

Exploring Electromyography (EMG) Signals for Prosthetic Control: A Comprehensive Survey

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Abstract— This comprehensive review explores about Electromyography (EMG) signals, and how it can be used for several applications. EMG is electrical current variations produced by muscle activities. EMG signal varies according to muscle activation and relaxation states, these signals can be captured using a hardware setup and can be used for many applications such as prosthetic control, rehabilitation, and human-computer interaction. This review focuses on EMG signals, prosthetics and how prosthetics is controlled using EMG. Prosthetic arm and legs are artificially 3D printed for helping amputees to an extent by mimicking the natural actions. Through proper real-time collection and preprocessing of EMG signals, prosthetic control can be achieved, and these EMG-based prosthetics enable intuitive control and enhances the user experience.

Index Terms— Electromyography signals (EMG), Prosthetic, 3D Printing, Non-Invasive, Machine learning, Deep learning.

I. INTRODUCTION

Electromyography (EMG) is a technique that measures the current generated in muscles during the muscle activities. The EMG signals can be collected by using surface EMG electrodes or Needle electrodes, the techniques are known as surface Electromyography (sEMG) and needle Electromyography (nEMG) respectively. EMG signals play major role in medical field for diagnosis of neurological and neuromuscular anomalies. In modern medical field acceptance of EMG signals for diverse applications are increasing day by day. These diverse applications include rehabilitations, prosthetic control, human-computer interactions. Rehabilitation helps people to regain their medical comfort which have been lost due to accidents, injuries, by birth and so on. There are several types of prosthetic arms are available, trans-radial and trans-humeral, activity specific, passive, hybrid body-powered are some of them. The arm can be chosen based on the requirements of individuals. The controlling of prosthetic arm using myoelectric signal provides intuitive control, natural movements, less stressful on muscles, higher pinch strength and this approach of prosthetics also provides confidence and comfort to those who are suffering from medical anomalies. In prosthetics, EMG-based 3-D printed arm and legs are increasingly adopted because of its dynamic working ability and it is much cheaper compared to others. Several studies are being conducted on this approach. Fig 1. (a) shows the process of acquiring EMG signals from hand using surface Electrodes. Fig 1. (b) shows the collected EMG signals in analog form, where x-axis shows the number of samples and y-axis shows the magnitude.

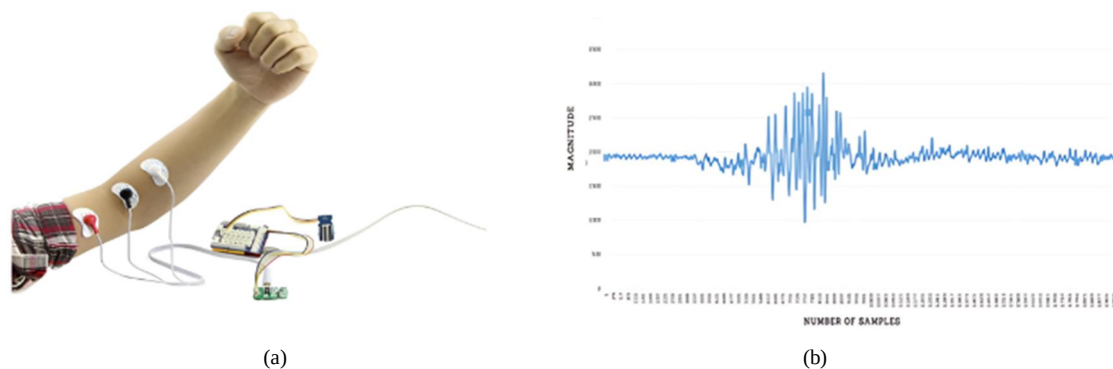


Fig 1. (a) EMG acquisition. (pc: A. A. Abdhul, D. Subramani, J. Ganesan, S. Subramaniam and K. G. Dharani [5]), (b) Analog form of EMG signal. (pc: E. Priya, C. N. Savithri, N. R. K L, S. M and V. K., [23]).

