, and Internet of Things-based control systems. This work aims to investigate methods to lower time delays, increase real-time responsiveness, and raise the performance of knee rehabilitation devices. Combining these developments seeks to maximize rehabilitation results and improve the quality of patient treatment. Emphasizing the need for real-time optimization and delay reduction to accommodate the rising prevalence of osteoarthritis and knee injuries worldwide, this paper addresses the clinical and technological issues of knee rehabilitation devices.

Keywords: Rehabilitation, Time Delay Reduction, Real-Time Feedback, Classification of EMG signal, IoT-based control, Controllers

1. Introduction

Our daily lives depend much on our knees. They enable leg movement, support when standing or walking, help to keep balance, and absorb impact during sports, including running and exercise (Cleveland Clinic, 2023). Knee injuries, including torn cartilage, falls, and sports-related conditions, are common in physical activities and high-impact sports. Furthermore, aggravating knee pain can be diseases including gout, arthritis, and infections. Common knee ailments include ACL tears, fractures, torn meniscuses, and knee bursitis. Mechanical issues, such as iliotibial band syndrome and loose bodies, can also cause knee pain (Mayo Clinic, 2023). Pseudo-locked knee is another condition characterized by the inability to extend the knee due to severe pain and swelling, despite the joint being physically capable of movement (Nunez, 2019). According to the World Health Organization (WHO), musculoskeletal disorders are the leading cause of disability globally, affecting over 1.71 billion people. Conditions such as low back pain, neck pain, fractures, osteoarthritis, rheumatoid arthritis, amputations, and other injuries account for the majority of disabilities across 160 countries. High-income nations are most affected, with 5.44% of their total population (441 million) experiencing these conditions. This is followed by South-East countries (369 million) and the WHO Western Pacific Region (427 million). Knee disorders rank as the second leading cause of years lived with disability (YLDs) globally, contributing to over 149 million YLDs, or 17% of the global total. In total, there are approximately 150 distinct conditions that affect the musculoskeletal system. These disorders significantly impair mobility and dexterity, often leading to early retirement, reduced well-being, and a diminished ability to participate in societal activities (Integrated Pain Consultants, 2019).

Furthermore, research conducted by the Consumer Product Safety Commission, using data from the National Electronic Injury Surveillance System, estimates that 2.29% of knee injuries occur per 1,000 persons annually (Ciezaet al., 2021). Unexpectedly, knee injuries are most common among individuals aged 15 to 75, while toddlers under five experience the fewest injuries, as shown in Figure 1 (Hartvigsen et al., 2018). After age 80, the number of reported knee injuries declines, likely due to reduced physical activity in this age group. Among knee injuries treated in U.S.

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emergency departments between 1999 and 2008, 42.1% were attributed to strains and sprains, followed by 27.1% caused by contusions and abrasions, and 10.5% resulted from puncture wounds and lacerations. This represents a total of 6,664,324 cases during the study period. Notably, nearly half (49.3%) of all knee injuries occurred during sports or other recreational activities (Williams et al., 2018).

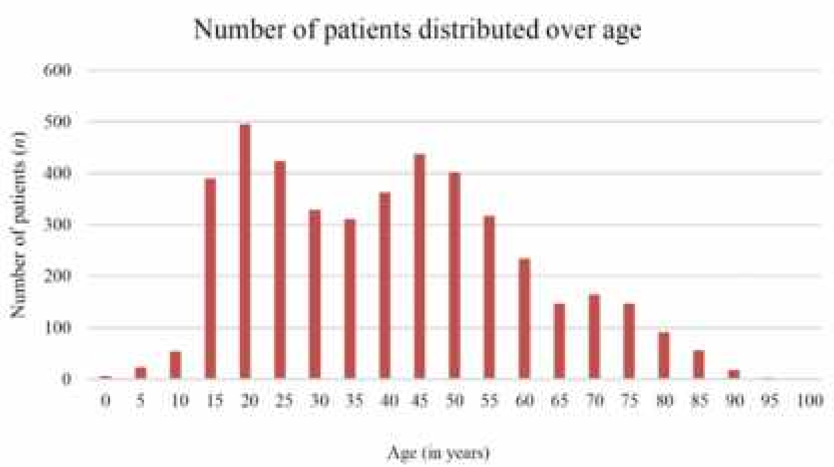

Figure 1: Number of patients distributed over age (Weber et al., 2020)

