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Development and evaluation of a novel force myography (FMG) based human-machine interface for transradial prosthetics: A comparative study with electromyography (EMG) techniques

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ABSTRACT

Human-Machine Interfaces (HMIs) must bridge human skills with machine control, notably in active prosthesis. Electromyography (EMG) is the most popular prosthesis actuation method. However, researchers need new HMIs for active prosthesis development. This research introduces Forcemyography (FMG)-based HMI using force-sensitive resistors (FSRs) to capture myoelectric data. A particularly constructed case with two integral parts—an internal and an exterior component—is FMG. This FMG enclosure adapts effortlessly to the user's limb and shape for best performance and comfort. FMG and sEMG were compared in the experimental evaluation. Stability, forecast accuracy, hair and sweat resistance, wearability, and cost-effectiveness were examined. FMG signals outperformed sEMG signals in this comprehensive examination. FMG outperformed sEMG in stability and prediction accuracy. FMG produced outstanding results right from capture without post-processing, a unique advantage. The specialised enclosure protected FSRs from outside interference and delivered precise signals. The Forcemyography (FMG)-based HMI is a breakthrough in active prosthesis technology. Its versatility, consistent signal acquisition, and user-centric design promise improved human-machine interactions. FMG leads the way to smooth, intuitive, and efficient human-machine interface.

1. Introduction

Amputation by any means always a traumatic event not only to amputees themselves but also to their families as it renders him/her to perform Activities of Daily Livings (ADLs). It has significant negative effect on amputee’s life not only physically but also psychologically. It is one of the most important social goal to rehabilitate these amputees by creating barrier free environment. Therefore, it is required to rehabilitate these individuals by providing them assistive devices which restore their lost functionalities. Such device is termed as ‘prosthetic device or prostheses. These devices are provided on the basis of amputation. Trans-tibial amputations (below the knee), trans-femoral amputations (above the knee), trans-humeral amputations (above the elbow), and trans-radial amputations (below the elbow) are the most common types [1]. Most common causes of amputations are traumatic accidents, burns, Peripheral vascular disease, Malignant tumours, Infections, Neurologic conditions and diabetes [2, 3]. According to statistical data, 60% of the upper limb amputations are trans-radial amputees [4]. It is reported that over 900,000 among 1,564,000 amputees have fingers and/or hand amputation in US alone [5]. This number could drastically increase if consider the whole world. Hence, trans-radial prosthesis shows its effectiveness in providing functionalities to upper limb amputees. Although from the last few decades, advancements were made in the development of trans-radial prosthesis such that to restore the biological function of human wrist and hand in amputees by developing their versatility and control [6]. However, necessity for further improvement in anthropomorphic hands are still required.

Passive prostheses and active prostheses are now used to recover upper limb functions lost due to amputation. Active prostheses, in addition to cosmetics, provide functionalities of actual limbs, while passive prostheses are primarily employed for cosmetic purposes and give very little or no functionality [7]. These active prostheses require Human-Machine Interfaces (HMIs) for acquiring myo-signals from amputated limb such that to control and operate these active prostheses. Two types of HMIs are used to acquired myosignals. One is invasive and other is non-invasive HMIs. Invasive HMIs are connected directly to the human muscle(s) and usually require surgery for installation in human body whereas in contrast to invasive HMI, non-invasive HMIs are mounted directly on the surface of the body [8]. Non-invasive HMIs are also termed as surface HMIs. However, for trans-radial prostheses myo-signal acquisition, non-invasive HMIs are commonly used. Most common surface HMI used for acquiring myo-signals are electromyography (EMG) technique. In this technology, muscle signal can be acquired by both invasive and non-invasive methods, either by using needle electrodes or surface electrodes respectively. Electrodes are the devices that are used to extract myo-signals signals from muscle activities. After extracting these signals, it contains noise content therefore it cannot be directly utilized. First the signal is cleaned and then processed by using various digital signal processing techniques. The EMG signal is unstable, with an amplitude that varies from a few hundred microvolts to a few millivolts; it is disrupted by the slightest limb movement, lowering the signal-to-noise ratio; it is affected by the presence of sweat and hair on the upper limb extremity; and the physiology of the EMG signal changes over time in response to the subject's level of fatigue. In light of these drawbacks of EMG control approaches, it is important to investigate alternative technologies that can efficiently acquire muscle signals at low cost and without the need for any specialised pre-processing [9]. Force sensitive resistor (FSR) is an alternative to this method. The electrical resistance of a force-sensitive resistor (FSR) varies when a force is applied to its surface, making it a useful pressure sensor. FSR is showing great potential as a sensing mechanism for expanding its use in the medical field. It's a way to acquire myo-signals from the human body without causing any harm to the subject. Noise levels in FSR sensor signals are lower than those in EMG signals [10]. Despite decades of research performed in properly controlling a robotic hand from an amputee upper extremity is, still nowadays, an open challenge. The purpose of the study is to introduce a novel technique for acquiring myo-signals from amputee upper extremity for controlling hand prosthesis using FSR sensors. A novel design for Forcemyography (FMG) based HMI was proposed and was tested on amputee limb. This paper also performs comparative study between myo-signals acquire from FMG and EMG based HMIs.