II. RELATED WORK

The study by S Pranoti and S Guruprasad [1], addresses the challenges posed by noise interference in EMG signals and presents various algorithms and methods for accurate signal detection, and processing. Building on the basic signal processing and noise reduction, S Pancholi, P Jain, A Varghese and A M Joshi [2], introduces a new feature called Peak Average Power (PAP) for enhancing electromyography (EMG) pattern recognition. The PAP feature aims to improve classification accuracy by capturing time and frequency information of EMG signals.

The research done by R. Agarwal, H. Kumar and S. Singh [3], investigates the relationship between EMG signals from forearm muscles and wrist angles under maximum clench in various wrist motions. The paper finalizes that EMG analysis at different wrist angles could help in designing more effective prosthetic devices by providing insights into muscle behaviour and grip force requirements. As a next level of this, S Inam, F. Amin and M Z ur Rehman [4], in their paper examines the gender differences in surface EMG signals for controlling upper-limb prosthetics, focusing on whether the EMG signal characteristics differ between males and females. These findings suggest that while most EMG features are consistent across genders, certain features like waveform length may vary, influencing prosthetic control applications.

A A Abdhul, D Subramani, J Ganesan, S. Subramaniam and K G Dharani [5], discusses the design and development of an EMG-based prosthetic arm aimed at providing a portable and efficient solution for people with upper limb disabilities. EMG signals are collected using electrodes placed on the skin to capture muscle signals, the device interprets neuromuscular signals to control the prosthesis and estimate the required force and torque for movement. Similarly, Anish C. Turlapaty and Balakrishna Gokaraju [6], focus on building a robotic hand for the persons who have been affected by a limb disability, with the help of EMG signals the working of the prosthetics were done. By using KNN algorithm they implemented the work successfully.

The study done by L. Z. Liao, Y. L. Tseng, H. H. Chiang and W. Y. Wang [7], presents an EMG-based classification technique for controlling an assistive robotic arm to mimic human arm movements and importance of careful feature selection to enhance the performance of assistive robotic systems driven by physiological signals like EMG.

The authors H. Chen, R. Tong, M. Chen, Y. Fang and H. Liu [8], presents a hybrid CNN-SVM model for recognizing hand gestures from surface electromyography (sEMG) signals – uses a CNN to automatically extract features from EMG images, followed by an SVM classifier for recognizing gestures. Experiments show that the hybrid model improves recognition accuracy. K. Fukano, K. Iiazawa, T. Soeda, A. Shirai and G. Capi [9], extend this using a deep learning-based approach for mapping surface EMG signals to hand gestures. The proposed method uses raw EMG data as input to a CNN, allowing the network to automatically learn relevant features for gesture classification. The results demonstrate that CNNs can be a viable solution for accurate and responsive control of myoelectric prosthetic hands.

The study done by D. Jiang, S. Song and Y.Xia [10], focuses on exploring the EMG base gesture recognition for human machine interactions using the deep learning techniques CNN, ResN, FCN, and FCRN. The FCRN has got the best accuracy with 24 subjects performing 49 gestures from the Ninaweb DB2 dataset. The results varied, with the 24th subject showing the lowest accuracy, possibly due to data redundancy from short-interval recordings.

