Chapter

Muscle Mechanics and Electromyography

Sarmad Shams, Muhammad Asif and Samreen Hussain

Abstract

This chapter will begin with the introduction to biomechanics and its relationship with the physiology and anatomy. Then it introduces the basic concepts of kinematics, kinetics, and anthropometry and discusses in detail the muscle mechanics and electromyography. The muscle is the actuator of the human body, especially the skeletal muscles which are attached with the skeleton play an important role in defining the movements of the human body. The human body controls the muscle through the nervous system, and this nervous system generates signals called electroencephalogram (EEG) which upon leaving the nerves excites the muscle and converted into muscle signals usually called electromyogram (EMG). In this chapter, we will discuss the mechanics of the muscle in conjunction with the EMG. EMG is the tool to study the activity of the muscles and hence the key to understand the mechanics of the human body.

Keywords: electromyogram (EMG), biomechanics, muscle mechanics

1. Introduction

What is Biomechanics? The biomechanics is the study of the structure and function of biological systems. "Bio" means "living" and "Mechanics" is "Forces and its

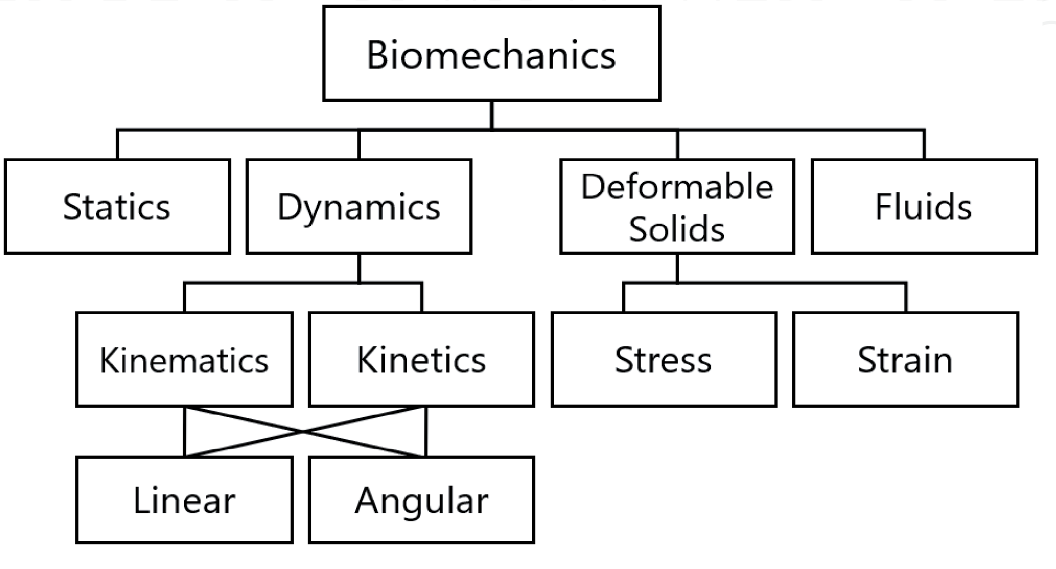

Figure 1.
The division of mechanics in a nutshell.

effects," hence "Biomechanics," terms evolved which literally means the forces and its effects on the living cells. The biomechanics includes the study of tissues including bones, cartilages, ligaments, tendons, muscles, and nerves, studying all these tissues at different levels and scales ranging from the single cell to tissues, to organs, and to the whole body level.

The biomechanics is divide into following **Figure 1**.

1.1 Relationship with physiology and anatomy

To study the biomechanics, one should know the basic of human structure and its functions, that is, anatomy and physiology of the human body.

2. Essentials of biomechanics

2.1 Kinematics

Kinematics is the study of motion without involving the factor that causes that motion. The whole kinematics theory and analysis will evolve around three basic variables of mechanics, which are as follows:

1. Displacement

2. Velocity

3. Acceleration

2.2 Kinetics

Kinetics is the study of motion, and the elements causes that motion, that is, force and torque. The kinetics as evident from the name kinetics will discuss the mechanics of the human body that are under motion, and the three basic variables that cause or influence the motion are as follows:

1. Force

2. Torque

3. Mass

2.3 Anthropometry

Anthropometery is a combination of two Greek words anthropos, which means "Human" and metron, which means "Measure." Therefore, the literal meaning of the anthropometry is the measurement of the human individual. When discussing the mechanics of the human body, the discussion and understanding of the anthropometry become essential, due to the fact that the mechanics cannot be complete without the measurement of the subject. The basic parameters under consideration when discussing the anthropometry are *Height, Weight, Size* and *Esthetics* of organs, limbs, and other body parts. A number of studies were carried out for the collection and compiling a database to standardize the anthropometry data, such as [1–3].