Figure 2 shows that the majority of patients with knee osteoarthritis (OA) had significant pain and functional limitations in their daily lives, according to a study done at Malaysian government hospitals (Foo et al., 2020). Patients with confirmed OA who were admitted to Hospital Serdang and Hospital Putrajaya in Selangor, Malaysia, between November 2015 and August 2016 were included in the study. According to medical evaluations, the participants, who ranged in age from 35 to 75, represented a variety of ethnic groups and had been diagnosed with primary knee OA. In line with an exploratory study on health-related quality of life among Malaysian knee OA patients, which also reported a predominantly female cohort (78.8%), the results showed that the majority of participants (82.7%) were female. According to the age distribution, over half (51.3%) of the participants were in the 56–75 age range (Foo et al., 2020). In addition, a significant percentage (58.2%) stated that they had been dealing with knee pain for one to five years (Zakaria et al., 2009). The study also showed that the prevalence of knee pain varied by ethnic group. Malay and Indian participants exhibited higher crude prevalence rates of knee pain and osteoarthritis than Chinese participants, potentially due to occupational factors, lifestyle differences, and other variables (Muraki et al., 2009). Data from 1,226 individuals informed the knee pain analysis presented in Figure 2.

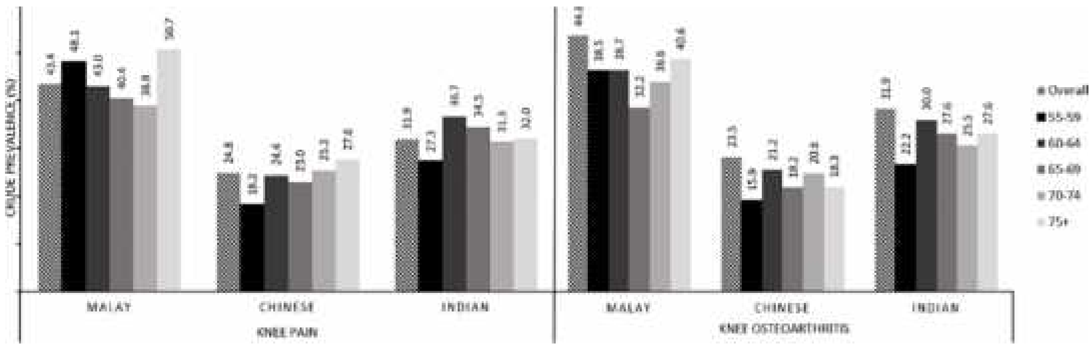

Figure 2: Gross incidence of osteoarthritis and knee discomfort by age group and ethnicity (Muraki et al., 2009)

Among the 1,226 individuals surveyed, 408 (33.3%) reported experiencing knee discomfort. Of those, 23 out of 32 participants (72%) were diagnosed with knee osteoarthritis. When adjusted for the population of Kuala Lumpur, the weighted prevalence among individuals aged 55 years and older was estimated to be 25.4% for knee pain and stiffness lasting at least one month in the past year, and 30.8% for overall knee pain. Specifically, 25.4% of survey participants reported experiencing knee pain and stiffness for at least one month over the previous 12 months. Additionally, 30.8% of residents aged 55 and older in the greater Kuala Lumpur area reported knee-related issues (Boling, Padua, & Prentice, 2021). Factors contributing to knee problems often include occupational demands, sports activities, daily routines, accidents, and inadequate care or maintenance of the knees.

Consequently, knee rehabilitation is crucial for patients, athletes, and the elderly dealing with knee issues. It helps reduce pain and swelling while restoring strength, flexibility, and range of motion. Rehabilitation also educates individuals about knee structure, injury mechanisms, and treatment, which can help prevent future injuries (Boling, Padua, & Prentice, n.d.). The benefits of knee rehabilitation exercises include strengthening the muscles surrounding the knee joint, maximizing the joint's range of motion, preventing stiffness and worsening discomfort, promoting tissue repair, and supporting the resumption of movement. These exercises help maintain healthy knees, prevent injuries, and reinforce the surrounding musculature to encourage sustained activity (Health Pages Team, 2018). Range of motion (ROM) exercises are beneficial in preventing contractures, muscular weakness, and joint stiffness. They aid in reducing pain and enhancing circulation (CNA Training Institute, 2022). For the knee joint, a full range of motion typically involves bending from 0° (straight) to 120° (fully bent) and returning from 120° (bent) to 0° (straight) (Raposo, Ramos, & Lúcia Cruz, 2021). When assessing knee joint mobility, physical therapists frequently compare the patient's range of motion to a baseline or the movement range of an average individual. By evaluating ROM alongside other clinical assessments and physical examinations, therapists can develop targeted treatments, such as strengthening, stretching, manual therapy, or splinting, to address specific mobility issues.

