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Processing and interpretation of surface electromyogram signal to design prosthetic device

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SUMMARY
The study of arm muscles for independent operations leading to prosthetic design was carried out. Feature extraction was done on the recorded signal for investigating the voluntary muscular contraction relationship for different arm motions and then repeated factorial analysis of variance (ANOVA) technique was implemented to analyze effectiveness of signal. The electronic design consisted of analog and digital signal processing and controlling circuit and mechanical assembly consisted of wrist, palm and the fingers to grip the object in addition to a screw arrangement connected to a low power DC motor and gear assembly to open or close the hand. The wrist is mechanically rotated to orient the hand in a direction suitable to pick up/hold the object. The entire set up is placed in a casing which provides a cosmetic appeal to the artificial hand and the connected arm. The design criteria include electronic control, reliability, light weight, variable grip force with ease of attachment for simple operations like opening, grasping and lifting objects of different weight with grip force slightly more than enough just like that of a natural hand.

KEYWORDS: Signal processing; Biomechanics; Microcontroller; Electromyogram; Variable grip force.

1. Introduction

In order to utilize surface electromyogram (SEMG) as input to control assistive devices or prosthesis, the essential step is the processing of the signal to extract features from it, and classify the signal for different types of desired motions.[1] Interpretation of SEMG signals using advanced techniques is a very important requirement in biomedical engineering. Recent advances in technologies of signal processing and mathematical models have made it possible to achieve this objective[2] and have encouraged human computer interactions[3–13] for developing myoelectric signal based prosthetic devices.

Many industrial workers lose their arm due to freak accidents while carrying out different type of machining tasks in the factory. Similarly, many military personnel have to undergo arm amputation during the war. Their lost arm is to be replaced by an artificial arm in order to rehabilitate them. These patients want devices which are as near-natural as possible, both functionally and cosmetically. This necessitates development of an arm quite similar to normal human arm.

This arm is to be excited by the muscle signal available at the residual stump of the patient. The muscle signal, called electromyogram (EMG) signal appears due to the electric currents generated in the muscle during its contraction and relaxation and can be picked up non-invasively[14] from the surface of skin. We collected the SEMG signal by placing electrodes over the muscle in question and processed it in order to extract information both in time and frequency domains. The generated control signals were then used for driving the motor used for opening and closing of the hand. The main objective of this work was to design a prosthetic device similar in size to the natural hand with controlled movements to fulfill normal grip requirement.

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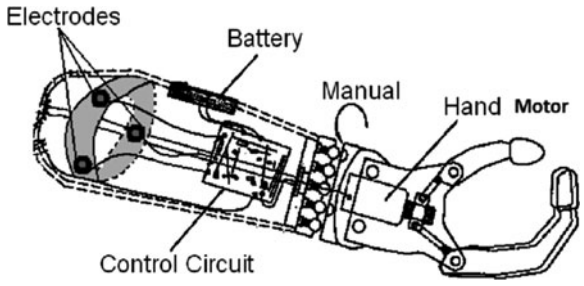


Fig. 1. The three electrodes arranged along the radial span of stump.

2. SEMG Signal Acquisition

For proper signal acquisition, electrode placement on the arm is very important. Since SEMG signal is generated by human muscle whenever it is activated, the frequency and amplitude of the signal changes based on the muscle's location within the body and the stress it undergoes. Quality signal acquisition requires accurate identification of the muscle. After thorough study and experimentation, flexor (A) and extensor (B) muscles of the residual limb were identified from which appreciable signal was obtained during voluntary contraction. Three gold plated surface electrodes were mounted above these muscles – one as reference, another as active and the third as ground electrode. The signal is random, very small in amplitude and mixed with noise of different frequencies.

Measured SEMG potentials range between 0 to 10 μ V depending on the muscle under observation. It contains frequency components in range of 2 to 10 kHz with maximum signal power between 20 and 300 Hz for surface, and needs 1000 samples/s or more sampling rate.[15,16] Aligning the electrodes along the muscle length close to each other results in an increase of higher frequency contents. Electrode impedance should be as low as possible but not more than 2 kΩ. The difference signal between reference and active electrode was processed to reduce noise in the system.[17,18]

For better contact between electrode and muscle, a jelly type conducting solution was used. Experiments were made to optimally place these electrodes and to identify the proper point of axial spread of muscle where the amplitude of signal was maximum. The electrode assembly cannot be placed axially along the muscles of the arm because the stump length available from such patients is generally not enough. The placement of this assembly in the transverse direction led to the difficulty that the surface of arm was not uniform throughout the radial span of the stump; it was rather curved. Also at the time of relaxation and contraction of the muscle, this curvature varies and the electrodes could not be fixed properly to pick the signal from a particular point.

