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Smart Prosthetics With AI-Based Motion Prediction

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Abstract: This study analyzes the transformational impact of artificial intelligence (AI) in prosthetics, particularly emphasizing the advancement of intelligent prosthetic devices aimed at improving mobility, flexibility, and user autonomy. Conventional prosthetic systems provide functional mobility but lack the intuitive and adaptable characteristics required for intricate movement. Advancements in machine learning and sensor technologies have enabled smart prostheses to provide users with a more natural and personalized experience. The research examines the design ideas, AI integration techniques, and user-centered methodologies in the creation of intelligent prostheses. Challenges like expenses, user education, and technological constraints are examined in conjunction with prospects for future progress. Case examples are used to demonstrate current breakthroughs, emphasizing the multidisciplinary teamwork propelling the area ahead. The report finishes by discussing future developments in AI-enhanced prosthetic development, which seek to promote the physiological health and psychological well-being of amputees.

Keywords: *Smart Prosthetics, Artificial Intelligence, Machine Learning, User-Centered Design, Prosthetic Mobility.*

INTRODUCTION

Prosthetic devices serve to substitute bodily parts lost due to accident, illness, or condition. Prosthetics seeks to enable people to maintain a regular lifestyle with little impairment of movement. They not only boost physical functions such as ambulation, locomotion, and grasping but also elevate an individual's psychological well-being by facilitating the restoration of aesthetic appearance and self-esteem. Mechatronic engineering enables the creation of limb replacements tailored to a patient's physiological requirements and lifestyle preferences. Replacements may also be equipped with enhanced artificial attributes, such as increased strength or sensory input. Prosthetic limbs were historically invented almost 3,000 years ago. Prosthetics, as we know them today, emerged in the mid-20th century, and the technology has gradually advanced since then. Conventional prostheses largely functioned to assist persons in ambulation by mechanically mimicking the capabilities of the substituted limb. The majority of contemporary prostheses continue to rely on this fundamental configuration. Smart prostheses, however, seek to enhance quality of life by offering active assistance during mobility as supplementary devices [1, 2]. User-centered design establishes the objectives of an advanced human-centric prosthetic device. Instrumented prosthetic feet and knees, capable of adapting to variations in terrain or walking pace, have facilitated advancements in intelligent prosthetic technology. Innovative sensors and digital technologies have facilitated prostheses to 'perceive' and 'comprehend' via pattern recognition, providing advanced control for personalized limb movement.

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The results are encouraging, since the novel ankle and knee systems provide more natural gait patterns and improved stability. Integrating artificial intelligence is very feasible, hence reducing the user's cognitive load in coordinating with the prosthesis and enhancing overall ease of living. The notion is seen as a technical advancement, particularly for those with lower-limb amputations; nonetheless, the hurdles associated with creating devices that function across many situations and mimic human agility are very intricate [3, 4]. Most of the previously stated solutions remain in the research domain (e.g., ultrasonic imaging, neural interfaces, IMES, pattern recognition) without clinical implementation. Pattern recognition facilitates the concurrent, autonomous management of many degrees of freedom (DoFs) (Ortiz-Catalan, M. et al. (2014)). However, performance is influenced by changes in arm posture, electrode location, fatigue, intrinsic cross talk in the surface signal, and muscle displacement during contraction. Pattern recognition requires extensive learning sessions; furthermore, its efficacy in real-world contexts diverges from laboratory conditions (Farina, D. et al. (2014)), hence limiting its therapeutic usefulness and adoption. In January 2015, the first gadget using pattern recognition and surface electrodes was launched.

Although the control of upper limb prostheses remains rudimentary, advancements in mechanics (Farina, D. et al. (2014)) are significant, as evidenced by the sophisticated multi-articulated myoelectric prosthetic hands currently available, such as the i-Limb4, Bebionic5, and Michelangelo6 prostheses illustrated in fig. 2 (Belter J. T. et al. (2013), Connolly, C. (2008), Lisi, G. (2009), Cutti, A. G. et al. (2012)). It is significant that these designs facilitate various gripping activities.

Figure 1: Evolution of the used methods for Bionic Prosthesis.