The work deals with the use of EMG signals to control artificial myoelectric arms for the disabled person this research done by R. Ahmed, R. Halder, M. Uddin, P. C. Mondal and A. K. Karmaker[11], shows that how it will work under different users for control information. it also explains the importance of extracting features to reduce noise and interface in raw EMG signals. A. A. Abdhul, D. Subramani, J. Ganesan, S. Subramaniam and K. G. Dharani also [12] presents design of an EMG based prosthetic arm for enhancing the capability of upper arm prosthetics. This uses EMG and neuromuscular signal processing to create a power-efficient, and low-cost prosthetic arm that act as natural hand. The sensors and control system together works to achieve the required output. The work done by K. Murugan, L. V. N. Reddy, C. Veerandra, S. S. Hussain, N. Amarnadh and M. Kumar [13], has developed a prosthetic hand using EMG signals. The system uses deep learning methods, specifically neural networks, this helps to decode EMG signals associated with different hand movements. The neural network model can analyze complex EMG patterns that allows a more accurate understanding of user intended motion. The authors Y. Liu et al. [14], focuses on prioritizes human centered evaluation and describes impact of different EMG based prosthetic control on task performance and cognitive workload. Differentiate three modes of controls direct controls, pattern recognition, continuous control. This lays a ground work for further design that can refine prosthetic design.

The work done by H. Kawasaki, T. Mouri, K. Iwase and H. Sakaeda [15], introduces a dual-mode system that combines speech and sEMG for controlling prosthetic arm for amputees. The mode of system is controlled by the own voice. The combined system ensures more reliability and it reduce the limitation of system that uses sEMG. The speech mode enables predefined movements and control grasping force, the sEMG mode controls finger joint angles based on Neural Networks (NN). The authors P. PonPriya and E. Priya [16], discuss about the non-invasive control of prosthetic arm for amputees using sEMG signals. Developed a wired prototype, includes direct current (DC) motors for controlling each finger of prosthetic arm. Suggests a wireless connection to improve mobility. Surface electrodes are placed in the forearm to capture sEMG signals for the effective control. The paper explore the mathematical modelling and control system for the prosthetic hand, the authors A. Mkhitarian and Z. Khanamiryan[17], found that it is derived from the euler lagrange equation it is used for determining the various forces . The control system, which helps in the operation of the prosthetic hand, is developed and tested in a simulation environment (MATLAB/Simulink). The study focuses on designing a PID (Proportional-Integral-Derivative) controller to control the movement and function of the prosthetic hand.

Y. Bandou, O. Fukuda, H. Okumura, K. Arai and N. Bu [18], had been proposed a combined system of controlling prosthetics by using EMG with a vision-based object classifier. The system uses deep convolutional neural network for recognizing objects and adjust posture. The system has high accuracy, more than 80 percentage of 25 target objects. The method has high potential to control various motions of prosthetic arm.

P. Hand, S. Prabhu and B. N. Shama [19] implement a low-cost prosthetic arm controlled by voice commands and hand gestures. The material used for prosthetic arm is polymorph, it is strong and light material. The arm is actuated by sensors through microcontroller. The gesture recognition is enabled by flex sensors and voice command control is done using the smart phone application. The authors S. A. A. Hiader, A. Nasir, M. Ameen, A. Raza, A. Waleed and Z. Ali [20], presents wirelessly controlled, affordable prosthetic arm for individuals with hand loss. By Using low-cost flex sensors, the hand imitates natural finger movements by varying resistance. The servo motors activate to imitate these gestures and provides grip and control. Can be used for remotely for hazardous applications. This work done by T. Kocejko, R. Weglerski, T. Zubowicz, J. Ruminski, J. Wtorek and K. Arminski [21], develops a low-cost 3D printed prosthetic arm having five degrees of freedom for people with severe movement disabilities. The arm is weighing under 6 kg and it is comparable function as human arm. Arm is controlled through eye tracking or other interfaces. It offers flexible movement for daily activities.it is accessible because the arm is fully 3D printed

M. M. Medhat, G. I. Alkady, R. M. Daoud, H. M. ElSayed, M. Arafa and H. H. Amer [22] presents a wi-fi based architecture for controlling modular prosthetic limb, focusing on increasing reliability and decrease the maintenance cost. The work includes a method to analyze and optimize redundancy of motor using Petri nets. Reliability is examined for various failure scenarios in the controllers and mechanical motors using Markov and petri nets.