During experiments with this assembly, it was noted that if electrodes are placed very close to each other, active and reference electrodes pick up almost the same signal from the same muscle. For this reason, to get substantial signal, we placed the electrodes as far as possible from each other in the transverse direction (Fig. 1).

3. Methodology

Ten amputee male volunteers, age 22–40 year's, weight 55–90 kg's, height 160 to 180 cm having active residual stump participated as subject in this reported work. Their written consent was sought prior to conducting the experiment. The SEMG signals were recorded from their residual muscles simultaneously. The very first stage in processing part is preamplifier stage. A differential amplifier has been used as a preamplifier, which amplified the signal by a gain of 5 with CMRR greater than 90 db. The SEMG signal was again amplified by a non-inverting amplifier in second stage with a gain of 1000. The purpose of the non-inverting amplifier was to provide fine tuning of the gain needed. In order to extract spectral components that contain frequency-based information, electrode's placement as far as possible from each other in transverse direction is necessary. The inter-electrode distance was kept as 1 cm. The sampling frequency used for the acquisition was 1000 Hz.

3.1. Activities performed

Subjects were seated on a chair with their head in front position. Dual channel experimental acquisition set up was used. Each subject was asked to perform four independent movements for different

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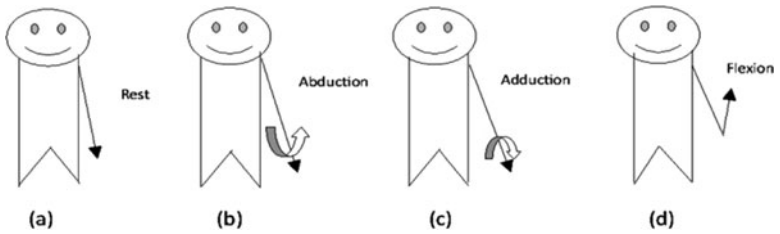


Fig. 2. Different arm movements.