The Role of Artificial Intelligence in Prosthetic Devices

Beyond exceptional speed, the real potential of AI lies in its adaptable learning methodologies. Machine learning facilitates the analysis of AIs' historical behaviors to forecast the actions of any prosthesis user. This enables the adaptation of AI behavior to user requirements. The automation of this process is essential for developing smart prostheses that can autonomously enhance their intelligence via the ongoing improvement of learning algorithms. The advancement of sensors and machine learning methodologies has driven the substitution of conventional control tactics in the latest generation of commercially accessible smart prostheses. These devices need an initial training period, often spanning several weeks, during which the AI's behavior is tailored to the patient's walking pattern [5, 6]. Similar to the human brain's accumulation of experience, AI-driven prostheses now exhibit gait detection and performance enhancing functionalities. The information produced by IMUs may be used throughout the calibration and learning phases. During calibration, users must walk a significant number of steps, and their gait is recorded. This training step is essential since individuals with prosthesis must use them and walk to "train the AI." The data gathered during this phase is crucial for effectively optimizing the algorithms used in the prosthesis. Every commercial smart prosthesis and the gait recognition system use artificial intelligence. The training information used to refine the AI's behavior is gathered and accurately reflects the target population of prosthesis about age, weight, gender, and other variables. Only in this manner can the AI adequately address the user's requirements [7, 8].

AI-Based Bionic Prosthesis Materials

The design employs the Arduino-Uno to meet the requirements of the new prosthetic arm. It is noteworthy that the Arduino is not part of the microcontroller family. It is predicated on an audio and video receiver and constructed inside its integrated development environment. The power supply ranges from 6V to 20V. It is advisable to provide 7 to 12V via direct current via the parallel jack current using the voltage pin. The benefit of the Arduino lies in its ease of integration with analog components, automated engines, sensors, and other automotive and electrical automation systems.

Diverse architectures may enhance gadgets with several features. The architecture need neither intricate nor lengthy code, since a plugin suffices to run a program. Nonetheless, a limitation of the Arduino is its capacity to execute just a single code concurrently; so, running numerous codes results in system sluggishness. The use of Arduino entails a significant learning curve that necessitates familiarity with the C or C++ programming languages. Consequently, the following standard materials were used in constructing the new design: • Arduino-UNO; • Myoware EMG sensor and electrodes; • eSun PLA filament; • Mojitech 3D printer; • Tower Pro servo motors; • Micro servo motor (Mg90s).

The Canva program was used for creating the simulated design and the block diagrams. The data were evaluated and processed using MATLAB at the Biomedical Engineering laboratory at the Faculty of Engineering, Beirut Arab University. Additionally, information was supplied on the data collecting and processing techniques, including the area of interest (ROI) and the picture specs. The following approach paragraph presents the data annotation and data augmentation techniques.

Challenges and Opportunities in Integrating AI with Prosthetics

Notwithstanding these promising advancements, the integration of AI and robotics with prostheses in adaptable and intelligent manners presents significant technological challenges. The advancement of robotic prostheses is more rapid, agile, and data-driven than software updates or operating system repairs, necessitating that the broader technical environment, including connections and hardware designs, conform to similar timelines. Companies' software capabilities and the incompatibility within the medical and healthcare sector pose technical challenges, while exorbitant costs represent a third barrier to the adoption of AI- and robotic-based products. Individuals with superior insurance coverage and financial resources may benefit from these advanced and tailored health solutions. Notwithstanding these limitations, several possibilities are there. Intelligent prosthetic devices enhance user convenience and facilitate daily activities. In the realm of wearable robotics, several researchers emphasize the need of assembling a multidisciplinary team of engineers, healthcare specialists, and consumers to create an optimal gadget that integrates effortlessly into the wearer's lifestyle. The integration of AI in some prosthetic devices may enhance an individual's ability to walk or move autonomously and efficiently. Regulatory best practices, security, dependability, and aftermarket service are critical considerations, as they are with any AI or smart prosthetic devices. Future study should examine the implications of these challenges, since such inquiry has the potential to revolutionize smart prostheses and their users. We must acknowledge that we are navigating two opposing silos: one characterized by technological push and the other by demand pull. Although it is tempting to be too optimistic about contemporary AI or robotic prostheses, it is essential to refrain from underestimating the potential they provide in the near future.

Testing Results of AI-Control

This work used a single-channel EMG for the novel low-cost prosthetic arm. This may lead to erroneous data with significant noise interference. Consequently, AI was used to address this problem. Numerous AI methodologies exist, ranging from machine learning to deep learning; nevertheless, the latter has shown superior efficacy in predictive tasks. The experimental testing was conducted as outlined below:

A substantial dataset for EMG sensor voltage was permuted, allocating 80% for training and 20% for testing.

The experiment was conducted on the computer, and the settings were configured on the Arduino edge device.

A value of 1 was assigned to the contraction gesture, whereas a value of 0 was designated for the relaxation gesture.