2. Literature Review

From last few decades a number of research were performed to develop a new technique for controlling anthropomorphic hands. In the framework of prosthetic hands, a key indicator to detect patient intent for biological signal is HMI which convert them into control signals for the anthropomorphic hands. Traditionally, the most common adopted technique is the surface EMG (sEMG). The signal derived from EMG electrodes has a very small amplitude, often between a few hundred micro volts and a few millivolts. In spite of low amplitude, the noise content is very high.

Table 1

Existing literature

Ref. No.	Sensors Used	Model/Technique Used	Accuracy	Contribution	Limitation
[1]	Hybrid on-body sensors (EMG, IMU)	Hybrid sensor fusion for upper-limb prosthesis control	~92%	Hybrid HMI system for accurate control	Limited real-life testing

[2]	EMG, FMG, EIT	EMG, FMG, Electrical Impedance Tomography (EIT)	EMG: ~88%, FMG: ~85%	Review of biosensors for prosthetics	EIT has limited practical deployment
[3]	Magnetic sensors	Magnetic detection of muscular contraction	~90%	Novel use of magnetic sensors for control	Prone to magnetic interference
[4]	FMG	Low-Density Force Myography (FMG)	~93%	FMG-based HMI for gesture classification	Limited to simple gestures
[7]	sEMG	Hand Gesture Recognition using sEMG	91.20%	Tailored sEMG system for prosthetic control	Needs recalibration for arm position changes
[8]	FMG, EMG, IMU	Combined FMG, EMG, and IMU for gesture classification	FMG: 88%, EMG: 85%	Multi-modal system for robust recognition	Increased computational complexity
[10]	EMG	Prosthetic Designs with EMG	~90%	Advances in prosthetic control using EMG	Noisy signals prone to interference
[12]	EMG	LSTM Recurrent Neural Networks (RNN) for EMG processing	~92%	LSTM improves EMG signal processing	High computational demands
[13]	sEMG, FMG	Multi-modal prosthesis control using sEMG, FMG, IMU	sEMG: ~90%, FMG: ~87%	Robust control with sensor fusion	FMG less sensitive to subtle contractions
[17]	FMG	Low-Density Force Myography (FMG)	92.40%	Novel FMG armband for gesture classification	Needs improvement for comfort in long-term use
[20]	EMG	EMG-based Prosthetic System	~89%	Intelligent prosthetic control system	Sensitive to external factors like sweat
[21]	sEMG, IMU	Myoelectric neural interfaces for prosthetic control	~90%	Bio-robotics research for prosthetics control	Limited long-term user studies

3. Materials and Methods

A novel FMG based HMI setup(casing) was developed for acquiring and acquisition of myo-signals for two Degree of Freedom (DoF) trans-radial prosthesis. EMG based HMI was also studied and developed in this study and its results were compared with newly developed FMG technique. A psychophysical experimental set up was developed, in order to determine the pros and cons of the two mentioned HMIs.