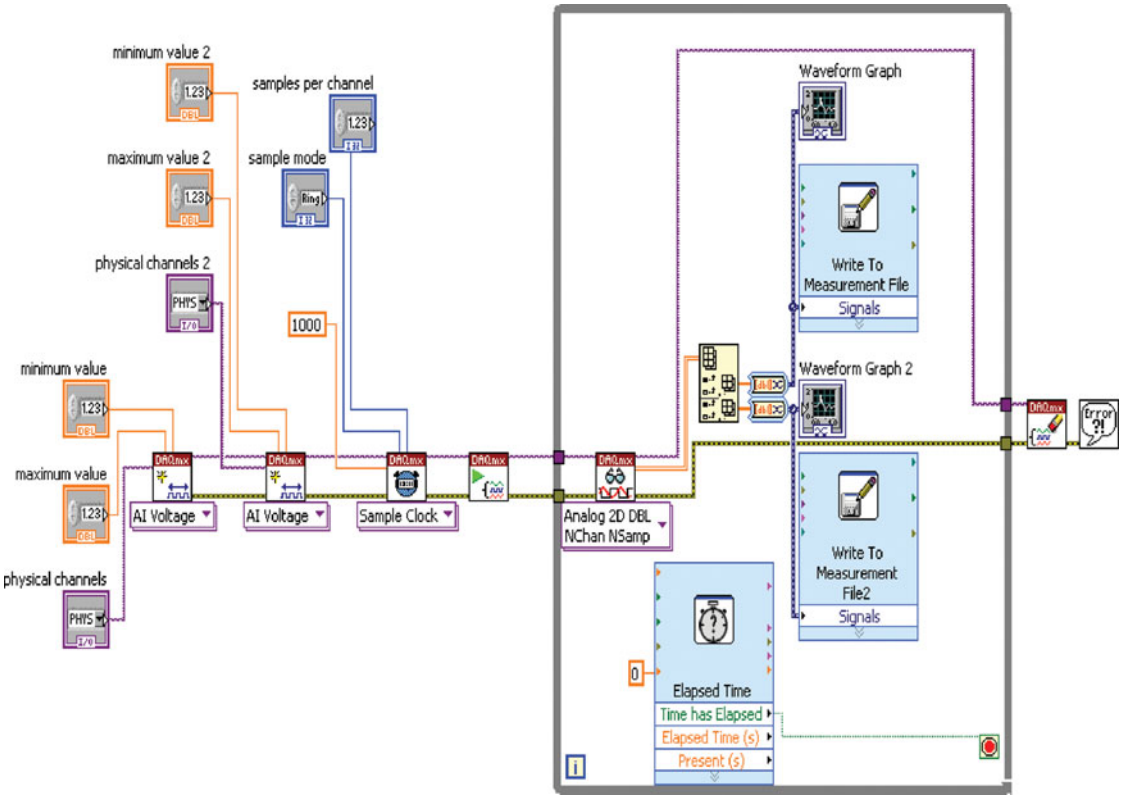


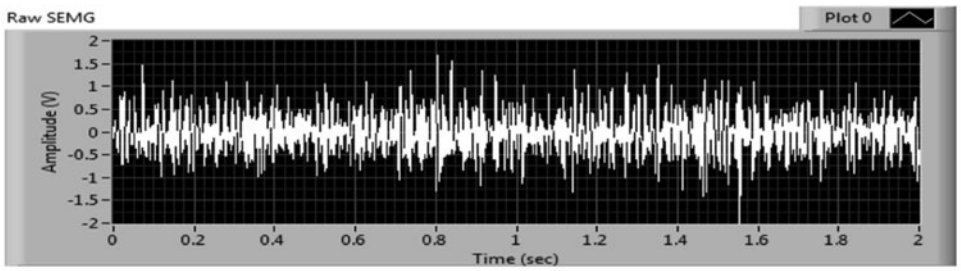
Fig. 3. Dual-channel Labview soft scope-based simulated code for signal acquisition.

muscles activation with maximum epoch time of 3 s for each movement, respectively, shown in Fig. 2.

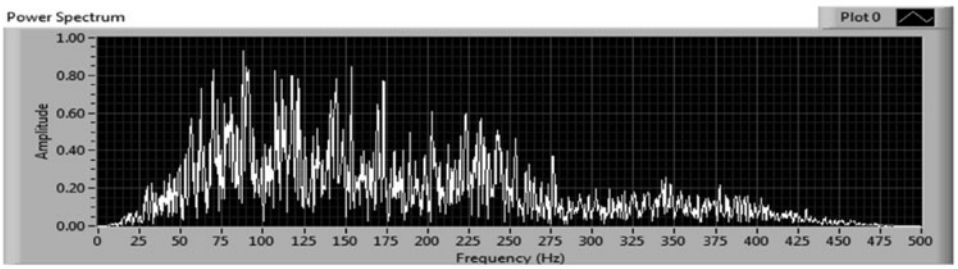
- Activity P1- arm was in rest with downward position parallel to body. This position is called arm extension.
- Activity P2- arm was moved voluntary from rest position (0°) to maximum position (90°) giving abduction direction.
- Activity P3- arm was rotated in adduction direction i.e. from rest position (0°) to maximum muscular contraction position (90°).
- Activity P4- arm was moved upside. This position is called flexion.

The recorded SEMG signals were processed and analyzed using Labview soft scope. Simulated code for acquiring the data is depicted in Fig. 3. The raw signal and its power spectrum taken from residual muscle for maximum dominating voluntary contraction are as shown in Fig. 4. The recorded SEMG signals were passed through band pass filter with cut off frequencies 10 and 500 Hz. Features were extracted from the recorded signal for its proper interpretation. Digitalized computerized data was analyzed using ANOVA technique. The data was first arranged into four independent groups, and then F ratio calculation was done for two different estimates i.e. variance of data between the group sum of square between (SSB) and variance within the group sum of square within (SSW). The

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(a)



(b)

Fig. 4. (a) Raw signal (b) power spectrum of recorded surface electromyogram signal.

last result of F ratio computed from the processed and analyzed data stored in workspace indicated that population means were not all equal.