3. Muscle mechanics

3.1 Muscular system

Contrary to the bones, which provide the structural strength and stability to the human body, muscles are responsible to hold the bones with the possible movement of each joint with the application of forces by contracting themselves. Muscles are not simply the force generators in the body; the force developed in the muscle depends on the level of neural excitation at the central nervous system (CNS) with the speed and length at which the muscle contracts. Almost all the muscles are arranged in pairs as agonistic and antagonistic muscles, and these pairs work against each other, as one muscle pull then the other muscle relaxes and stretched in response. There are almost 320 muscle pairs that exist in a human body which make up almost 40% of the whole body mass.

4. Electromyography

Electromyography is the study of electromyograph (EMG). EMG is the recording of the electrical activity of the muscle. This electrical activity is produced due to the ionic movement in the muscle in response of the conducting signal from the motor unit of a neuron. This motor unit (MU) acquires single or multiple muscle fibers to perform the actuation of the muscle; this selection of the muscle fiber is random and it is not necessary that the previously acquired MU will acquire the same muscle fiber.

5. EMG signal

Electromyogram (EMG) is the electrical activity produced by a contracting muscle. EMG signal is extensively used in the field of rehabilitation, biomechanics, orthopedics, ergonomic product design, and prostheses. Due to the fact that EMG allows directly looking into the muscle and measuring the muscular performance, it also helps in decision-making both before and after surgery. The basic functional element that is responsible for producing the EMG signal is called the motor unit (MU). The MU consists of an $\alpha - motorneuron$ that has cell body in the spinal cord and extends its axon from the spinal cord to the skeletal muscle fiber (as shown in the **Figure 2**), where it innervates and forms a junction, usually called motor end-plates.

The signal from the $\alpha -$ motorneuron causes depolarization in the muscle fiber that travels in either direction from the junction and creates a potential difference. This difference is measured by the electrodes. The muscle fibers connected to a single neuron react together and hence termed as motor unit. The signal generates by the MU is called motor unit action potential (MUP). The resulting EMG signal is the sum of all activated MUs during the contraction of that muscle. When the signal is acquired using surface electrodes, the signal has to travel through the remaining tissues before reaching the electrodes. This traveling of the signal results in the decaying of the signal amplitude.