3.1 Development Of FMG Based HMI

FMG based HMIs usually acquire Force Sensitive Resistor (FSR) for converting muscle pressure to myo-signals. The FSR being a sensitive sensor, has the capability to detect a very little amount of physical pressure exerted on it. However, FSR as an HMI in anthropomorphic hands, it is better to measure only muscle pressure and perceive other pressures as noise arises as a result of surrounding forces, hand weight or movement. These unwanted pressures can be prevented by developing special housing for the FSR sensor, which protects the FSR sensor from unwanted pressure and measures only the desired movement of muscles. In this study, a special housing for FSR sensor was developed such that to eliminate the unwanted/undesired pressures. The housing/casing of FSR comprises of two parts; 1) internal casing 2) external casing. Internal casing contained film seat along with connector on top side whereas a threaded hole at the bottom. FSR interlink 408 model was selected for detection of stimuli of forearm muscles. This sensor has dimensions of 609.22 x 5.08 x 0.28 mm (LxWxT) with sensitivity of 0.2 N to 40 N. To best fit in the film seat, FSR sensor was cut into square shape having area of 5.6 mm2. The modified FSR sensor strip was placed inside film seat of internal casing and connected with the terminals of internal casing. The internal casing cap having rectangular step was created and placed above the film seat. This rectangular step exerts force on the FSR sensor when muscle actuates. Fig. No.1 to 5 illustrates step by step placing of FSR sensor in internal casing.