3.2. Signal processing for controlled design of prosthetic device

For developing the artificial hand, EMG signal is analyzed in the frequency domain using Fast Fourier Transform (FFT) so that different discrete frequency components could become known. This FFT consists of components of both signal and noise. To distinguish the signal from noise, we identified those frequency components which responded quickly and significantly due to contraction and relaxation of muscles. Experimentally, it was seen that the frequency components of SEMG signal varying due to contraction and relaxation of arm muscles in the process of opening and closing of hand fell in the range of below 40 Hz.

To get these frequency components, a low pass filter with a cut off frequency of 40 Hz was used followed by an AC coupled high gain amplifier to improve the signal quality and to block drift and DC part of the signal. Power frequency noise of 50 Hz was minimized by Twin-T-Notch Filter. To derive a DC voltage proportional to amplitude of the signal, an RMS to DC converter was used whose output is low in relaxed state and high during the contraction stage. As the strength of the SEMG signal varies from person to person, a variable gain DC amplifier was used in order to adjust the level of the signal. The signal is then digitized and fed to microcontroller to generate signals for the motor driver and control unit.

3.3. Motor driving and control

This unit consists of an 8-bit microcontroller 89C2051, D-type flip-flops, relays and limit switches. Two micro switches fitted in the hand indicate the extreme positions of the hand. L_{OPEN} is the switch used as open limit switch, whose value is high by default and low when maximum opening limit is reached. L_{CLOSE} is the switch used as close limit switch, whose value is high by default and low when maximum closing limit is reached.

The microcontroller processes the digital signal obtained from the muscle and controls a pair of flip flops accordingly. These flip-flops operate the relays to drive the motor to open or close the hand. The motor set up has a single lead screw arrangement which is connected to the artificial fingers of

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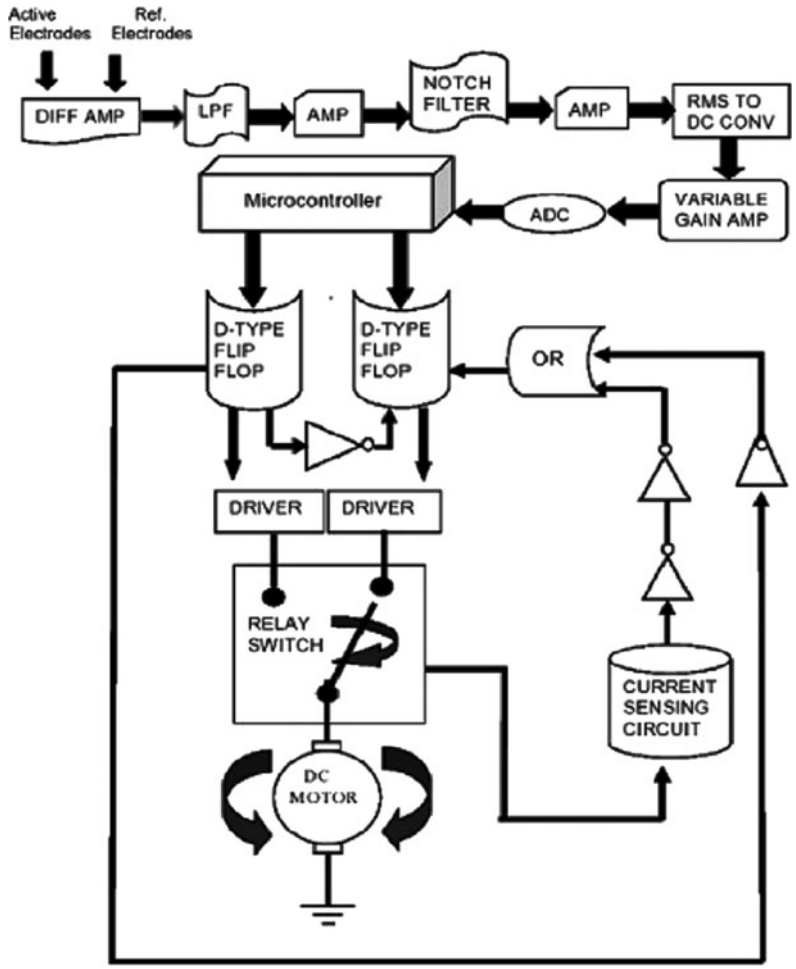


Fig. 5. Block diagram of the designed myoelectric arm.