E. Priya, C. N. Savithri, N. R. K L, S. M and V. K [23] shows an innovative approach to enhance the quality of life who have lost their hands due to accidents and genetic disorders. Such people struggle with physical, mental and social challenges. In order to address these issues, a myoelectric prosthetic arm that uses s-EMG signals was developed. The s-EMG signals collected from the residual are collected, classified and used for control of prosthetic arm to mimic the natural human hand actions. Machine learning approach outperforms the traditional prosthetic arms and benefits in developing human friendly prosthetic arm. M. I. Uygun, B. Recber, M. A. Celikli and Y. Oniz [24], explains that through proper EMG muscle sensor placement during muscle contraction, signals

can be captured, filtered, and classified to decode the user's intended movement. Classification machine learning algorithms can be used to analyze different muscle states and can be used for effectively translating the filtered signals to commands for the prosthetic arm. On Integrating haptics, heat sensor, pressure sensor the prosthetic would be more user friendly.

F. I. Anik, N. Sakib, A. D. Roy and M. H. A. Nahayan [25], examines current challenges of prosthetics in enabling adaptive control over grip force during object handling. EMG signals that are linked to distinct finger movements can be utilized for adaptive grasp control. Using machine learning approach, it was able to distinguish and classify the underlying pattern of finger and grasp movements. These findings offer insights for the dynamic control of human motor control, which is the basic and important step in the prosthetic control. L. Tian et al. [26], addresses the major challenges of current prosthetic arm, by developing a real-time Control System for Prosthesis (RCSP) along with a lightweight prosthetic hand named S-Hand. The work also investigates multi-degree freedom of movement for prosthetics can be enabled using EMG signal pattern recognition (PR) algorithms. This system enables both abled and non-abled individual to stimulate real world scenarios, such as Box and Block Test and Clothes Pin Relocation test. By the integration EMG PR algorithms, development of protheses that can closely mimics natural limb functions was possible. A. A. Abdhul, D. Subramani, J. Ganesan, S. Subramaniam and K. G. Dharani [27], also investigates current prosthetics challenges in portability and performance in myoelectric control system. This prototype interprets neuromuscular signals from the residual limb muscles, to control force and torque which enables natural and advanced movement of the prosthetic arm. The embedded sensors and control system work in sync to mimic the natural human hand movement. By utilizing a low-cost, efficient actuation and control system showed a significant improvement over traditional myoelectric protheses.

The work presented by M. Moradi, K. Hashtrudi-Zaad, K. Mountjoy and E. Morin [28], discuss about combination of EMG signals and kinematic data can enhance the performance of prosthetic arm's movement and force modulation. By analyzing the EMG signals from the residual arm and kinematic data from the prosthetic's arm joints through Artificial neural network helps in predicting the user's intended force at the tip of the arm. This method is tested in a healthy person and the result was good. This method increases the performance of prosthetic with a human friendly approach.

The study of J. Hussian, H. E. Gelani, B. Ahmad, A. Ali, S. Rehman and W. Arshad [29], introduces an affordable and efficient approach to prosthetic arm design, aiming to increase accessibility by reducing cost and reliance on conventional power sources. A custom muscle sensor was developed and it reduced the cost 10 times compared to the standard sensor available in the market. The system also had a piezoelectric generator to enable battery charging through walking. A 1.5mile walk can fully charge the prosthetic arm battery. This is a convenient and sustainable solution is for battery problem in real-world activities. The custom EMG sensor, which produces 70 dB signal-to-noise ratio was used on a 3-D printed prosthetic arm and 6 degrees of freedom of movements was possible. The overall cost was 350\$. In the work presented by N. Sakib and M. K. Islam [30], a cost-effective solution for prosthetic arm was presented. In Bangladesh the average cost of the prosthetic arm was around 100,000 BDT. Using a 3D printer, a prosthetic arm was constructed. The EMG recorder was assembled on a PCB using locally sourced components. The total cost for this work was about 4000 BDT, making it a cost-effective option for amputees. A. Z. Kenza, M. Baby and M. George [31], developed a prosthetic arm that was 3D printed, with Innofil3D PLA biocompatible material for the limb, paired with Arduino-based signal processing. This prosthetic arm works on the basis of EMG signals collected from the arm. 3D printing offers cost-effectiveness, customizable solutions, facilitative replacement, and upgrade at low cost. DC motors were used for their precision and ease of control, essential for accurately managing finger movement. A. Cañizares, J. Pazos and D. Benítez [32], in their paper investigates the use of 3D printing to create affordable prosthetic arms. The study focuses on developing two prototypes: a five-fingered hand controlled by a glove and a hand-arm controlled through EMG signals with the help of servomotors for finger movement, with microcontrollers to manage the rotation based on signals from sensors.