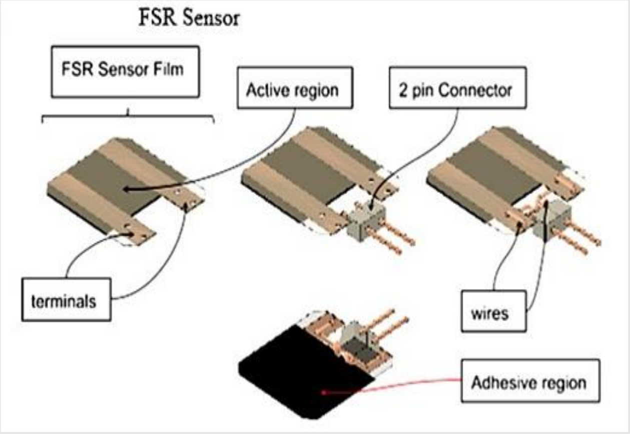

Fig. 1. FSR Sensor

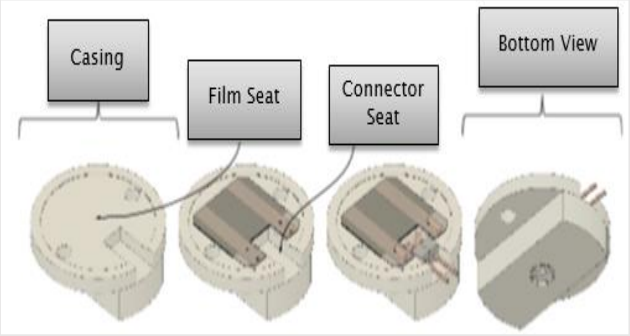

Fig. 2. Sensor Casing

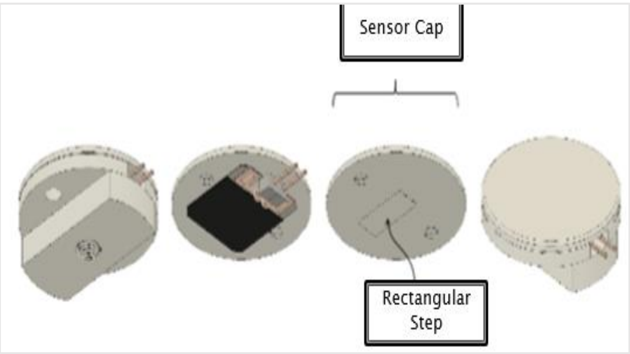

Fig. 3. Sensor Cap

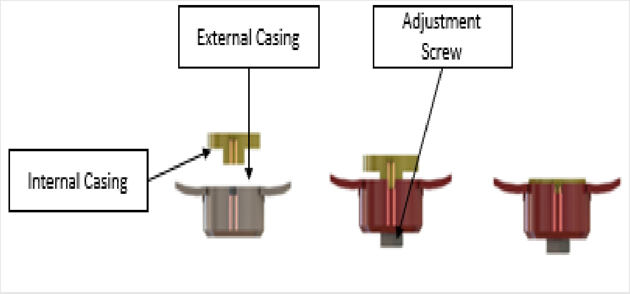

Fig. 4. Adjustment Screw

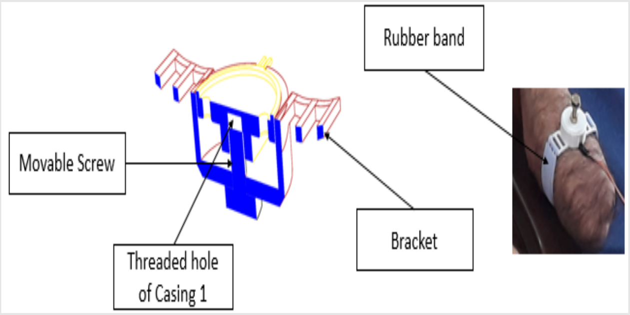

Fig. 5. Sensor Strip And Internal Casing

External casing was designed for placing and adjusting the position of internal casing with respect to forearm muscles. For positioning of internal casing, the M3 screw was used to push/pull the internal casing towards or away from the stimuli muscles of subject, respectively. This mechanism was developed such that the two casing could be fitted/mounted on any type of forearm regardless of the shape and size of forearm. External casing had two brackets which were used to tie a rubber band round the arm of the amputee. Fig. 7 illustrates the relation between internal and external casings.

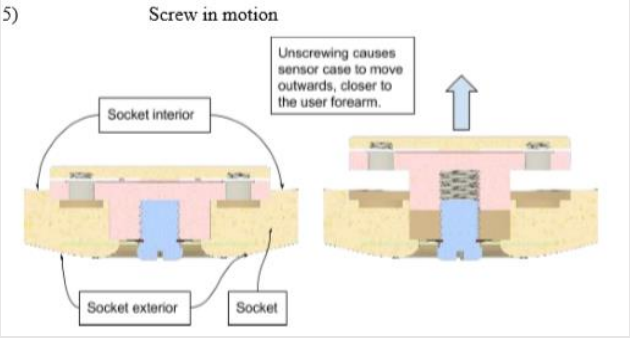

Fig. 6. Screw Motion

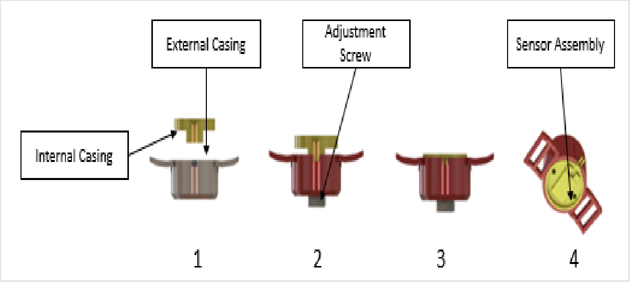

Fig. 7. External And Internal Casing Assembly

3.2 External Casing FSR

Both the internal and external casing was fabricated using polymer based additive manufacturing technology. Poly Lactic Acid (PLA) material was used in fabrication of both casings as it is a rigid material and having required strength to sustain undesired external force without being failure. The total time taken by printing both casings were 45 mins and the weight of internal and external casing was 10 and 13 grams respectively.

3.3 Development Of Experimental Setup For EMG Based HMI

EMG sensor along with three surface electrodes were used in the study to extract myo-signal from targeted muscle. These electrodes were mounted in such a manner that two electrodes extract myo-signals from targeted muscle and the third one was connected to a bony region of stump as shown in Fig. 8 below.