Knee rehabilitation equipment is designed to assist individuals in their recuperation following knee replacements and injuries. This device can help strengthen the muscles around the knee joint, reduce swelling, and increase the range of motion of the knee (Mavroidis, Kahn, & Mavroidis, 2005). Current knee rehabilitation devices suffer from temporal delays in real-time feedback systems. These delays hinder synchronization between patient movements and device responses, negatively impacting the rehabilitation process and delaying recovery. Nevertheless, certain individuals are not suitable for such devices, including those with cardiovascular issues, open wounds and infection, deep vein thrombosis, and severe injuries (Cluett, 2023). Using these devices in such cases may aggravate wounds, increase the cardiovascular strain, or potentially trigger cardiovascular diseases during exercise. EMG signal classification accuracy is frequently impacted by noise, artefacts, and insufficient machine learning methods. (Mejía Gallón, 2024) This results in inaccurate activity identification, which lessens the ability of the device to customize rehabilitative exercises. Current rehabilitation equipment lacks IoT integration, which limits its ability to provide data-driven insights, individualized modifications, and remote monitoring. (Li et al., 2024) High latency, constrained processing power, and inadequate scalability are common issues with current IoT solutions. There are still difficulties, especially with the controller system. In order to enhance system performance and provide real-time feedback, the controller must reduce operational time delays. This problem might be resolved by machine learning techniques, which are extensively used in many different fields. The rehabilitation process might be greatly improved by lowering time delays and increasing the device's efficacy through the integration of machine learning into the controller.

This study explores state-of-the-art machine learning and computing techniques to reduce real-time delays. Since they allow for precise and quick feedback, these advancements significantly improve the rehabilitation process. It is guaranteed that the rehabilitation activities will be more closely tailored to the patient's requirements. This work not only identifies the technological limitations in knee rehabilitation but also offers integrative methods that combine real-time feedback optimization, EMG signal accuracy enhancement, and IoT-based control. By doing the provision of a thorough framework for creating effective, scalable, and patient-centered next-generation knee rehabilitation devices, the research advances the field. In addition, it opens the door for the wider use of intelligent rehabilitation technologies in the medical field, which will eventually enhance patient outcomes and lessen the prevalence of musculoskeletal disorders worldwide.

2. LITERATURE REVIEW

2.1 CLASSIFIER FOR ACTIVITY RECOGNITION BASED ON EMG SIGNAL

The activities must be categorized to determine which speed control is best for the rehabilitation device. The device can respond to commands quickly, minimize overshoot while operating, and reach the desired speed with the controller's assistance. This review seeks to identify knowledge gaps, summarize and integrate the results of previous studies on the subject, and suggest possible lines of inquiry for further study. Classifiers for machine learning algorithms in hand-prosthesis control were investigated in a related study by Esposito et al. (2020). To identify hand gestures, a novel array armband with piezoresistive sensors is proposed. The armband has three sensors that target specific forearm muscles. A force-sensitive resistor (FSR) and a particular mechanical coupler are used in the construction of each sensor, which measures muscle swelling during contraction. Hand gestures are classified using a variety of machine learning techniques, and classification performance is assessed using both leave-one-out and 10-fold cross-validations. Classifying hand gestures was part of the study, and the classification process had an average accuracy of 96%. The results of Esposito et al. show how machine learning algorithms can efficiently recognize and classify movements, offering feedback and control in real time. These developments could be expanded to improve the creation of knee rehabilitation equipment, with the potential to modify muscle contraction sensors to monitor extra muscles. The changes may open the door to a variety of future human-machine interface (HMI) applications based on electromyography (EMG). Additionally, the machine learning algorithm is a popular trend for classifying the EMG signal and produces a higher mean accuracy for the classifier of hand activities. As a result, it will serve as the standard for future knee rehabilitation devices, which target a different body muscle.

A comprehensive review of current methods, difficulties, and possible uses of real-time electromyography (EMG)-based pattern recognition control for hand prostheses was carried out by Parajuli et al. (2019). The study underlined that both voluntary muscle contraction and visual feedback are necessary for virtual prosthesis control to help users learn tasks. It has been demonstrated that integrating surface EMG (sEMG) with inertial sensors improves classification performance while reducing the requirement for extra sensors. High accuracy was shown in recognizing multiple hand motions using advanced techniques like artificial neural networks (ANNs); however, difficulties still exist, especially when it comes to obtaining robust multi-degree-of-freedom (multi-DOF) control. The researchers also investigated targeted muscle reinnervation (TMR) to enhance control. Their results demonstrated the potential of this strategy with classification accuracies of 88% for TMR patients and 97% for control participants. The study's methodology could be modified for use in knee flexion and extension control applications, where the speed of the model could be controlled by EMG signals. The process flow for processing real-time EMG signals in relation to data collection and classification is depicted in Figure 3 (Parajuli et al., 2019). The authors acknowledged a number of difficulties in practical applications in spite of these developments. Increased classification errors result from irregularities introduced by myosignal contraction variability brought on by changing loads and orientations. Uncertainty in classification accuracy, poor user interfaces, and temporal variations in signal patterns are important problems that can lead to task failures, user annoyance, and even device rejection. These difficulties highlight the urgent need for increased reliability, better user experience, and strong pattern recognition algorithms to guarantee natural and intuitive control over prosthetic devices.