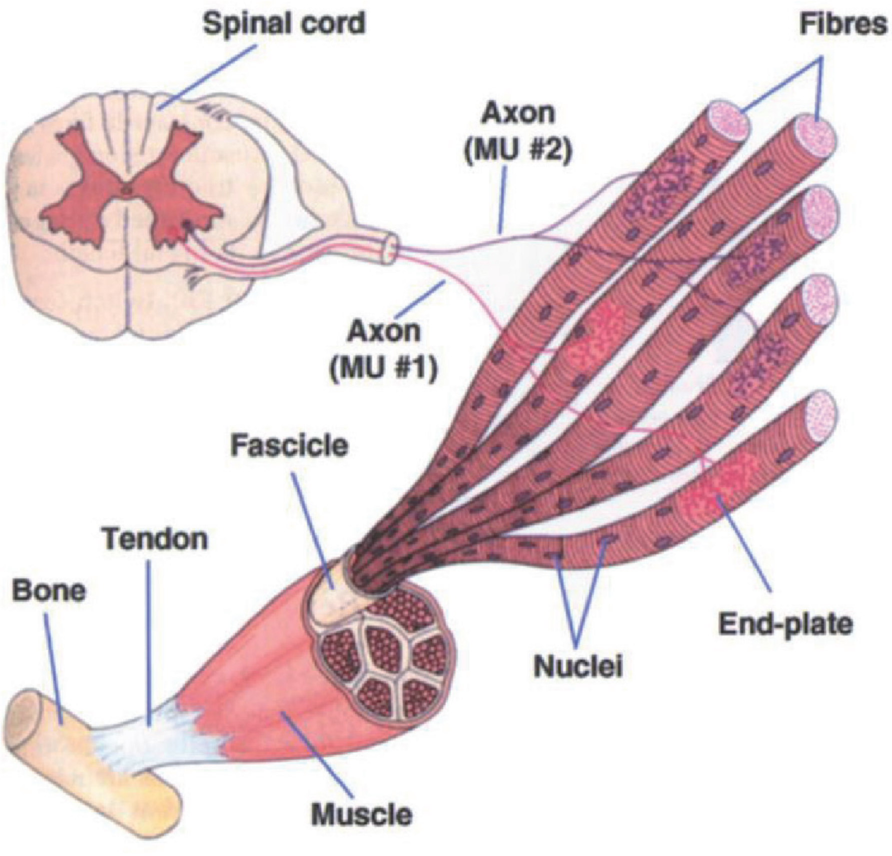

Figure 2.
A typical α – motorneuron extends from the spinal cords and ends at the motor end-plates in the skeleton muscle fiber [4].

6. Acquisition of the EMG signal

The signal generates due to the contraction of the muscle can be detected by placing the electrode on the surface of the muscle. The electrode placement is the main challenge in the acquisition of the surface EMG (sEMG), as the strength of EMG signal varies significantly if the electrodes are slightly displaced from the previous position [5]. In this research, the electrodes have been placed on the triceps and biceps muscles. The placement on the triceps muscle is quite a challenge due to its small size. We searched the spot on the subject for the best EMG signal acquisition. The signal detects by the surface electrodes can be seen in the **Figure** 3**a** and termed as a raw EMG signal.

The raw EMG signal is then passed through an instrumentation amplifier with high common mode rejection ratio (CMRR). The instrumentation amplifier is configured in differential amplification mode to eliminate the noises using the CMRR feature. The gain of the instrumentation amplifier is set as high as 1000 to amplify the minute EMG signal, as the typical EMG signal amplitude measures around 100 μV. After successfully eliminating the common noises and amplification, the amplified EMG signal is passed through a bandpass filter of a low cutoff frequency of 450 Hz and a high cutoff filter of 10 Hz for further filtration. This filtered EMG signal is then passed through a notch filter to eliminate the 50 Hz line frequency. The final filtered EMG signal is then rectified and passes through a smoothing filter to obtain the processed EMG signal. This signal is then used by the controller to execute the control algorithm. **Figure 4** shows the flow of the EMG signal acquisition and process while **Figure 5** shows the EMG signal obtained at each step of the EMG signal acquisition, that is, after the acquisition, then filtration, then rectification, and then smoothing process (moving average filter and RMS).