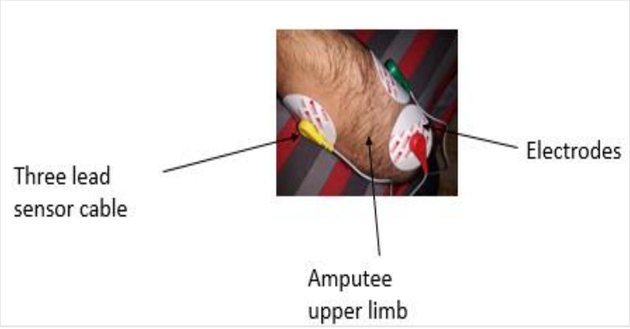

Fig. 8. EMG Sensor

These electrodes give these extracted myo-signals from targeted muscle to EMG sensor via three lead sensors cable. EMG muscle sensor has the ability to measure, filter, and rectify the muscle activity of the muscle. The size of the sensor model was 27mm × 27mm. This sensor model requires 18 V therefore two 9 V batteries are connected in series. Furthermore, the record muscle activities were sent to Arduino uno for further classifications. The schematic of EMG sensor is shown below in Fig. 9.

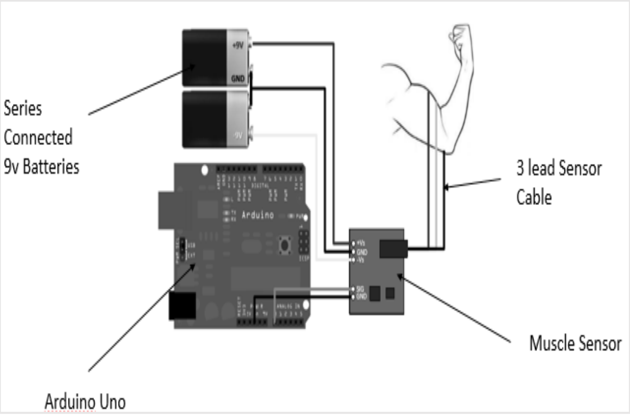

Fig. 9. Experimental Setup Of EMG Sensor

3.4 Data Collection

Total of Ten subjects voluntarily participated in this experimental study. All the subjects were healthy and having ages between 21 to 32 years. Among these ten subjects, seven were right-handed whereas the remaining were left-handed. Each of participant was informed about both the developed HMIs of FSR and EMG and they willingly agreed upon performing experiments. The experiment was duly approved by ethical committee at PIPOS, Pakistan and inform consent was signed prior to participating in the study. The subjects were trained on both the HMIs and data were collected. Data were collected for two Degree of Freedoms (DoFs). As the available active trans-radial prosthesis have two DoFs, one DoF in opening/closing of three fingers simultaneously and other DoF was for wrist rotation. For opening/closing of hand fingers, standard pulse is required to operate whereas for second DoF extended pulse from forearm muscle is required. This extended pulse must be larger than the standard pulse. FSR bracelet and EMG electrodes were mounted on the targeted muscle of participants. Participants were given the option to take a rest or break whenever they want. All the participants were seated on the chair such that to make them comfortable. Minimum of 30 minutes break were given between data collection from both the HMIs. Ten trials were performed by each participant on each of the developed HMIs. After recording the data, root mean square error (RMSE) were calculated for trials taken by each participant on each of the HMI. The effect of sweat and hair on myo-signals acquired from both HMIs were also observed.