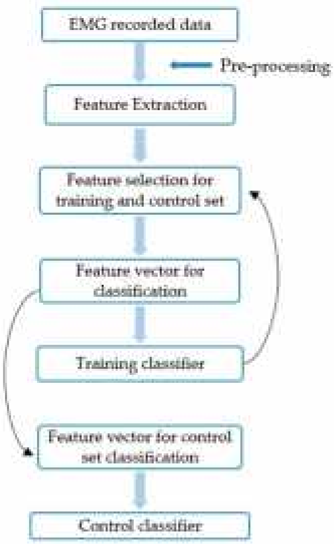

Figure 3: Process Flow of EMG signal classifier (Parajuli et al., 2019)

The goal of Toledo-Pérez et al.'s (2019) thorough analysis of support vector machine (SVM)-based EMG signal classification methods was to maximize accuracy in foot movement control. The study investigated the gathering, processing, and categorization of EMG signals. Signals from nine electrodes positioned on eight healthy subjects were analyzed, filtered, and amplified using MATLAB and LIBSVM. To produce the dataset for analysis, each participant completed 20 repetitions of different foot movement classes, including rest. Time-domain characteristics like mean absolute value (MAV), zero crossings (ZC), waveform length (WL), and slope sign changes (SSC) were used for classification. Performance was assessed by applying an SVM classifier with varying window sizes. The findings showed that the vastus lateralis (VL) muscle had the highest classification accuracy, while the tibialis anterior (TA) muscle had the lowest because of its decreased activation and involvement in particular movements. Furthermore, there were only slight increases in classification accuracy when the window size was increased beyond 500 ms. While a greater number of channels can lower variability, they are not necessary to achieve high precision, according to the findings, which focused on resource efficiency. By utilizing opposing muscle groups, reducing the number of channels, and making algorithmic adjustments, optimal classification was achieved. The study emphasized the importance of electrode placement, window size, and channel selection in improving EMG-based classification systems for real-time control applications. Their primary domain for classifying the foot's EMG signal will be the features of mean absolute value (MAV), zero crossings (ZC), waveform length (WL), and slope sign changes (SSC). The vastus lateralis (VL) muscle can be tested for accuracy with various exercises, and the technique can be applied to other body muscles, such as knee motions. The authors suggested investigating systems with more channels for future research to reduce variability brought on by sample size or subject-specific factors.

The potential of convolutional neural networks (CNNs) for knee activity classification was demonstrated by Kim et al. (2020), who proposed a subject-transfer framework for single-trial EMG analysis. The NinaPro datasets 2 and 3, which include 49 hand motions executed by 40 healthy participants and 11 amputees, were used to assess the effectiveness of the framework. According to the experimental findings, the suggested framework performed better in both healthy and amputee participants than the self-decoding method, which trains classifiers only using the target subject's data. The system demonstrated superior accuracy in offline trials with 50 classes by pre-training classifiers on data from other participants and fine-tuning them with single-trial EMG analysis. The study identified several performance-influencing variables, such as environmental factors, signal processing methods, and muscle fatigue. Although the framework consistently performed better than self-decoding techniques for healthy participants, amputee subjects showed less consistent results, suggesting that additional validation is necessary. Expanding the testing to more amputee participants, running multi-day trials, and investigating real-world applications like 3D games and robotic arm control are some of the future directions suggested by the authors. The efficacy of several classifier types and time- and frequency-domain features was also carefully investigated in the study, with differing degrees of success. This methodology establishes the foundation for resilient, broadly applicable EMG-based systems that may find use in a variety of domains, such as assistive technology and knee rehabilitation.

