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The comparison and processing of Electromyography (EMG) signals under different actions

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Abstract. The experiment first investigates the working principle and the applications of Electromyography (EMG). Then, the effect of electrode location and electrode size on the EMG signal is explored by the raw data and theory. The reasons for choosing generic surface Ag/AgCl adhesive electrodes are also described. After obtaining the raw EMG signals, suitable data processing methods, such as Root Mean Square (RMS) and digital filtering are applied to generate signals that can drive the motor of a prosthetic arm. The results obtained by the two methods are also compared, where RMS can provide larger peak and mean values, and the digital filtering method can minimise the phase shift. Finally, the limitations of the EMG for prostheses are also analysed by three aspects: different flexion forces, individual finger motion and different reference locations.

Keywords: Electromyography (EMG), Root Mean Square (RMS), digital filtering.

1. Introduction

When the muscles are activated, the action current will be generated and flow through the medium of tissues. Meanwhile, the gradients of the voltage will be produced and recorded as the myoelectric signals [1]. The technique of Electromyography (EMG) will study muscle function by recording, analysing and developing these myelectric signals [2]. Neurological EMG analyzes the artificial muscle response due to external electrical stimulation in static conditions. But Kinesiological EMG focus on the voluntary neuromuscular activation of muscles in functional movements [3]. In this section, the working principles and the applications of electromyography will be presented.

1.1. Motor Unit (MU)

The smallest functional unit to control muscular contraction is called Motor Unit (MU), which is combined as an α-motoneuron in the spinal cord and the innervated muscle fibres [3]. The α-motoneuron is the final aggregation point of all descending and reflex inputs. The discharge pattern of the motor unit depends on different net membrane induced currents. Research [4] shows that the number of MUs per muscle is about 100 for hand muscles and 1000 or more for limb muscles. Additionally, different MUs in different muscles show different force generating capacities [3].

1.2. Action Potential

The process of the excitability of muscles can be explained by the semi-permeable membrane model. Usually, the ion pump will remain the resting potential at the membrane by controlling ionic difference. When the α-motor cell is activated, the motor nerve will conduct and the transmitter substances will be released at the motor endplates [3]. Briefly, the diffusion characteristics will be changed and Na+ ions will flow in, which leads to membrane depolarization. After that, the potential will be restored by ion-pump exchange, which is called repolarization [3]. After the activation, the action potential quickly changes from -80mV to +30mV during the depolarization process. Then, the potential will return to -80mV after the repolarization and after-hyperpolarization process. The EMG signal depends on the action potential changes from the depolarization and repolarization process as mentioned above. After the excitation, the depolarized membrane zone will travel along the muscle fibre and pass through two electrodes.

1.3. Electrical model and raw EMG signal

The cycle of depolarization and repolarization will generate a depolarization wave along the surface of the muscle fibre [3]. Therefore, EMG measures the signals from bipolar electrodes using a differential amplifier. For example, research [5] illustrated this process in single muscle fibre between two electrodes, which is shown in Figure 1: The depolarization wave starts from T1 and travels along two electrodes. The potential generally increases and becomes highest at T2. If the distance between the electrodes is equal to the diploe arrives, the potential difference will pass through the zero line and become the highest at T4, which is the shortest distance to electrode 2 [3]. The motor unit consists of many muscle fibres and electrodes will measure all the fibres within the motor unit. The summation of action potential of motor units is called motor unit action potential (MUAP). The superposed signal will be seen as the bipolar signal with the symmetric distribution of positive and negative amplitudes. The unfiltered and unprocessed signal measuring superposed motor unit action potentials is called theraw EMG signal [3]. The baseline can be seen when muscles are relaxed. The quality of the baseline depends on the EMG amplifier, environment noise and detection conditions, which is an important indicator of each measurement. Generally, the frequency of the raw sENG is in the range of 6 to 500Hz [3].