4. Results and Discussion

4.1 Stability Over Time

Stability over time is an important parameter in evaluation of any HMI for prosthetic devices. This parameter was evaluated on both the developed HMIs on different types of forearm gestures and orientations. Four forearm orientation/gesture were selected such as relaxed hand, forearm at normal orientation (palmar side towards face), forearm at 90 degree to the normal orientation and forearm at 180 degree. These are selected such that to evaluate and compare the impact of forearm positions/orientations on the myoelectric signal at both developed HMIs. These four gestures/orientations on both of DoFs are depicted in below Fig. No.10 and 11 For rest position, both myosignals were stable. However, FMG signal was more stable as compare to sEMG signal. There were some little substantial changes in the EMG signal. Both DoFs on normal orientation on FMG HMI were more stable than sEMG. FMG exhibit quite smooth and noise free signals on both DoFs. At 90- and 180-degree orientation, sEMG experiences disrupts as the forearm muscle positions changes and EMG being a very sensitive can detect a very little muscular fatigue which in case of prosthesis-based HMI detect as noise/undesired signal. Whereas the developed FMG on the other hand eliminates those minor muscles movements or fatigues and detect on desired signals.

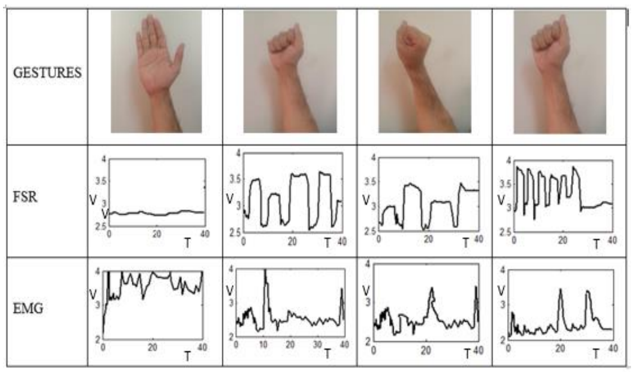

Fig. 10. First Degree Of Freedom

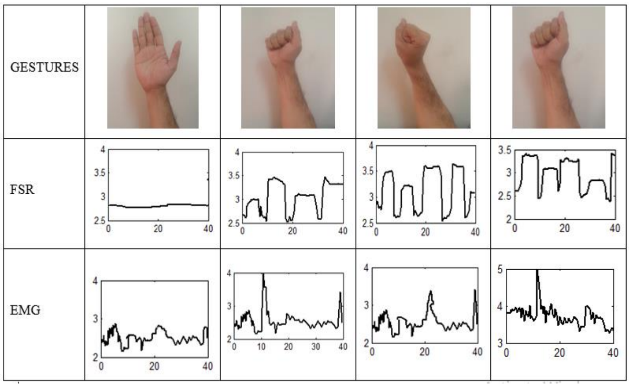

Fig. 11. Second Degree Of Freedom

4.2 Prediction Accuracy

Fig. No 12 and 13 shows prediction accuracy obtained by subjects on repetitions of both degree of freedoms. The nRMSE values in FMG based HMI for both DoFs were more uniform as compared to sEMG based HMI. The nRMSE for first DoF in FMG was in range of 0.17±0.01 to 0.20±0.03 whereas for sEMG this range were 0.19±0.021 to 0.34±0.03. For second degree of freedom, ranges of nRMSE for FMG and sEMG were 0.19±0.02 to 0.23±0.04 and 0.23±0.03 to 0.52±0.04, respectively. The results indicated that there is an abrupt increase in the prediction sEMG for second degree of freedom. This is due to the extended pulse in second DoF and sEMG being sensitive device effect the accuracy of the trials.

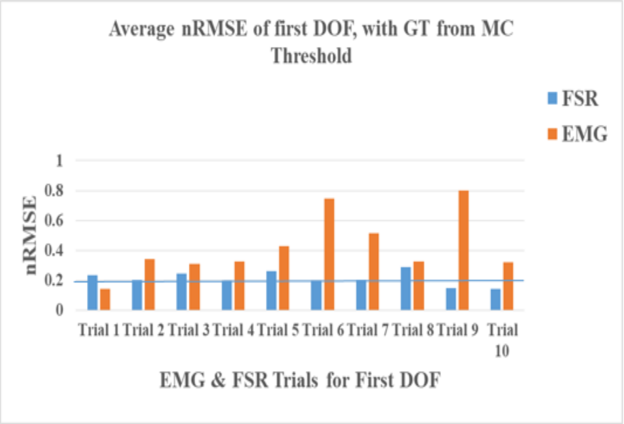

Fig. 12. First Degree Of Freedom (DOF) Normal Root Mean Square Error (Nrmse) Diagram