Bird et al. (2020) looked into how cross-domain transfer learning can be used to process biological signals, with an emphasis on EMG and EEG data. While the Muse EEG Headband was used to collect EEG data during a three-class mental state classification task, the Myo Armband was used to collect EMG signals during a four-class gesture categorization experiment. The accuracy of the optimized models was 62.37% for EEG and 84.76% for EMG. With the use of pre-trained weights, the classification accuracy increased to 85.12% for EMG and 93.82% for EEG. EMG networks outperformed EEG models, demonstrating that cross-domain transfer learning allowed for efficient knowledge transfer. The transfer of knowledge from EMG to EEG was further validated by CNN-based experiments, underscoring the adaptability and promise of this methodology. The authors demonstrated the practical applicability of their multi-layer perceptron (MLP) and convolutional neural network (CNN) transfer learning framework by successfully applying it to the classification of knee activity using EMG signals. It still requires work, though, such as expanding hyperparameter optimization, implementing advanced feature selection strategies, and investigating other biological signals like electrocardiograms (ECGs). This method could lead to better performance in biological signal-based applications by improving human-machine interaction and reducing computational complexity.

Additionally, an EMG-controlled knee exoskeleton was developed by Lyu et al. (2019) to facilitate at-home rehabilitation in a gaming environment. The potential applications of knee activity classification based on EMG data are demonstrated by the successful integration of an EMG signal classification system with a rehabilitation tool. By filling in current knowledge gaps and exploring new research avenues, this study lays the groundwork for the development of knee rehabilitation devices and offers chances to advance intuitive, user-friendly solutions for people with knee-related problems.

3. INTERNET OF THINGS DATA PROCESSING FOR KNEE REHABILITATION DEVICE

For easier and more effective control, the knee rehabilitation device must be connected to a smartphone. It is widely acknowledged that Internet of Things (IoT) data processing plays a crucial role in enabling this connection. Robotics and EMG signals can be integrated with the Internet of Things to control the device. For applications like knee rehabilitation devices, researchers have proposed a number of designs, techniques, and technologies that leverage software-defined networking (SDN) and other ingenious tactics to effectively handle and process IoT data. The revolutionary potential of the Internet of Things (IoT) in allowing devices to be accessed and controlled remotely via the Internet was emphasized by Nunsanga et al. (2020). In their study, they presented an application that uses IoT technologies and electromyography (EMG) signals to control a robotic arm using muscular movements. The system is operated online via an Android application, and a robotic arm attached to the bot is controlled by EMG signals produced by the user. The transmitting and receiving units make up the two parts of the system architecture. Additionally, a mobile application is used to control the wheels of the robot. Five participants in the experiment showed that threshold values that were tailored for each user enabled the robotic arm to successfully perform tasks like opening, closing, and resting, in addition to regulating the bot movement. Individual customization is still necessary for the current system of the study, and the generalized EMG control system is still unable to accommodate all users. To guarantee more accuracy and functionality in the future, they can strengthen the mechanical design and increase signal sensitivity.

The IoT-train-deep technique for intelligent software-defined networking was presented by Tam et al. (2021) in order to address issues with IoT data processing, such as lowering accuracy limitations, storage needs, and delay. A convolutional neural network (CNN) and surface high-density electromyography (HD-EMG) were used in this study to describe a real-time myoelectric hand prosthesis control method. To reduce training time, streamline installation, and accommodate each distinct muscle contraction pattern, the system made use of transfer learning. Twelve able-bodied participants participated in real-time testing, and the method performed exceptionally well. The mean and median positive predictive values (PPV) for all six grip modes were 93.43% and 100%, respectively. Predictions were made in 116 milliseconds, and gestures switched between modes seamlessly without the need for human adjustments. Setting up took less than ten minutes thanks to transfer learning, which drastically cut setup time by 89.4%. Although the system performed well in tests with physically fit users, there are no clinical trials with amputees in the research to confirm its effectiveness in wider applications. This method demonstrates the possibility of bridging the gap between cutting-edge AI capabilities and workable, approachable prosthesis solutions. Knee rehabilitation devices could benefit from the intelligent data processing concept presented in this study, particularly the use of the Internet of Things and transfer learning to minimize delay. The responsiveness and effectiveness of rehabilitation controllers could be improved by machine learning algorithms that achieve shorter response times through optimized data processing and decision-making (Tam et al., 2021).

A thorough analysis of federated learning for resource-constrained IoT devices was carried out by Imteaj et al. (2022), who also highlighted the opportunities and difficulties of federated learning implementation in IoT systems. The study highlighted how federated learning can facilitate safe and effective handling of dispersed data, which makes it especially pertinent to Internet of Things applications in the medical field. These results offer important new information about using federated learning to process IoT data in knee rehabilitation device control, where resource-efficient and real-time data handling is essential. This study uses federated learning and the Internet of Things to control the device rather than EMG data and muscle. Future use of the IoT-enabled knee rehabilitation device control and federated learning to create more effective devices is possible. The Convolutional Recurrent Autoencoder was used by Yin et al. (2022) to propose an anomaly detection method specifically designed for IoT time-series data. This technique showed strong performance in identifying abnormalities, providing direction for creating anomaly detection algorithms that can be used with IoT data produced by knee rehabilitation equipment. This method could improve the accuracy and dependability of IoT-based rehabilitation systems by detecting anomalies in real time, guaranteeing peak device performance (Yin, Zhang, Wang, & Xiong, 2022).