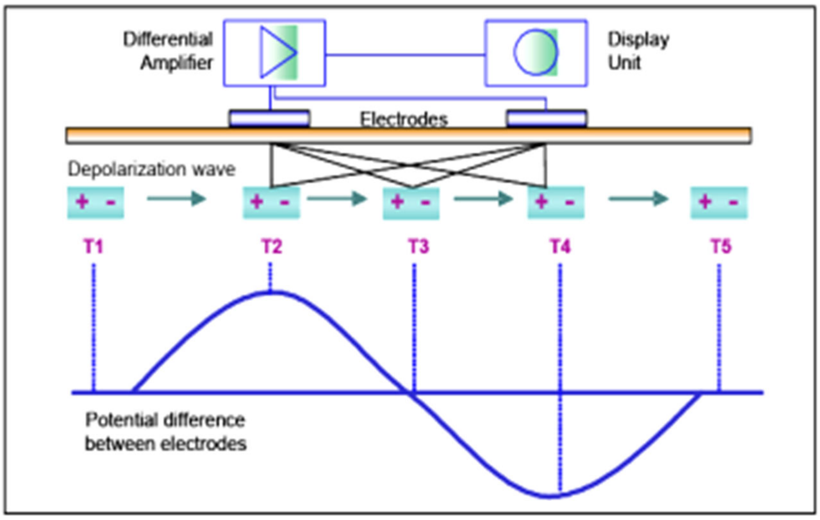


Figure 1. The model of depolarization wave on the membranes [5]

1.4. Key applications

Based on the continuous research on the EMG technique, it has been widely applied in various fields so far [3]:

1) Medical area

EMG plays an important role in orthopaedics by assessing the function and activities of muscles, which helps orthopaedic surgeons check the activities of muscles. In the surgical area. EMG can provide immediate feedback on the nerve and muscle function and assist in the preservation of critical neural structures. Additionally, EMG can diagnose nervous disorders and inform tailored programs for gait and posture.

2) Rehabilitation

After accidents, EMG can monitor the recovery of muscles and provide rehabilitation strate- gies. In active training therapy, EMG offers real-time feedback on muscle engagement and performance, facilitating personalized training programs for enhanced effectiveness.

3) Ergonomics and sport science

EMG technology aids in the design of ergonomic workspaces and equipment to optimize efficiency and reduce the risk of musculoskeletal disorders. In the sports science, EMG can assess the patterns of muscle activation during athletic movements and help coaches design training programs to enhance performance and prevent injuries.

2. Materials and methods

Mikro Elektronika ECG 2 Click board with three generic Ag/AgCl electrodes and cables are used for raw data EMG signal collection. Among the three electrodes, one electrode is considered as the reference and two electrodes for measurement. The circuit board amplifies the electrical signals from the muscles, filters out the noise and converts the signals to digital signals. This data is then transferred to the mother development board via SPI. A Driven Right Leg (DRL) circuit is added to reduce Common-mode interference. For each experiment, 5000 sets of raw EMG signals are recorded in 10 seconds (Δ t: 2ms). The reference electrode is connected to the black connector, electrodes 1 and 2 are connected to red and white connectors. Firstly, electrodes 1 and 2 were parallel to the forearm axis and the reference electrode is on the back of the hand, which could be seen in the following Figure 2:

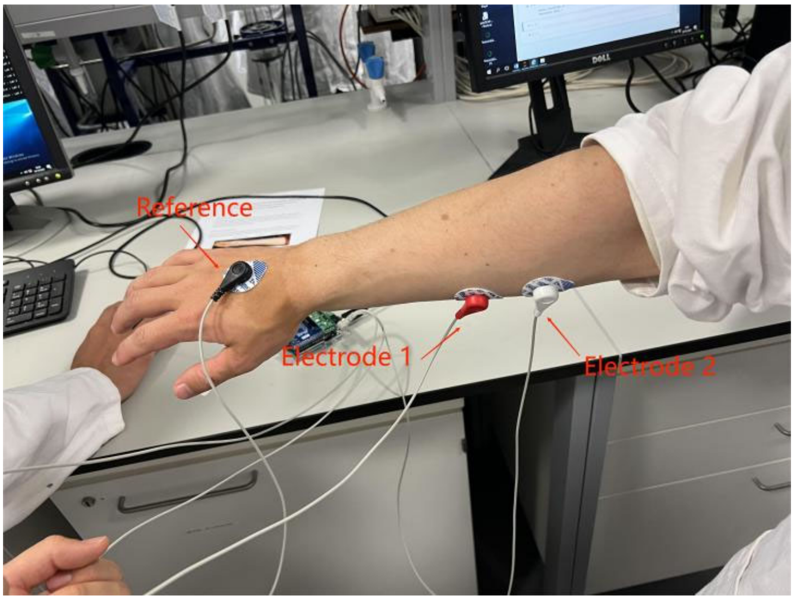


Figure 2. Two parallel electrodes with back-hand reference

For a more comprehensive comparison, the muscle activities under wrist flexion, extension and twisting were all conducted with different forces. Next, the experiments for electrodes 1 and 2 perpendicular to the forearm axis and covered by the papers were both conducted. Finally, the position of the reference electrode was changed to the ankle and head.

3. Results and discussions

3.1. Dependence of EMG recordings on experimental configuration

3.1.1. Effect of electrode location

Most EMG signals of limb and trunk muscles can be obtained by the surface electrodes [2]. The position of electrodes affects the measured EMG signal. In this experiment, the activities of brachioradialis, flexor carpum radialis and flexor carpum ulnaris mainly affect the raw EMG signal with surface electrodes according to their positions. Meanwhile, some small muscle activities also affect EMG signal recordings. The insertions and actions of each muscle are shown in the following Table 1 [6]:

Table 1. Insertions and actions of frontal forearm muscles

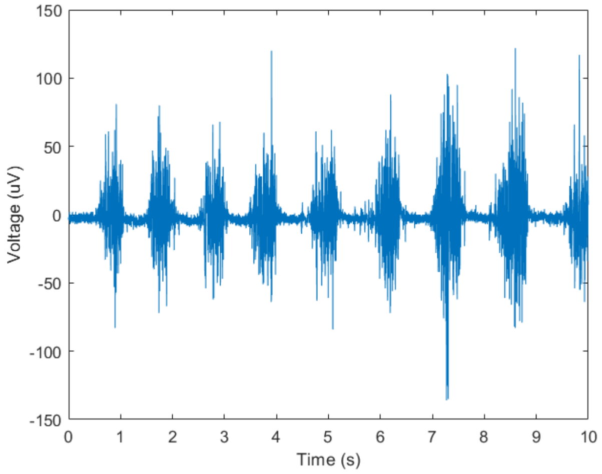
	Insertion	Action
Flexor carpi radialis	Bases of metacarpal bones 2-3	Wrist flexion, wrist abduction
Flexor carpi ulnaris	Pisiform bone, hamate bone Base of metacarpal bone 5	Wrist flexion, wrist adduction
Brachioradialis	Styloid process of radius	Forearm flexion when semi pronated

Flexor carpi radialis is located in the anterior forearm, which originates from the medial epicondyle of humerus through the common flexor tendon, and surrounding fascia. Because of the oblique flexor carpi radialis, it can pull the hand proximally and laterally. Therefore, wrist flexion and wrist abduction can be produced by the flexor carpi radialis.

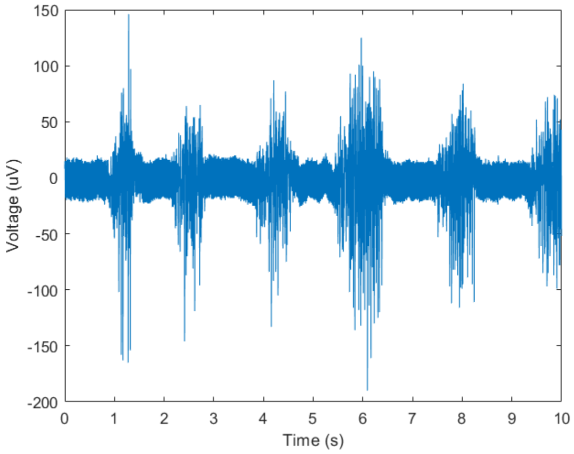
Flexor carpi ulnaris is also located in the anterior forearm. It originates from two heads, which are linked through tendinous arch. Flexor carpi ulnaris can control the hands sideways. Contracting together with flexor carpi radialis, the balanced flexion of hand can be produced without abduction.

Brachioradialis is located in the lateral part of the posterior forearm. The rather flexion of the forearm can be produced because of the fibre orientation, especially when the forearm is semi-pronated.