This study of K. Murugan, L. V. N. Reddy, C. Veerandra, S. S. Hussain, N. Amarnadh and M. Kumar [13], involves a novel EMG-Driven smart prosthetic hand that utilizes deep learning, aiming to produce the functional capabilities and quality of life of amputees. By acquiring EMG signal from the muscle through non-invasive method, user's intended action can be predicted and hence can be converted in to commands for the prosthetic arm. To process and decode the complex EMG signals convolutional neural networks (CNN) was used. This intelligent approach offers a smooth control of the prosthetics. The paper of B. L. Nadjib, C. Bilal and R. Karima [34], also presents a deep learning method to predict the hand movements using sEMG signals for prosthetic control. Classification is done using deep learning methods like Convolutional neural network (CNN) and Long Short-Term Memory (LSTM). The model achieved an accuracy of 98.8% using "sEMG for Basic Hand

Movements” dataset. A prosthetic arm was made and it was capable of doing 6 different actions, that includes cylindrical, hook, lateral, palmar, spherical and peripheral. This shows the suitability of this approach in real-world situations.

This work of F. F. Rupom, S. Jannat, F. F. Tamanna, G. M. Al Johan and M. M. Islam [35], addresses the need for real-time accurate gesture prediction using sEMG for Human-Computer Interface (HCI) and prosthetic controls. The focus was to classify different hand gestures such as Rock, Paper, Spherical Grip and All right using different machine learning algorithms such as SVM and KNN. Several methods are used to extract features like variance, waveform length, zero crossings, slope sign changes and integral of EMG. The signals are preprocessed using an offline server. This real-time gesture recognition system, significantly benefits amputees in developing countries.

This work of Minsang Seo, Dukchan Yoon, J. Kim and Y. Choi [36], introduces a control system for prosthetic hands for trans-radial amputees, using sEMG signals and converting it in to commands. This system enables control over 10 joints, including 4 active joints powered by electrical motors, allowing complex movements. The system is tested in real-time and working of each individual fingers where achieved. This prosthetic arm showed great result in tasks like peg-in-hole test based on phantom-hand movement.

N. Sawake, S. Gupta, A. Ghatge, A. Khatri and K. M. Bhurchandi [37], introduces an initial approach for designing a prosthetic leg for above-knee amputees using sEMG signals. The EMG signals are collected from the calf muscles through an EMG acquisition system, which is further preprocessed and sent to the micro controller to control the joint movement of the leg. The prototype follows a motor driven knee joint, which enables the walking.

M. Orban, X. Zhang, Z. Lu, A. Marcal, A. Emad and G. Masengo [38], presents a way to control a prosthetic hand using surface EMG signal. The researchers aimed to improve the accuracy of finger movement control using a PID controller, which adjusts the position of each finger based on these muscle signals. They tested two tuning methods for the PID controller. The study showed that the genetic algorithm achieved better control with faster response time.

A. Rafiq, Z. Talukder, A. Hamim, J. Firdous and K. I. Uddin Ahmed [39], presents a new approach for controlling prosthetic arms using surface EMG signals combined with embedded machine learning. The authors used five sensors on the forearm to collect muscle signals. This setup allows users to control hand gestures like open and closed fists with high accuracy (97.2%) and minimal processing delay (about 100 ms) and provides a cost-effective solution that doesn't need internet access, making it more accessible for amputees.