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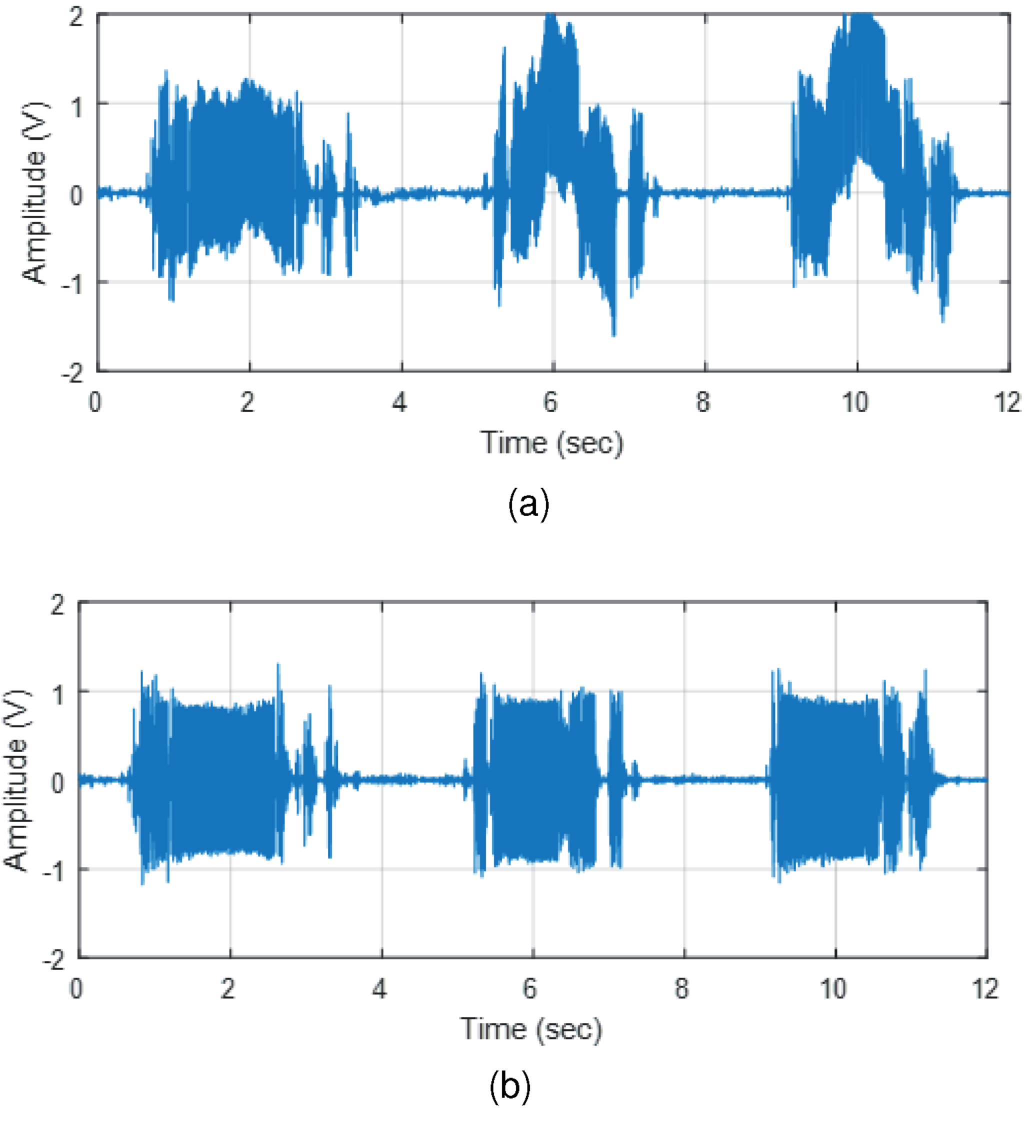

Figure 3.
The EMG signal at every step of the EMG signal acquisition. (a) Raw EMG of three biceps contraction; (b) EMG signal after filtration process.

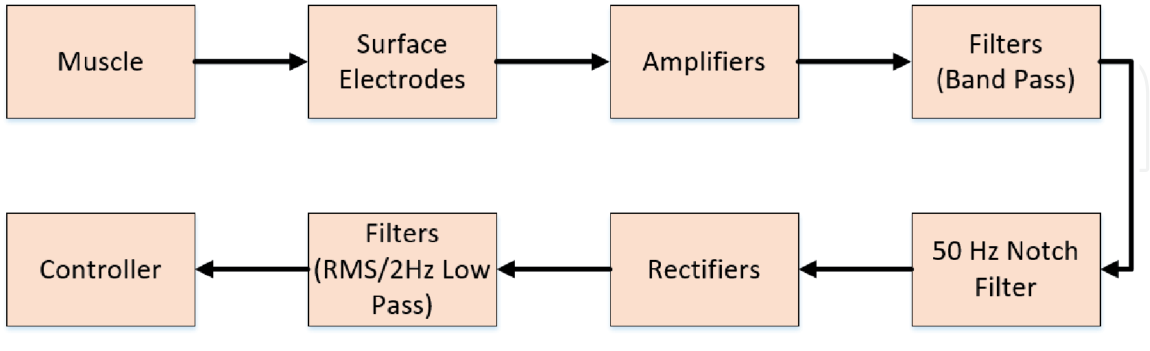

Figure 4.
sEMG signal acquisition flow chart.