To evaluate the effect of the electrode locations, First, the experiments of wrist flexion with electrodes parallel and perpendicular to the forearm axis were conducted and the EMG signals are shown below Figure 3.



(a) Wrist flexion with electrodes parallel to the forearm axis



(b) Wrist flexion with electrodes perpendicular to the forearm axis

Figure 3. EMG signals of wrist flexion

The whole EMG signal is shifted 210uV to make the baseline back to the zero line. Therefore, the mean value of the raw EMG will be equal to zero. Additionally, the baseline with much noise can be seen when the electrodes are perpendicular to the forearm axis. This is because the flexion of the wrist relates to the flexor carpi radialis and flexor carpi ulnaris and they follow the direction of the forearm axis. The depolarization-repolarization cycles generate a depolarization wave, which travels along the muscle fibre. Therefore, the EMG signal can be collected accurately when the electrodes are parallel to the forearm. But the signals through the two electrodes are not the whole depolarization wave and with more noise when electrodes are perpendicular to the forearm. Although there are some bursts from Figure 3(b), they can not represent the main kinesiological active muscles, such as flexor carpi radialis and flexor carpi ulnaris. They are generated by some other small muscle groups which can be measured by the perpendicular electrodes. Additionally, more neighbouring muscles are involved and produce other EMG signals when the electrodes are perpendicular, which is called ”Physiological cross talk” . There are superposition spikes in these two conditions because two or more motor units are fired and the signal is superposed. However, the EMG signals of muscles in the right arm are measured and the effect of ECG artifacts can be reduced. It’s worth pointing out that the electrode positions are changed between the two experiments, which also affects the EMG signal and noise.

3.1.2. Effect of the electrode size

In this section, whether the factor of electrode size affects the EMG recording will be evaluated. First, the type of the electrodes needs to be considered. Because surface electrodes are usually used in kinesiological studies [2], the generic Ag/AgCI surface electrodes are chosen. The reason is that the muscles researched in this experiment are relatively large and shallower, therefore, surface electrodes are enough to obtain the correct EMG signal. Although wet-gel electrodes have better conduction and lower impedance conditions, the adhesive gel electrodes are chosen in this experiment. The reason for choosing this type is that they can be used and re-positioned in different experiments without replacing other electrodes. Due to the EMG experiment requiring to change the position of electrodes, the adhesive gel electrode is a better choice. In this experiment, the half area of electrodes 1 and 2 was covered using paper. The EMG signals for the wrist flexion with covering using paper can be seen below Figure 4.

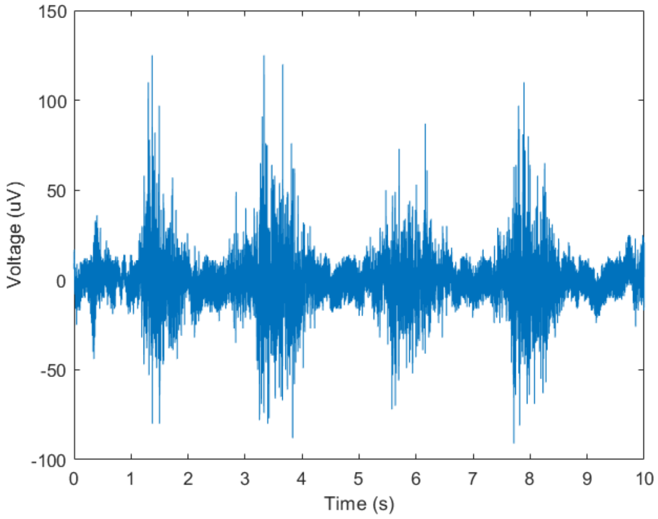


Figure 4. EMG signal of wrist flexion with covering

The EMG signal without covering paper can be in Figure 3(a). When there is without covering paper, the collected EMG signal has less noise and is almost without baseline shift. However, the EMG signal with covering is almost indistinguishable with too much noise. This is probably because the covering paper has affected the conductivity of the electrodes and a lot of external noise is collected.

Covering half the conduction area can be considered to be a change in conduction characteristics. The paper changes the good electrical conduction characteristics of human skin. Additionally, there are some baseline shifts with covering and it's hard to distinguish the baseline. This shift usually happens when the electrodes and cables shake too much or the distance between muscles and electrodes is changed [2]. When there is a paper covering half of the conduction area of the electrodes, the connection between the skin and the electrodes is loose. That also leads to the distance change between muscles and electrodes.