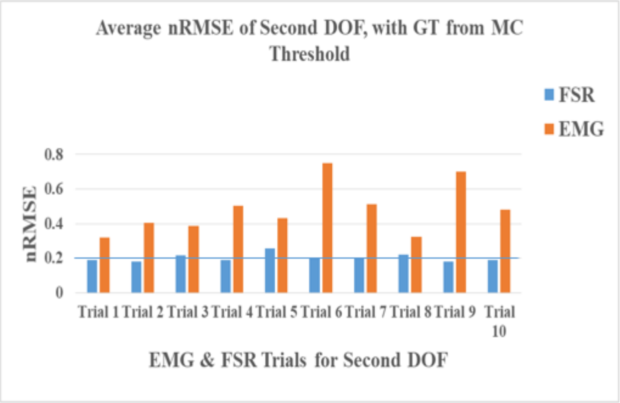

Fig. 13. Second Degree Of Freedom Normal Root Mean Square Error Diagram

4.3 Effect Of Heat And Sweat

Hair and sweat conditions were also tested such that to evaluate the its effect on developed FMG HMI and also validate the limitation of sEMG based HMIs. Fig. No.14 to 17 shows the effect of hair and sweat on both of HMIs. It was observed that the FMG signals was not affected by hair and/or sweat. As the FMG used FSR sensors and they are enclosed in casing and are not directly in contact with the subject's skin. Therefore, they only detect and measured only the intended stimulus of the forearm muscles. On the other hand, sEMG exhibit noises due to hair and sweat and therefore they cannot be recommended for long term use. This is because of the limitations of sEMG sensors themselves as they are affected by these conditions and add noises to their signals.