Every five EMG voltages were subjected to smoothing using three techniques: exponential averaging, arithmetic averaging, and median filtering. The three values served as inputs to the neural network after normalization to a range of 0 to 1. The exponential average, the arithmetic mean, and the median were divided by 10434.046, 10489.604, and 10480.335, respectively. The output was partitioned into two neurons, with 0 producing [1,0] and 1 producing [0,1]. These data were obtained from normal participants for testing purposes. The dataset for the contraction gesture, obtained from a single patient, is shown in Fig. 2. Figure 2 (a) illustrates the sensor's values, whereas Figure 2 (b) demonstrates the impact of EWMA. The results indicated the disparity between the standard sensor data and the EWMA values, with the EWMA exhibiting a more refined and pronounced behavior for analysis. Additionally, the dataset sample for the relaxation gesture is shown in Figure 3. Figure 3 (a) displays the sensor's values, whereas Figure 3 (b) illustrates the impact of Exponentially Weighted Moving Average (EWMA). Analogous to contraction, the relaxation outcome demonstrated the fluctuation of the standard sensor values relative to the EWMA values, whereby the EWMA behavior seemed more fluid and pronounced for analysis.

The following actions were undertaken to get EWMA values:

The gathered data were inputted into Microsoft Excel. After inputting these variables into Excel, an equation was included by using Add-ins in the workplace settings, thereby enabling the Analysis ToolPak for users to use EWMA. Subsequent to the automated computation of EWMA, the resultant values were shown.

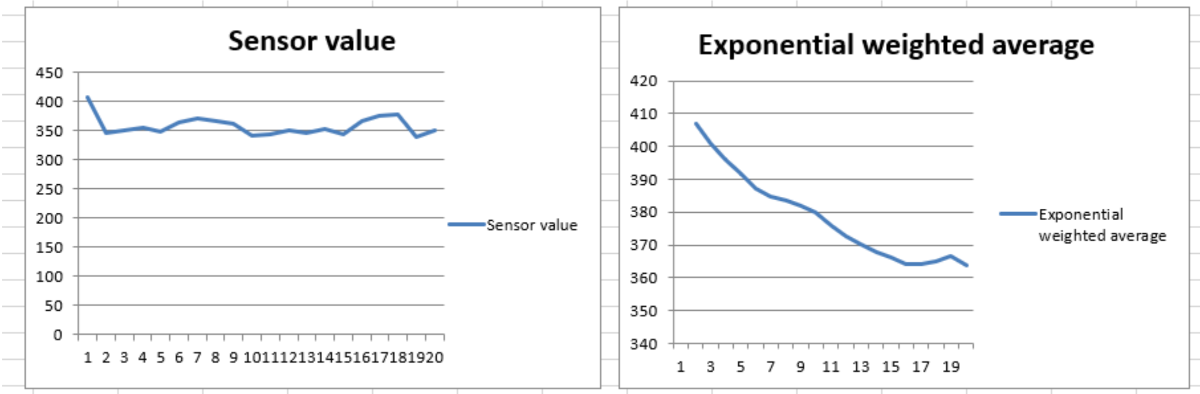

Figure 2: The plot of a sample of contraction gesture dataset. (a) A sample of the normal sensor's readings of a patient's dataset. (b) A sample of EWMA readings of a patient's dataset.

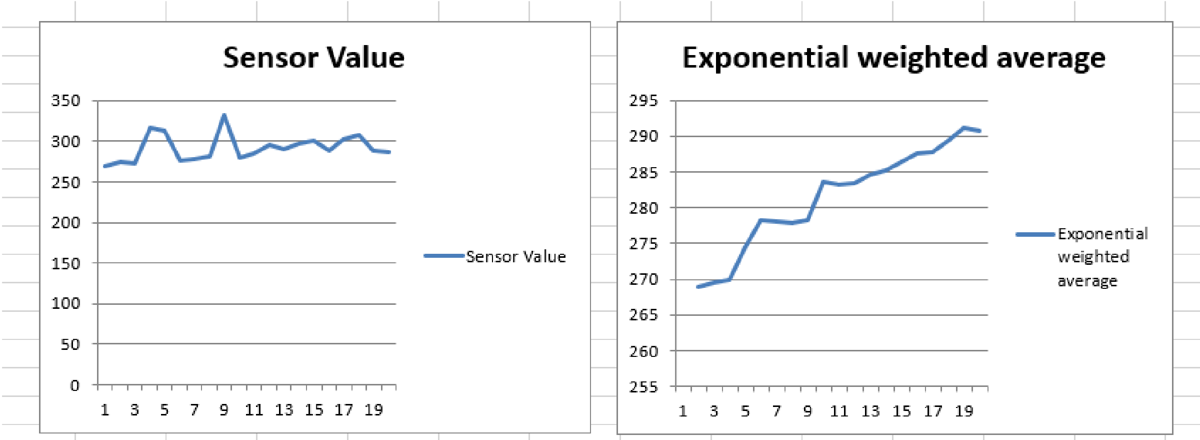

Figure 3: The plot of a sample of relaxation gesture dataset. (a) A sample of a normal sensor's readings of a patient's dataset. (b) A sample of EWMA readings of a patient's dataset.