6.1 Electrode placement for EMG signal

Since 1980, researchers are working on the development of protocols and standards for the surface electromyogram (sEMG) electrode placement procedures. Initial attempt was done by the International Society of Electrophysiological Kinesiology in 1980 [6]. After few years, more detailed and in-depth report was published as surface EMG for a non-invasive assessment of muscles (SENIAM).

This report was published with the support of European Union. SENIAM was reviewed and further deliberated by a number of laboratories around the world and more refined booklet was published as SENIAM 8: European Recommendations for Surface Electromyography, 1999 [7]. Few of SENIAM recommendations are as follows:

- sEMG sensor—In sEMG sensor, the SENIAM recommend the electrode shape, size, and constructions for different muscle size and volume. This category also includes details of electrode material and electrode inner distance, etc.

- Sensor placement—The sensor placement is the most critical part of the sEMG signal acquisition during the preparation of the subjects' skin and selection of sensor location. This category also includes the standards for the placement and fixation and testing of the connections.

- Sensor locations—The last and final standardized category in the SENIAM is the optimal sensor location for the best sEMG signal with minimal crosstalk and artifacts. Almost all the upper and lower body details can be found in this catalog.

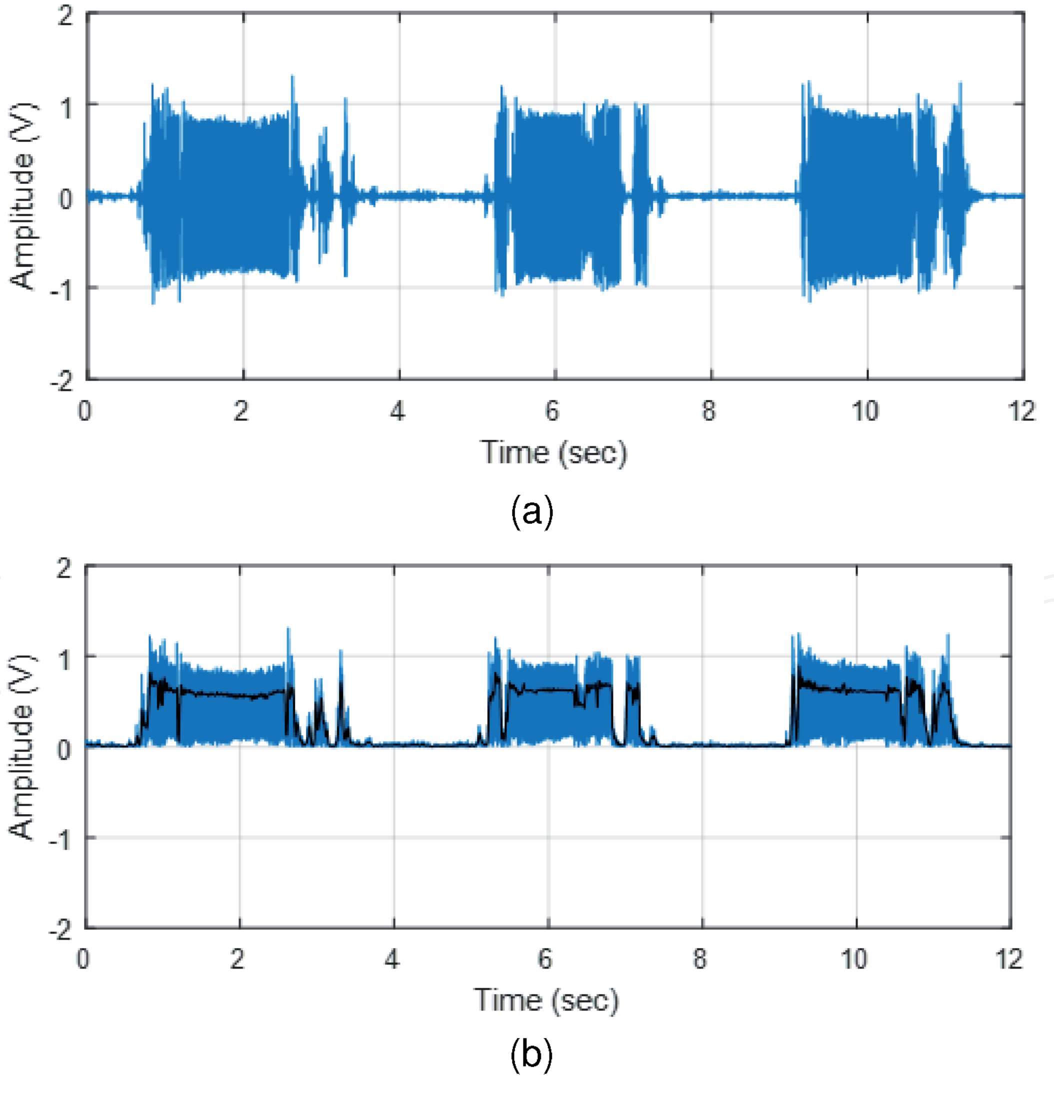

Figure 5.
The EMG signal (a) after band pass filter (b) after rectification in blue and EMG signal after smoothing filter in black.

6.2 Selection of amplifier gain