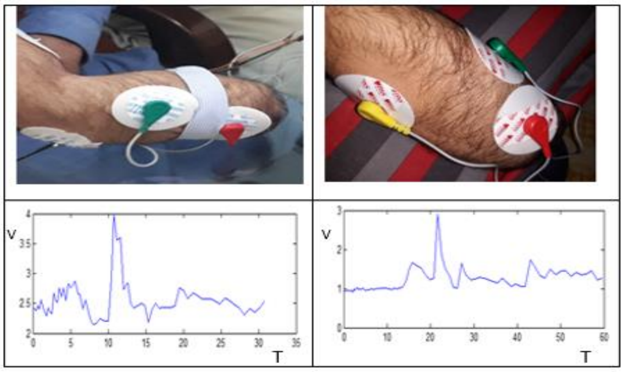

Fig. 14. EMG Without Hair And With Hair

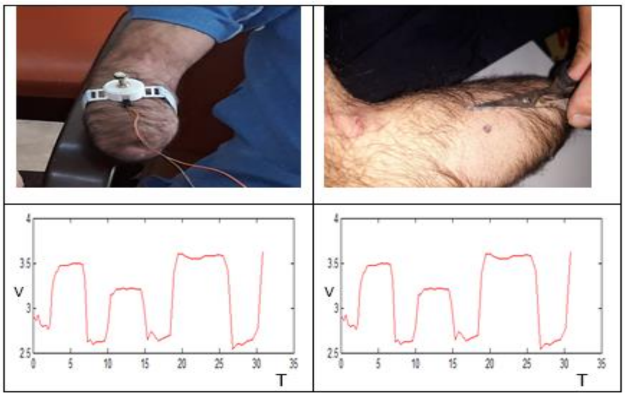

Fig. 15. Hairy and Hairless FSR

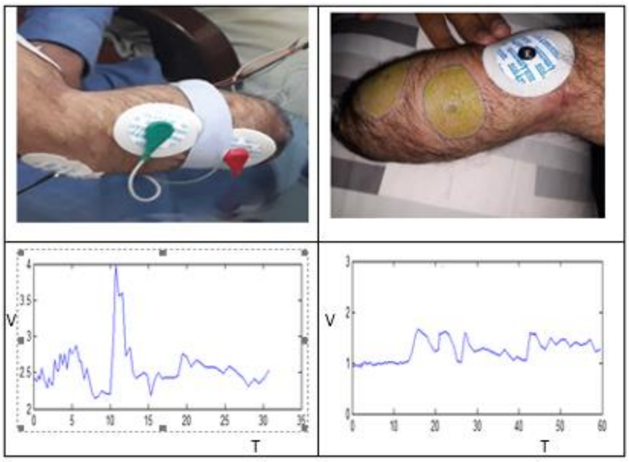

Fig. 16. EMG With And Without Sweat

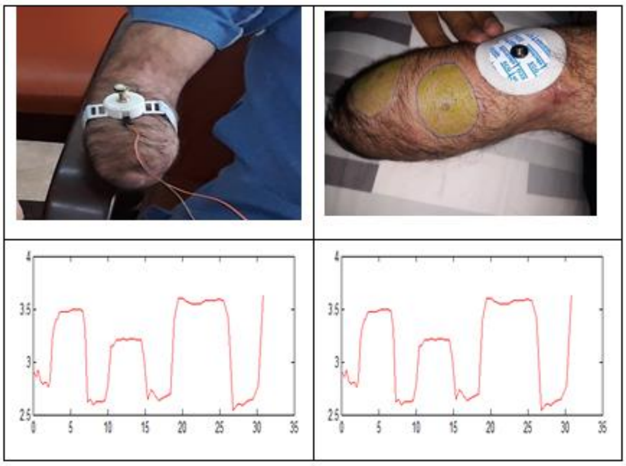

Fig. 17. FSR With And Without Sweat

4.4 Wearability And Cost

Wearability of sEMG and newly developed FMG HMIs were asked from all the subjects. The outcomes of their feedback concluded that eight out of ten subjects find no such difference in wearability of FMG and sEMG sensors. However, two subjects (subject # 7 and 9) found it more comfortable wearing sEMG electrodes than FSR casing. Assessment of wearability was also checked by asking subjects to mount both HMIs on their forearm and acquire myo-signals from the targeted muscle. It was observed that seven out of ten subjects were mounted sEMG electrodes on the wrong position/orientation and because of which it affects their acquired myo-signals. However, all the FMG signals were acquired correctly and they didn’t find it difficult to mount this newly developed HMI. It was observed that sEMG based HMI requires extensive training or professional practitioners for their mounting and adjustments.

The inexpensive EMG electrodes used in the study cost between 150 to 300 Pakistani Rupees (1 US Dollars) each, although it should be emphasised that when removed from the forearm, these electrodes lose their sensitivity and are unable to produce the same results. As compared to EMG based HMI, the FMG cost was 800 per HMI (4.5USD) approx. (including FSR and casing fabrication and material cost). But this FMG HMI could be used for a longer time as FSR sensor are not in contact and according to FSR 408 datasheet they can be robust for more than 10 milling trials and even capable of taking 1 kg of continues drift for more than 35 days.

5. Conclusion And Future Recommendations

A new 3D printed FMG based HMI using an FSR sensor was developed and compared with the most commonly used sEMG base HMI. It was concluded that the FMG based HMI were more stable and more effective than EMG based HMI. nRMSE for FMG based HMI were in range of 0.17±0.01 to 0.23±0.04 whereas for EMG, it was in range of 0.19±0.021 to 0.52±0.04. FMG signals were not affected from hair and sweat. Furthermore, total cost on developing the FMG HMI was 4.5 USD approximately.

Future work can be directed to develop more compact and Flexible FSR casing for FMG based HMIs. To assess the robustness of the classification of the FMG technology, a larger sample size should now be considered, with more differences in limb length and anatomical structure. In addition, systems that incorporate FSR sensors in sockets connected to end prosthetic devices should be used to create more realistic conditions for the end user. This must be done to assess the impact of the dynamic mechanical environment on the socket, change the volume characteristics in the residue and assess the impact of weight on the comfort and function of the prosthesis.

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