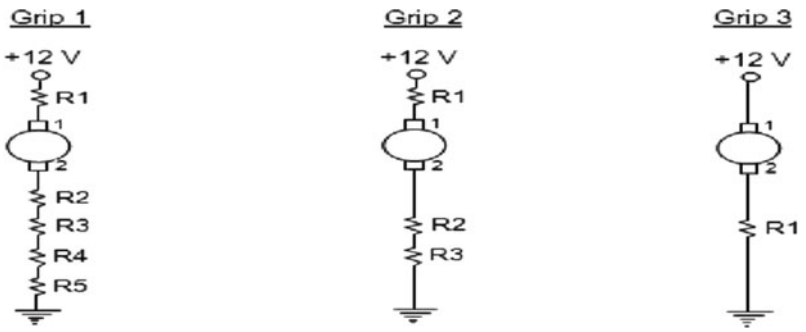


Fig. 6. Logic for implementing variable Gripping.

the hand. A feedback circuit is provided which cuts off the supply of the motor when an object is gripped by the hand. The block diagram for the myoelectric arm is as shown in Fig. 5.

To implement the variable gripping force, a relay switching system was designed[19] which consisted of relays meant for closing and opening the hand to switch different values of resistances in series with motor armature (Fig. 6). Two relays are used for opening and closing limit switches and another two relays are used for implementation of grip control logic function. This function depends on the activation of particular relay switching at different time instants, according to the instructions received from microcontroller. The logic is set for three different levels of forces. Grip 1 is the lowest level logic, Grip 2 is for medium level logic and Grip 3 is for high level logic. Based on the SEMG

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Table I. Signal features (averaged) on residual muscle (A) for different motions.

Motions	Surface electromyogram signal quality	Root mean square	Standard deviation
Extension (P1)	Low	0.13	0.084
Abduction (P2)	Medium	0.166	0.113
Adduction (P3)	Moderate	0.138	0.089
Flexion (P4)	High	0.556	0.443

Table II. Signal features (averaged) on residual muscle (B) for different motions.

Motions	Surface electromyogram signal quality	Root mean square	Standard deviation
Extension (P1)	Low	0.14	0.088
Abduction (P2)	Medium	0.226	0.192
Adduction (P3)	High	0.402	0.278
Flexion (P4)	Moderate	0.206	0.142

Table III. Repeated factorial analysis of variance result on residual (A) muscle.

Source of variation	Sum of squares	Degree of freedom	Mean square	Fisher ratio	Significance (p value)	Critical value (fc)
Sum of square between group	0.638	3	0.212	5.22	0.0001	3.23
Sum of square within/group	0.096	16				
Total sum of square	0.734	19				

Table IV. Repeated factorial analysis result on residual (B) muscle.

Source of variation	Sum of squares	Degree of freedom	Mean square	Fisher ratio	Significance (p value)	Critical value (fc)
Sum of square between group	0.186	3	0.062	5.22	0.0001	3.23
Sum of square within/group	0.190	16	0.011			
Total sum of square	0.377	19				

signal exerted by the user, different resistances are selected by a relay matrix which varies the current through the motor, thus, varying the grip force.

4. Results

As we want to investigate the behavior of muscle fiber during voluntary contractions, the estimation of variation in the amplitude of surface electromyogram signal needs to be calculated and quantified. Evaluation of signal in terms of root mean square value and standard deviation for identifying prominent locations on residual muscles (A & B) corresponding to independent arm movements was investigated. The values of these parameters are shown in Tables I and II after averaging over the number of volunteers.

As the electrical activity of muscles being measured by SEMG exhibits non-linearity, it was thought that the statistical theory may be a better approach than traditional linear methods in characterizing the intrinsic nature of signal. This type of characterization can contribute to the understanding of the signal dynamics and underlying muscles processes. Therefore, statistical techniques were implemented for the interpretation of arm operations in order to identify the best SEMG signal amplitude for different motions with different muscle positions. In order to compare the means of the four independent variable groups (G1–G4) and to decide about the effectiveness of the SEMG signal for different motions, a one way repeated ANOVA was carried out. The result associated with ANOVA with four different groups of arm motions is shown in Tables III and IV.