Discussion

Subsequent to the development of the new AI-based robotic arm system, the whole system was evaluated with regard to the software's contribution. The system achieved the established goals. The AI-based control achieved an accuracy of 89% and 93% after the implementation of the deep learning neural network. The designated accuracy range encompassed the overall accuracy of the new system, factoring in the AI accuracy of 100%, the accuracy of the electrodes and circuitry, which varied between 83% and 89.3%, and the accuracy of the motors, which ranged from 84% to 90.3%. The total accuracy ranged from 89% (calculated as (100+84+83)/3) to 93.2% (calculated as (100+90.3+89.3)/3). Various configurations of Artificial Neural Networks (ANN) with differing quantities of hidden neurons were evaluated and verified throughout the training phase to ascertain the predictive accuracy of the newly developed network system for output classifications. Through the simulation of the network using several hidden neurons and distinct training techniques, the network's responses were assessed, and its functionality was validated by statistical analysis employing exponential weighted moving average (EWMA) and the median. The three inputs to the neural network produced the desired outcomes and reduced the noise that was disrupting the EMG data. EWMA facilitated the smoothing of the graphic for every five data gathered by the sensor and sent to the Arduino. Furthermore, via several stages of empirical testing, the system has independently acquired AI knowledge, and this procedure was consistently applicable each time. The EMG sensor exhibited an accuracy of 90%, since some readings may be omitted. The neural network facilitated the categorization of the datasets by using the median of every five values, along with averaging and weighted exponential averaging techniques. Furthermore, the sigmoid function demonstrated considerable accuracy in establishing a closed feedback system by regulating the arm via the provision of binary values, namely 0 or 1, which correspond to the contraction or relaxation gestures.

Manually selected delays during calibration resulted in optimal arm opening and shutting. Furthermore, the embedded code was designed for future editability, and all necessary comments were duly considered. The programming included universal features that are accessible for all designers in subsequent projects. Moreover, after evaluating the hardware contribution, the servo motors demonstrated significant compatibility with the system by offering an optimal delay time. The selected servo motors delivered the requisite speed and torque with a 4.8 V power source. The plastic used in the arm's manufacture demonstrated robust performance under weight loads. Furthermore, the curved grips produced by the 3-D printer facilitated effective grasping, while the fishing lines, serving as controllers, exhibited durability and longevity until subjected to excessive cutting pressure. The elastic paracord ropes provided elasticity and facilitated the natural bending motion of the fingers. The engineered motor holder was suitable for the system, and no interference from motor strings was detected.

CONCLUSION

The use of AI in prostheses represents a substantial advancement in mobility support technology, allowing amputees to attain enhanced functioning and autonomy. Intelligent prosthetics including adaptive algorithms and sophisticated sensors demonstrate the capacity for real-time response and individualized assistance. Notwithstanding present obstacles, like elevated expenses and the need for prolonged user training, the progress in AI-driven control systems and materials science indicates a hopeful future for the evolution of intelligent prosthetics. Ongoing research, especially in optimizing adaptive algorithms and improving cost-effectiveness, will be essential in rendering these sophisticated prostheses available to a wider array of consumers. By emphasizing user-centered design and multidisciplinary cooperation, the prosthetic industry is positioned to markedly enhance the quality of life and mobility for individuals with limb loss, therefore facilitating their social integration and mental well-being.

Future Work

The limits of this system development emphasize a sequential approach, necessitating the calibration and testing of each component individually before integrating all elements to assess their compatibility. Consequently, the equipment and materials must be improved in accordance with the ongoing technological advancements. This system may be integrated with Telemedicine via apps for rehabilitation purposes and must be evaluated in real-time across a diverse patient population; moreover, further AI algorithms for control must be investigated.

The foundation of future work is associated with advancements in the software and hardware of AI-driven bionic prosthetic arms. In relation to the software, the incorporation of new AI-driven features may be contemplated to facilitate the assessment of more applicants with impairments. Comparing the efficacy of EWMA with other noise reduction techniques, such as the Kalman filter and others, may be warranted. Furthermore, developing a novel user interface that is voice-activated, with an application tailored specifically for this arm, while ensuring the security of patient information. Conversely, including voice control into the system might assist illiterate individuals in impoverished nations, enabling patients to choose their preferred language as the system articulates ongoing procedures, so facilitating comprehension of the process. Concerning the hardware, an internal configuration for the EMG sensor may be contemplated, along with the potential implementation of angular limiters or a software-based feedback system as a precaution against over-rotation. Additionally, develop a motor holder capable of accommodating five motors instead of four, allowing for internal control of the thumb finger rather than direct motor placement on the finger. All subsequent processes facilitate the investigation and enhancement of the newly suggested design, as well as the promotion of healthcare and rehabilitation objectives.

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