J. V. Patricks, G. Thing Thing, L. Z. Hong and A. Zourmand [40], examines the design of prosthetic hands that can aid individuals with upper limb amputations by restoring some natural hand functions. This project aims to create a prosthetic hand system that senses muscle contractions on the skin's surface to control finger movements.

Using the Myo-Ware muscle sensor, surface electromyography (sEMG) signals are collected and processed to facilitate finger movement. Francesco Tenore, Ander Ramos, Amir Fahmy, Soumyadipta Acharya, Ralph Etienne Cummings, Nitish V Thakor [33], introduced a new framework to enable precise control of individual fingers in prosthetic hands. By placing surface-EMG electrodes on the forearm of an able-bodied participant, the authors captured signals associated with distinct finger flexion and extension movements.

Time-domain feature extraction methods were used to process these signals, which were then given into a neural network classifier. The results demonstrate that the framework can decode 12 different finger movements with over 98% accuracy.

III. FINDINGS AND OBSERVATIONS

- **Deep Learning for Gesture Recognition:** Many studies highlight the effectiveness of deep learning models like CNNs and LSTMs for accurate hand gesture recognition using EMG signals. These models improve feature extraction and classification accuracy, facilitating responsive prosthetic control.
- **Feature Extraction Techniques:** Advanced feature extraction methods such as mean frequency, waveform length, and Peak Average Power (PAP) enhance EMG pattern recognition. Optimized feature selection is important for improving model performance and prosthetic responsiveness.
- **Noise Reduction:** Accurate EMG signal is challenged by noise. Several papers propose innovative noise-reduction algorithms and preprocessing techniques to ensure more reliable prosthetic control.
- **3D Printing and Cost Efficiency:** The use of 3D printing in developing prosthetic arms presents a cost-effective solution, making advanced prosthetics more accessible. Customizable and low-cost designs can be adapted for specific user needs, improving both affordability and functionality.

- **Sensor Placement and Data Quality:** Accurate placement of EMG sensors and the quality of collected data are vital for reliable signal classification. It also reduces the noise in the data set.
- **Hybrid Model Efficiency:** Combining models, such as CNNs with SVMs, shows significant improvement in recognition accuracy for EMG-based gesture control. This hybrid approach shows the feature extraction power of CNNs and the classification capability of SVMs.
- **Portability and Real-Time Control:** Studies emphasize the importance of creating lightweight, portable prosthetic devices with real-time control capabilities. Implementations using microcontrollers and Raspberry Pi highlight advancements in responsive prosthetic technology with low latency.
- **Gender-Based Performance Insights:** Research indicates slight variations in EMG signal processing across genders, influencing control precision. Tailoring prosthetic designs to these differences can enhance functionality for diverse users.
- **Sustainability and Cost Reduction:** The use of 3D printing and locally sourced components for prosthetic arms has been explored to make devices more affordable. Studies reveal that customized, cost-effective solutions can significantly reduce production costs without compromising functionality.
- **Machine Learning in Prosthetics:** The integration of machine learning algorithms, such as neural networks and deep learning techniques, improves the interpretation of complex EMG signal patterns, enabling smoother, more adaptive control of prosthetic limbs.

IV. CONCLUSION

EMG signals are part of emerging technology, many studies and works are being conducted on this topic to demonstrate various pathways to explore the diverse applications using EMG. Prosthetics is one of the most important among them.

In this review, EMG, different prosthetics and prosthetics using EMG was discussed. This paper gives an idea about prosthetics using EMG, how it works, challenges in current prosthetics. By integrating proper hardware, preprocessing techniques, feature extraction, classification of muscle states in real-time enables dynamic control of prosthetics.

This EMG based 3D printed prosthetic design is a cost-effective solution and this approach would be a great help for amputees who are financially backwards.

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