Amplifier gain plays an important role in the acquisition of quality and noise-free sEMG signal after the selection of electrode and its placement. The sEMG signal of a normal adult ranges from few hundreds microvolts to 2 mV. Contrary, in athletes, the sEMG signals 5 mV is recorded during maximum voluntary muscle (MVC) [8]. Selection of the amplifier gain considerably depends on the application and requirement of the system. However, for 2 mV input sEMG signal, a gain of 1000 can be used. This gain will results in an output of 2 V. This amount of amplification will also lead in the magnification of noises which can be ignored otherwise. To overcome the amplification of noises acquired with the sEMG signal, one can use the electrodes in differential configuration. In a typical differential amplifier, two electrodes are used with one common or ground electrode. The two electrodes are connected with the positive and negative terminal of an amplifier as shown in **Figure 6**. A typical differential configuration of operational amplifier (op-amp) is shown in **Figure 6**. The gain of the op-amp in differential configuration can be set using the Eq. (1). Whereas the output voltage V_{out} can be calculated with reference to the input voltages V_1 and V_2 using Eq. (2) if both the input and feedback resistors as shown in **Figure 6** are same.

$$A_v = \frac{V_{in}}{V_{out}} = \frac{V_{out}}{V_2 - V_1} \quad (1)$$

$$V_{out} = \frac{R_f}{R_i}(V_2 - V_1) \quad (2)$$

The main advantage of using differential configuration op-amps is to eliminate the noises common to both the input pins. The common noises will be canceled out due to the positive and negative input terminals resulting in a phenomenon known as common mode rejection ratio (CMRR) which is discussed in detail in the Section 6.4.

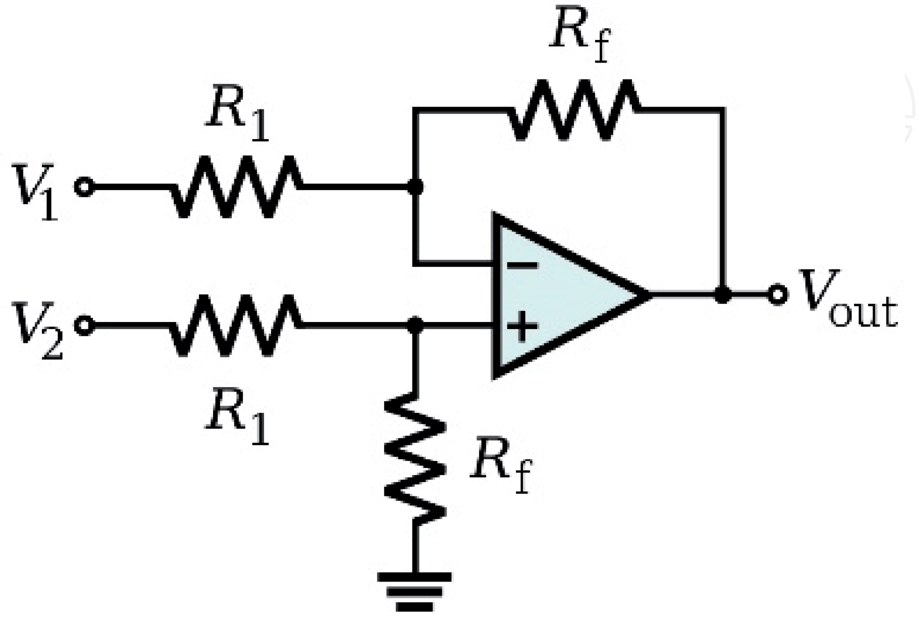

Figure 6.
A typical operational amplifier in differential amplifier configuration.