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The experimental recorded data was extensively divided into four broad groups with respect to motion of arm (extension; abduction; adduction and flexion, respectively). One way repeated factorial ANOVA was performed for all four ranges in the summary tables, p value stands for probability or level of significance (rejection of the null hypothesis when $p < 0.05$); fc is critical f value (rejection of null hypothesis when test statistic < critical value, i.e., F < fc). Here, in these cases the p value is <0.05, and F > fc, so the hypothesis that no difference exists in the percentage of event detection due to different arm motions can be rejected. Since the p value is <0.05; so, the null hypothesis is rejected, meaning that their interaction have significant factor contributing to the response "arm motion event detection."

The basic procedure is to derive two different estimates of variance from data and then calculate a statistic from the ratio of these two estimates. One of these estimates, SSB is a measure of the effect of the independent variable combined with error variance. The other estimate, SSW is of error variance by itself. The f-ratio is the ratio of between- groups variance to that within groups. A significant[20] F-ratio indicates that the population means are probably not all equal. The F-ratio is the statistic used to test the hypothesis that the means are significantly different from one another. Since F is ratio of SSB to the SSW (SSB/SSW), so a large value of F indicates relatively more difference between groups than within groups. Next V^2 (which gives the percent variance due to variations between group variations) can be calculated as $V^2 = \text{SSB/SST}$.

There is a significant difference in amplitude gain across different motions; for example, value of $F(3, 16) = 35.11$, $p < 0.05$ for one muscle while it is 5.223 for another one. From both Tables, since F ratio is greater than critical value (fc), means are significantly different and it is concluded that there is significant difference between the groups (SSB) than within groups (SSW). So the null hypotheses of equal means are rejected and finally, it is concluded that the test statistic is significant at this level. Thus one way repeated factorial ANOVA found statistical differences between electrode positions ($p < 0.05$), surface electrode conditions, and the interaction between all groups.

The result of extracted features shown in Tables I and II and ANOVA depicted in Tables III and IV, helps in understanding the operations which were observed to be easy to be realized by the developed prosthetic device. Finally the fabrication and testing of the designed arm was carried out in the laboratory. Experimentally, the frequency components up to 40 Hz were found to undergo change due to muscle action. The signal was, therefore, low-pass filtered up to 40 Hz and amplified to increase the sensitivity. The amplitude of amplified EMG signal was found as 0.4–0.8 volts in the relaxed state and 2.3–4.0 volts during contraction in different subjects. To offset the variability of signal, we designed a variable gain amplifier which may be set to give less than 1 volt signal in relaxed state and more than 2.5 volt during contraction. The threshold between opening and closing of hand was then set to 2 volts. The motor current during normal closing of hand was recorded as 67 mA which rises to more than 500 mA when an object is gripped. A threshold of 400 mA was set to cut-off the motor supply. The Flow chart showing working of prosthetic device is presented as below in Fig. 7.

5. Discussion and Conclusion

The relevant aspects covered under the development of arm constitutes two stage – first stage, the signal conditioning with controlling and second stage, its mechanical assembly. Electronic design consisted of analog and digital signal processing and controlling circuit. The EMG signal from the stump of the subject was picked up through surface electrodes, amplified and artifacts were removed in a controlled manner so that minimum signal loss occurs due to processing. Further before evaluating and interpreting SEMG signal, the FFT was analyzed, as it provides information about the frequency contents in the signal.

Then signal interpretation utilizing computing techniques was applied to compare variation among data and the results showed significant variation among data for stated groups. The statistical analysis was considered, using sum of squares of deviations of data points from their sample means in analyzing the different arm movements based on SEMG signal. Finally the mechanical assembly consisted of wrist, palm and the fingers to grip the object in addition to a screw arrangement connected to a low power DC motor and gear assembly to open or close the hand. The wrist is mechanically rotated to orient the hand in a direction suitable to pick up the object. The entire set up is placed in a casing which provides a cosmetic appeal to the artificial hand and the connected arm.