An inventive Internet of Things (IoT) system that uses wearable technology, specifically wristbands, to assess hand function was presented by Zhi et al. in 2024. The system provides all-inclusive therapeutic services and remote health management solutions. Electromyography (EMG) data taken from the arm is used to assess hand function. This allows for accurate measurement of grip strength and intelligent motion recognition using sophisticated classification and regression algorithms. The Random Forest Regression (RFR) model outperformed the other models when tested, demonstrating the accuracy and dependability of the system with a regression value of 0.9563 on test data. This result shows the potential of the IoT-based system in health monitoring and rehabilitation contexts and validates the usefulness of the wearable wristband in evaluating hand performance. The study focuses on the EMG muscle of the arm and excludes comparisons with other regression models for the partnership with the IoT device. Future studies can concentrate on increasing model training speed, studying various muscles, and adding more sensors to enable more thorough and multifaceted assessments.

4. REAL-TIME DELAY IN KNEE REHABILITATION DEVICE

For people recuperating from knee surgeries and injuries, knee rehabilitation equipment is essential to regaining function and mobility. Reducing real-time delay is a crucial factor in the creation of these devices since it can have a big influence on how well the rehabilitation process works. Delay-free knee rehabilitation equipment can avoid accidents and ensure that the activity is completed on schedule. A wearable and retractable badge-reel-like sensor was presented by Li et al. (2021) and showed notable advancements in the detection of joint and spinal bending and stretching movements. Their device reduced cumulative delays for joint and spinal movement detection by 31.39% and 62.10%, respectively, in comparison to benchmark approaches. The apparatus uses a grating-structured triboelectric nanogenerator as a stretch-sensing mechanism, providing exceptional durability, low hysteresis, and high stretching sensitivity. The main properties of the sensor were thoroughly defined by theoretical and experimental analyses. By monitoring spinal movements of the human subjects and comparing the results to those of commercial devices, such as

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a hunchback device and a commercial inclinometer, its effectiveness was confirmed. The accuracy, low hysteresis, and resistance to environmental interferences outperformed those of conventional commercial devices. Additionally, the device can be easily incorporated into clothing items like vests and kneepads, which makes it appropriate for use in spinal disorder prevention, rehabilitation monitoring, and personal healthcare. The fabrication process, which includes flexible PCB technology, 3D printing, and nanostructure characterization, is also described in the study. In order to improve its practical usability, future developments will concentrate on improving the accuracy of real-time monitoring and resolving problems like sensor slippage on the skin.

Similarly, for software-defined network (SDN)-based wireless networks in mobile edge computing (MEC) environments, Kiran et al. (2020) suggested a combined resource allocation and compute offloading strategy. For the purpose of reducing delays and preserving device battery life, the study tackles important issues with task offloading and resource allocation. The authors presented a Software Defined Edge Cloudlet (SDEC) framework that uses Q-learning and cooperative Q-learning reinforcement learning techniques to improve service quality. Dynamic optimization in time-varying environments is made possible by these methods. In comparison to conventional Q-learning and other benchmark techniques, simulation results show notable performance gains, with a 31.39% and 62.10% decrease in total delay, respectively. The framework successfully solves the non-convex task offloading and resource allocation problem by utilizing machine learning techniques. Furthermore, by effectively satisfying latency requirements and exchanging learning experiences, the cooperative Q-learning approach improves the user experience. This framework might be used as a guide to solve time delay problems in applications like knee rehabilitation equipment. (Wang, Yin, Pan, and Kiran, 2020)

For rehabilitation therapy, Nasri et al. (2020) used deep learning techniques to create a 3D game that is controlled by surface electromyography (sEMG) signals, with a focus on real-time hand gesture detection. With the goal of training a Conv-GRU deep learning model for gesture recognition, a unique dataset of seven hand gestures was gathered using the Myo armband. A 20-round user study was used to assess the system's performance after it was tested in a live setting with numerous participants. The high accuracy of the system in classifying hand gestures and enhancing user engagement during rehabilitation activities was demonstrated by the results. For gesture recognition, the study found that the test accuracy was 82.15% and the training accuracy was 99.8%. During live testing with four additional participants, the system demonstrated reliable performance; however, the gaming experience was negatively affected by Unity's reaction latency to frequent commands. To address this, a 1-second delay was introduced between neural network commands and game activities to reduce system polarization. While the primary focus was on hand gesture detection, the methodologies employed in this study could be adapted for knee rehabilitation devices to minimize real-time delay. The authors highlighted that training and validation processes experienced data loss during iterations (as depicted in Figure 4), which could influence the results. Future work aims to improve system accuracy, introduce customizable gestures, and design more challenging game levels to enhance rehabilitation outcomes.