3.2. Processing of EMG recordings

The raw EMG signal can provide the ”off-on” and ”more-less” characteristics [2]. However, the raw signal can not provide enough information when the amplitude or frequency analysis is needed. Therefore, to eliminate motion artefacts, environment and equipment noise, suitable methods of signal processing are researched to increase the reliability and validity of recordings [2]. Because the hardware filter will affect the collection of raw EMG signals, only the amplifier bandpass filter maybe needed to reduce the effects of anti-aliasing. To further process the raw signal, the software processing method will be applied. The steps for processing the raw data can be seen below:

1) Baseline Offset

Because the baseline is not in zero voltage, the first step is to shift the baseline to the correct position. The baseline offsets usually occur after the auto-calibration or when the muscle is not relaxed at measurement start.

2) Full wave rectification

After that, the full wave rectification is applied to the EMG signal. That means the negative spikes are moved up to positive. The reason is that the rectified signal can be further processed using standard amplitude methods, such as mean, peak and max. The EMG signal before rectification has a mean value of 0.

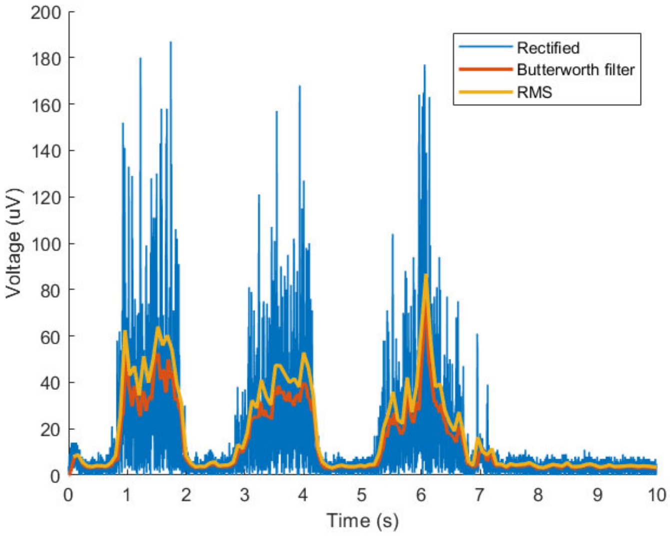
3) Smoothing: Root Mean Square (RMS)

For different forces, the amplitudes of EMG signals are different, therefore, the amplitude (envelope of the EMG signal) characteristics will be needed to drive a motor of a prosthetic arm. RMS is chosen to extract the characteristics because it provides the amplitude of the muscle activity and reduces the noise due to interference.

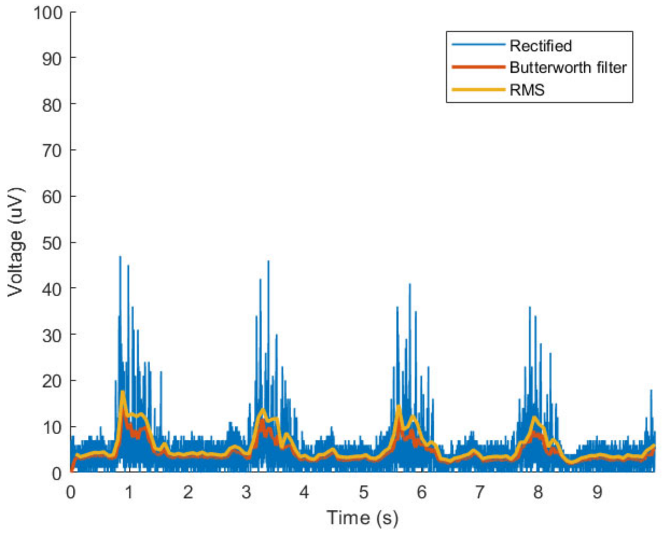
4) Another Smoothing: Digital Filtering

In addition to amplifier bandpass filtering, conventional kinematic EMG studies do not require additional filtering. To create a linear envelope EMG, digital filters can be applied (e.g. Butterworth Lowpass filter). The frequency response of the Butterworth filter is as flat as possible in the passband, which is also known as a maximum flat amplitude filter. The digital filter can recursively minimize the phase shift [2]. The cutoff frequency ωn is chosen to be 0.02π rad/sample in the program.