6.3 Input impedance

Human skin behaves different to different things (such as gel, oil, cream, drugs), especially current and voltages of different frequencies and amplitudes [9]. The resistance experienced by the electrodes during the acquisition of the sEMG signal can be reduced by using the gel in between the electrodes and skin [10].

6.4 Common mode rejection of noises

The amplification circuit has an ability to reject the common signal to both of its input if the signal is in phase and has same amplitude. This property of the amplifier is referred to as common mode rejection ratio (CMRR). In the acquisition of the biopotentials, like EEG, ECG, and sEMG, this property of the amplifier comes in handy if it is used in the differential configuration. Almost, all the op-amps inherit this property with the variation of the CMRR value. Ideally, an op-amp should have infinite amount of CMRR, but in real, it is limited to the range of 70–120 dB [11]. The typical formula to calculate CMRR is shown in Eq. (3). Where A_{DM} is the *differential mode gain* and A_{CM} is the *common mode gain*. Eq. (4) shows the CMRR formula to convert it into *deci Bell*.

$$CMRR = \frac{A_{DM}}{A_{CM}} \tag{3}$$

$$CMR(dB) = 20\log_{10}(CMRR) \tag{4}$$

6.5 Crosstalk of the EMG signal

It is quite difficult to identify the muscle when the sEMG signal acquired from the skin surface which contains a bunch of muscles underneath especially the forearm muscles. A cross-sectional view of the forearm is shown in **Figure 7**. The sEMG signal acquired from the forearm will be resulting from the contraction of multiple muscles due to the reason that the muscles are bundled and overlap each other in the forearm area. It is quite impossible to avoid crosstalk in this area as the active small motor unit range is around 0.5 cm and large motor unit range is around 1.5 cm [12]. Therefore, the electrode placed on the surface will acquire the sEMG signal produced by the contraction of multiple muscles' motor units which are under it. This crosstalk can be minimized by the following techniques:

- Manually checking the muscle resistance
- Using cross-correlation technique of signal processing.

Manual identification of the muscle resistance is not feasible in all cases. Therefore, the most successful technique is to use the cross-correlation method [13]. A general formula for the detection of cross-correlation is shown in Eq. (5); however, detail discussion is beyond the scope of the book.

$$R_{xy}(\tau) = \frac{\frac{1}{T}\int_{0}^{T} x(t)\,y(t-\tau)\,dt}{\sqrt{R_{xx}(0)R_{yy}(0)}} \tag{5}$$