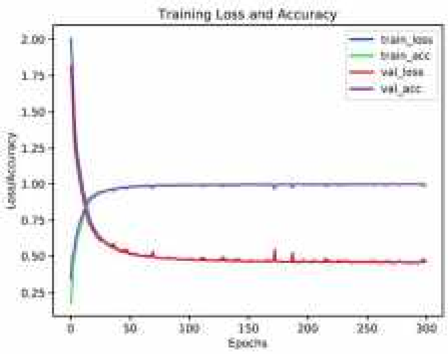

Figure 4: Example of Loss and accuracy graph (Nasri, Orts-Escolano & Cazorla, 2020)

Shaymaa et al. (2022) introduced advanced control techniques to address real-time delay in knee rehabilitation devices by developing an enhanced active disturbance rejection control scheme for trajectory tracking in lower-limb robotic rehabilitation exoskeletons. This study proposed an adaptive synergetic control approach tailored for knee rehabilitation systems, utilizing adaptive control laws to ensure system stability. Additionally, particle swarm optimization (PSO) was employed to fine-tune controller parameters for optimal tracking performance. When compared to conventional trial-and-error parameter tuning techniques, the PSO algorithm improved dynamic performance by achieving a 5% improvement in velocity tracking and an 8% improvement in joint angle tracking accuracy, albeit at the cost of higher torque requirements. Employing efficient drift prevention, parameter boundedness, and system stability under parameter uncertainties, the adaptive synergetic controller outperformed classical controllers. To further improve the efficacy of the suggested system, future development directions include investigating different optimization strategies, putting real-time applications into practice, and comparing the suggested system to other control methodologies.

Zhu et al. (2022) suggested a CNN-LSTM model for sEMG-based lower limb motion prediction in conjunction with an improved PCA optimization method. This method was created to enhance human uphill motion prediction and control in real time. Ten participants in the study walked on a ramp, and their gait was recorded in order to examine the movements of their knee joints. The enhanced PCA method was used to minimize time delays and reduce dimensionality, while the CNN-LSTM model was created to predict knee joint angles. With an error of 1.34 ± 0.25 degrees and a prediction time of 25 ms, the suggested method outperformed traditional models like BP, RF, and SVR. These findings open the door for the creation of neuro-controlled exoskeletons by demonstrating the efficacy of the improved PCA + CNN-LSTM technique for sEMG-based lower limb activity detection. This approach may have consequences for knee rehabilitation equipment that needs to predict and control motion in real time. The study has highlighted the potential of wearable technology, edge computing, advanced control strategies, and innovative applications for reducing real-time delay in knee rehabilitation devices. Future research areas will look into the use of deep learning techniques, smartphone applications, and complex control systems to solve the issue and improve the real-time performance of knee rehabilitation devices.

5. SPEED CONTROLLER OF KNEE REHABILITATION DEVICE

For patients undergoing rehabilitation, safe and efficient recovery depends heavily on the control of knee rehabilitation equipment. With the objective of determining the best strategy for managing the speed of the device and reducing operating delays, this study investigates a variety of controller types. The study intends to highlight possible directions for further research in this field and offer insightful information about current practices by synthesizing the findings on controller implementations. The robust design of a blade pitch controller for wind energy conversion systems (WECS) based on an adaptive neuro-fuzzy inference system (ANFIS) was the main focus of Elsisi et al. (2021). The study tackled issues brought on by variations in wind speed, load demand, system unpredictability, and communication delays. The Mayfly Optimization Algorithm (MOA), which was created especially to improve the training of the ANFIS model, was used to refine the dataset that the researchers used to optimize the controller. By employing a unique time-domain statistical technique, the MOA successfully optimized PID controller settings, reducing overshoot and settling time. Under conditions of fluctuating wind speeds, varying load demands, parameter uncertainties, and communication disruptions, the results showed that the ANFIS controller could improve system stability and minimize delays. The sturdy characteristics of this control design provide potential flexibility for improving the performance and dependability of controllers utilized in knee rehabilitation devices, where comparable problems with uncertainty, stability, and delay need to be resolved. (Elsisi, Mahmoud, Lehtonen, Tran, & Darwish, 2021).