Another smoothing method is Moving average (Movag), which can also be used for data processing. However, due to the peak and mean values of the processed signal being usually smaller than RMS and digital filter [2], this method will not be chosen. In addition to the regular process, some special data processing methods may be applied. For example, if ECG artifacts affect the EMG signal measurement, ECG reduction algorithms also need to be employed. However, this experiment does not involve the influence of ECG artifacts, so the complex algorithms will not be presented. The processed signals after smoothing for different forces of wrist flexion can be seen in figure 5 below:



(a) EMG signal of wrist flexion with strong force



(b) EMG signal of wrist flexion with light force

Figure 5. EMG signals of wrist flexion with different forces

Generally, there are small differences in processed results between the Butterworth filter and the RMS algorithm. The peaks and the mean values using digital filter are smaller compared with the RMS EMG results. Since driving the prostheses needs to obtain the amplitude characteristics of the processed EMG signal, therefore, it may be more appropriate to use the RMS method. But both methods can be used to drive the motor of a prosthetic arm because they can both provide enough information.

The overall burst amplitude with strong force is much larger than that with light force. Therefore, different forces can be represented by different threshold levels of EMG signal amplitude. The choice of threshold levels relates to the noise level and the double threshold method gives better results than the single threshold method [7] for EMG detection. The prosthetic arm can generate different forces utilising the different threshold levels of the processed EMG signals. There are already some examples of controlling the prosthetic arm using the RMS EMG signals [8-9]. However, it’s hard to control a prosthetic arm to produce different movements using this simple way because many movements can generate the same amplitude. More signal characteristics and complex algorithms may be needed to distinguish the differences for each arm movement.

3.3. Limitations of the EMG for prostheses

3.3.1. Different flexion force

Although the amplitude characteristic of the RMS EMG can be used to control the prosthetic arm, the high sensitivity to noise also influences the extraction of characteristics. However, it is hard to determine what amplitude level is used to represent the corresponding force. For example, the prosthetic arm may not recognise the difference between a strong force and the strongest force after processing because the algorithms applied will eliminate the peaks. Especially under the threshold method, it is difficult to distinguish between forces that are very close to each other. Therefore, the processed EMG signals can only be used in rough-force prosthetic arms, which may only have some rough-force levels. Additionally, the prosthetic arm can not recognise the movements and many movements can generate the same amplitude.

3.3.2. Finger motion

To control hand prostheses, the processed EMG signals are needed. Similarly, the same methods of signal processing are applied. Since the results of the digital filter are similar to those of the RMS algorithm, the RMS EMG results of three-finger flexion are shown as an example in figure 6:

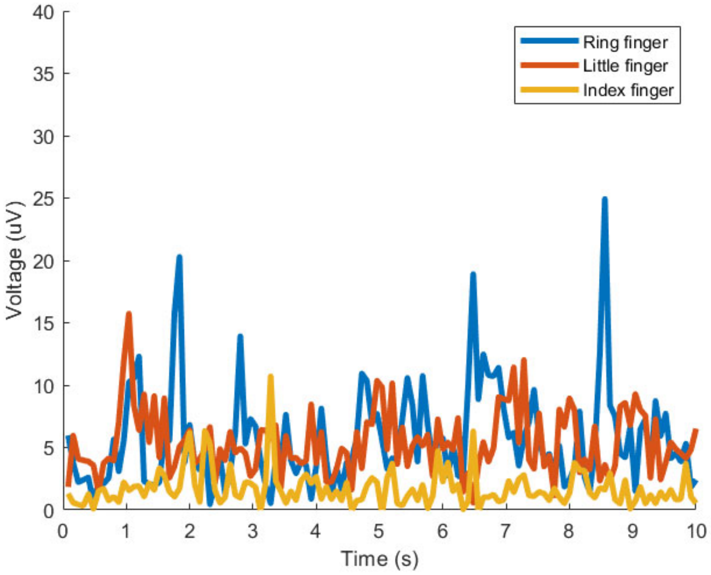


Figure 6. RMS EMG signals of three fingers flexion

According to the insertions and actions of forearm muscles, different muscles control different finger flexions. Therefore, the peaks of EMG signals are different for each finger. The EMG signals produced by different finger motions are also consistent with previous analyses of muscle anatomy. However, due to the noise effect, there are small voltages when the muscles are relaxed, which affect the processed RMS EMG signals. Roughly, the burst amplitude level and the peak of the ring finger are the highest. The amplitude characteristics can be used to control the hand prostheses. However, the amplitude level differences between three finger flexions are not obvious, which is the limitation of hand prostheses using EMG. That means that only the amplitude characteristics are not enough, other characteristics after processing may be needed to achieve accurate control. In addition, the finger motion also affects the collection of EMG signals for the arm prostheses.

3.3.3. Reference locations

Each measurement needs one neutral reference electrode. The position of the reference electrode affects the EMG recordings. Usually, the electrically unaffected and nearby area is the suitable position for reference electrode. The following figure 7 show the RMS EMG of wrist flexion using different references:

The force used is as consistent as possible in all three measurements. Compared with the correct position of the reference electrode (back of hand), the noise level using ankle and forehead reference is larger. Additionally, the peak amplitudes of RMS EMG of ankle and forehead are also lower. The reason is that the chosen reference position is far away from the measured electrodes. Because the position of reference electrodes affects the voltage amplitude and noise level. Therefore, the generated EMG signal will be different when the reference is not fixed, which is also one limitation of using EMG for prostheses. It is also difficult to choose a suitable position for the reference electrode. Moreover, the ECG artifacts affect the collection of EMG signals when measuring the trunk muscles on the left side. Therefore, when considering a left-arm prosthesis, the ECG artifacts need to be reduced by modifying the position of the reference electrode.

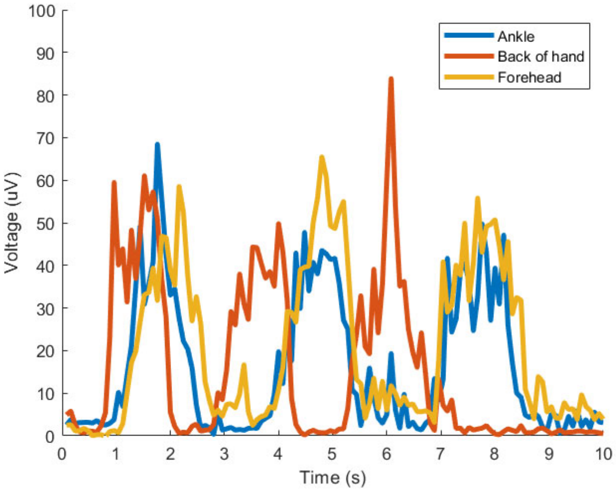


Figure 7. RMS EMG signals of wrist flexion using different reference locations

4. Conclusion

The definition of Motor Unit (MU), the working principles and the applications of electromyography (EMG) are first presented with details. Since this experiment concerns kinesiological studies, the muscles studied are larger and shallower, surface Ag/AgCl electrodes are sufficient to conduct the study. In addition, to conduct multiple experiments, adhesive electrodes are chosen. Based on muscle anatomy and experimental validation, the effect of electrode position on the measurement of EMG raw data is also described. Since the muscles studied are parallel to the forearm and the depolarisation wave also follows the forearm arm, the electrodes parallel to the forearm axis provide more accurate results with less noise. Then, how the area of the electrodes affects the EMG recordings and the reasons for this effect are also analysed. The added paper changes the conduction of the skin, adding a lot of noise to the signal. After obtaining the raw EMG signals, the subsequent processing of the data is very important. To drive the motor of the prosthetic arm, the Root Mean Square (RMS) and Digital filtering methods (Butterworth filter) can both process the data. The results show that there is little difference between the two methods and RMS is a better choice. But both methods can be used as a suitable processing method for prostheses because they can provide enough amplitude characteristics. The RMS has a larger peak and mean value, but the high-order digital filter can minimise the phase shift phenomenon. Although the processed data can be used as a signal to drive the prosthesis, there are still some limitations, such as the different flexion force, the finger motion and reference locations.

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