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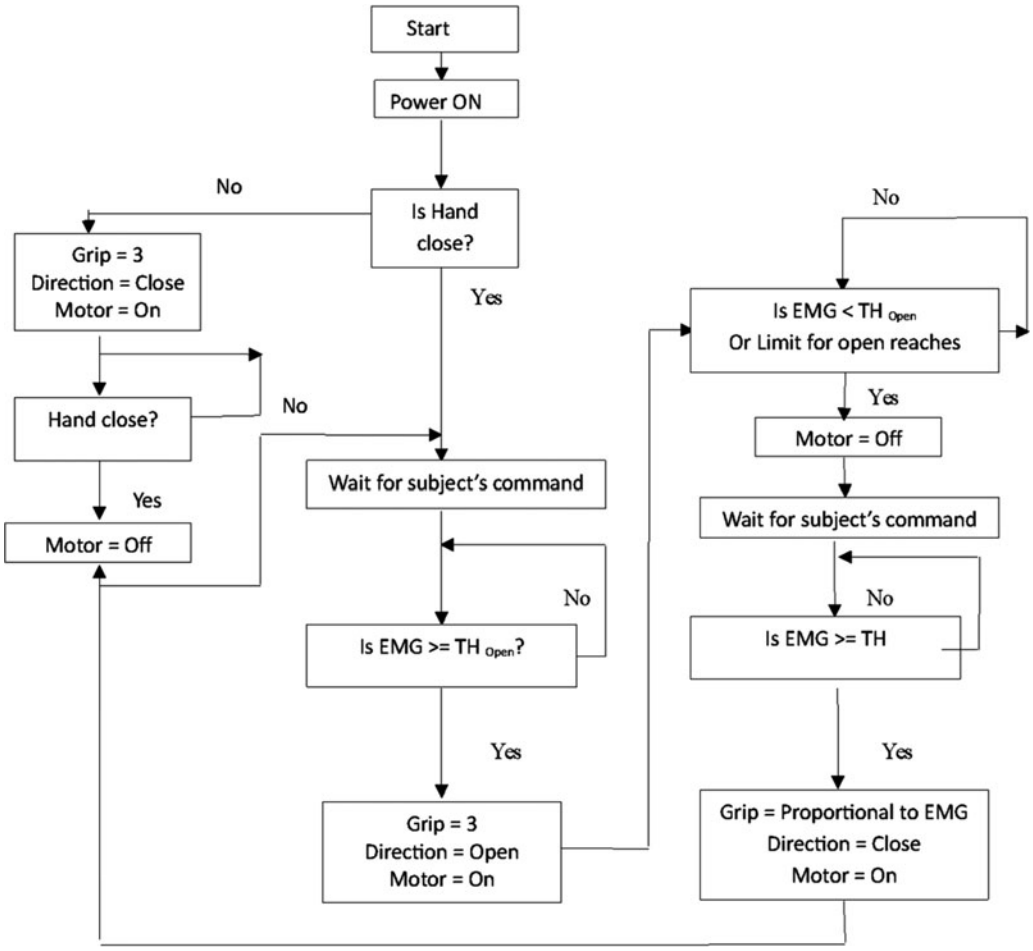


Fig. 7. Flow chart for the complete operation of myoelectric arm.

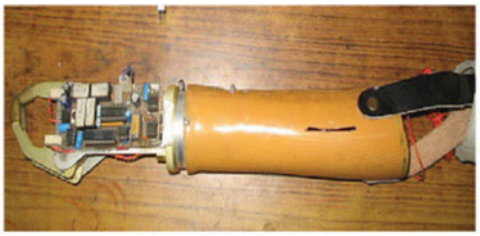


Fig. 8. Surface electromyogram-based designed prosthetic device.

Further for acquiring SEMG signal from subjects, active electrodes were used as these electrodes do not need jelly while making and maintain suitable contact with skin and, therefore, result in good SEMG collection. The SEMG signal based fabricated arm (Fig. 8) with three different grip force patterns on subjects was tested successfully. The subjects were quite comfortable in opening and closing of hand according to the muscle activity and, could hold the object and place it at different place with ease. Even it had the capability to reverse its motion from the ongoing direction as the natural hand does. Implementation of this type of system gives the prosthetic user capability to perform different tasks with maximum efficiency in daily living. A load of up to 1.5 kg can be lifted by the developed device. Performance of whole system can be improved if low torque motor is replaced by high torque, higher efficiency motor so in future heavy objects may be manipulated.

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