A cascaded PI-fractional order PID (PI-FOPID) controller was proposed by Ali et al. (2021) to improve hybrid microgrid systems' frequency responsiveness. The Gorilla Troops Optimizer (GTO) was used in the study to optimize the controller parameters. Real wind and solar data are used to validate the hybrid microgrid system that this study models, which combines energy storage units, renewable energy sources, and diesel generators. The performance of the proposed controller was benchmarked against FOPID controllers and other optimization techniques, such as Genetic Algorithm and Particle Swarm Optimization. Results showed that the PI-FOPID controller significantly reduced maximum overshoot and undershoot by 99.8% and decreased settling time by 75.9%, achieving faster and more stable frequency responses under varying load and renewable energy conditions. The design of the cascaded PI-FOPID controller, illustrated in Figure 5, indicates its potential applicability to knee rehabilitation devices. Similar control strategies could improve system stability, minimize delays, and enhance speed control in such devices. The robustness and adaptability of the proposed method also make it suitable for multi-area microgrid systems subjected to complex disturbances.

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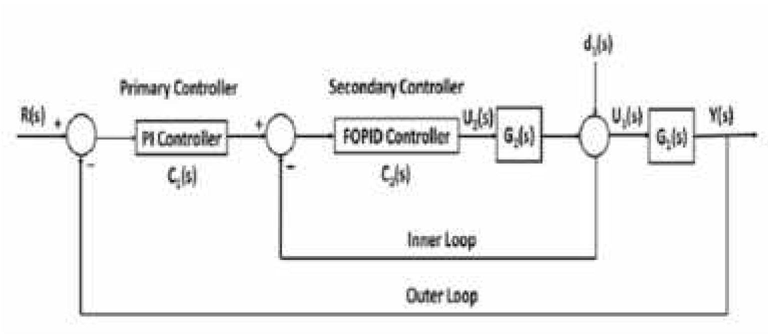

Figure 5: Cascaded controller for the PI and FOPID controller (Soriano-Sánchez, Rodríguez-Licea, Pérez-Pinal, & Vázquez-López, 2020)

A fractional-order PID controller for a DC-DC converter was proposed by Soriano-Sánchez et al. (2020), who used a biquadratic approximation to produce a flat phase response over a constrained frequency range. This approach prioritizes robustness and desired closed-loop characteristics while streamlining the tuning process. When compared to conventional PID controllers, the fractional-order PID controller provides faster and more stable regulation, as shown by the transfer function analysis and time-domain simulations. The findings demonstrated that the fractional-order PID controller considerably improves regulation speed, achieving settling times that are 1/3 to 1/2 shorter than those of traditional PID controllers while preserving strong stability margins. The controller also efficiently handles time delay problems in system response and reduces steady-state errors. It is especially well-suited for applications that demand quick and accurate reaction times because of these characteristics. The design will be expanded to dual-loop controllers in future studies, and its fast-response capabilities will be investigated in various power converter configurations, including boost converters. In order to increase the speed and accuracy of rehabilitation devices, where precise and responsive control is essential, this study offers insightful information about the use of fractional-order PID controllers.

To optimize the performance of DC motors, Siddiqi et al. (2024) presented a simulation and design framework for a neural network-based controller. The study addressed difficulties in accurate modeling and control brought on by a lack of motor characteristic data using an artificial neural network (ANN) to predict important motor parameters, such as back-EMF, moment of inertia, and armature resistance. In contrast to conventional methods, the ANN reduced computation costs and estimation time while enabling accurate predictions through the use of sophisticated learning techniques and realistic constraints. Under various operating conditions, the simulations showed the approach's efficacy and dependability, underscoring its potential to improve DC motor performance and reduce delays in industrial automation and control systems. Although DC motors were the primary focus of the study, the concepts and techniques created have wider uses. For example, the self-learning and adaptive features of the neural network controller might help optimize speed control in knee rehabilitation equipment, enabling customized modifications according to user requirements and advancement. In summary, the study emphasizes how well different controllers work to solve complicated system problems, especially when it comes to cutting down on operating delay times. By reducing delay times and optimizing device performance for better patient outcomes, the results show how these sophisticated control strategies can improve the speed and responsiveness of the knee rehabilitation device.

4. Conclusions

In conclusion, this study shows how real-time optimization in knee rehabilitation can be achieved using cutting-edge technologies like IoT-based control systems and EMG signal classification. The accuracy, responsiveness, and general efficacy of rehabilitation devices can be greatly increased by these innovations, which also improve the synchronization between patient movements and device actions and decrease time delays. Incorporating these technologies presents promising opportunities to improve patient care and speed recovery times as knee-related musculoskeletal disorders continue to rise globally. Future studies ought to concentrate on improving these technologies and investigating how they can be used practically in clinical settings to satisfy the growing need for efficient, real-time rehabilitation solutions.

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