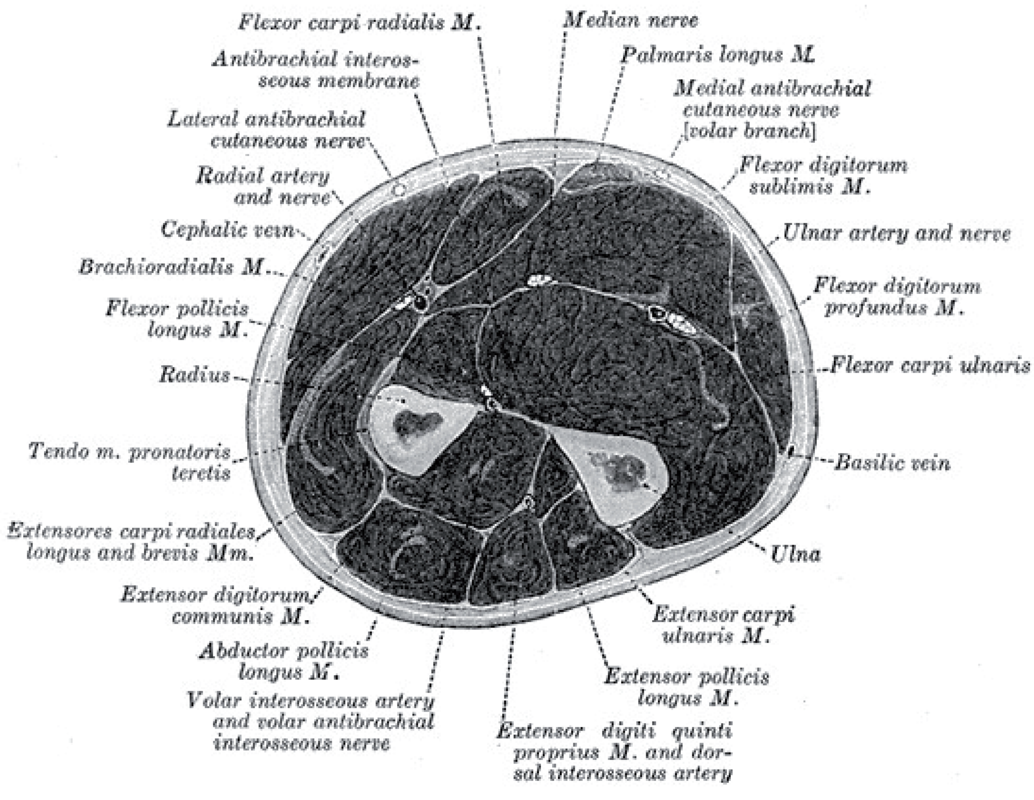

Figure 7.
Cross-sectional view of human forearm, image courtesy [14].

7. EMG signal processing

After the acquisition and amplification of the sEMG signal, the signal processing has been started as shown in **Figure 4**. The following blocks are essential for the signal processing of the sEMG signal, and the sequential process is shown in **Figure 8**.

- Filters (bandpass)
- Notch Filter (50 Hz)
- Rectification
- Smoothing filters

7.1 Filters—bandpass

Not only the amplitude of the sEMG signal depends on the site of acquisition but also the frequencies vary with it. Other factors depend on the subject physical health as the sEMG signal of athletes has higher amplitude and frequencies as compared with the normal subject [8]. The recommended cutoff frequencies setting for the bandpass filter are from 10 to 500 Hz [7]. However, in some cases, a tight band of 10–250 Hz may be used.

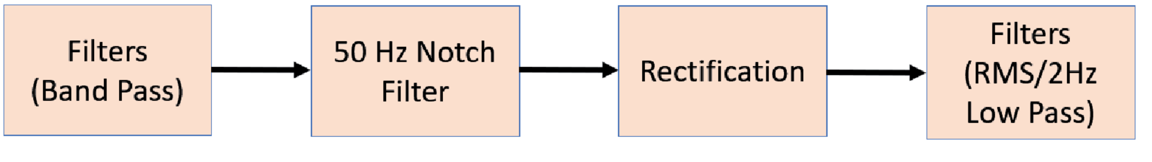

Figure 8.
The signal processing blocks in a typical sEMG acquisition system.

7.2 Rectification

In electrical, rectification is referred to a process that converts the alternating current (AC) to direct current (DC). In signal processing, the rectification is referred to convert the negative values of a signal into positive. In other words, the rectification is similar to take the absolute value of the signal. **Figure 5a** shows the signal of sEMG obtained during the contraction of bicep muscle. The rectified sEMG signal can be seen in **Figure 5b**. The signal in the black color (in **Figure 5b**) is obtained after the smoothing filter which will be discussed in the next section.

7.3 Smoothing filters

The sEMG signal is random and cannot be reproduced again with same amplitude, frequency, and shape. Therefore, sEMG undergoes signal smoothing techniques to minimize the effect of the non-reproducible part of the signal. Mostly, following techniques are used for smoothing the sEMG signal and one can select anyone of the techniques depending on the system requirements.

7.3.1 Root mean square (RMS)

The root mean square or RMS is the most commonly used technique among the signal processing community for the smoothing of signal. The RMS calculation is based on the square root and the mean power of the signal as shown in the Eq. (6).

$$RMS = \sqrt{\frac{\sum_{i=1}^{n} x_i^2}{N}} \tag{6}$$

7.3.2 Moving average filter (MA)

As the name depicts, the moving average (MA) filter takes average of the samples as it moves forward. In other words, a window is set defined for a specific number of samples, then the data in the window are averaged by the sliding window technique resulting in the smoothing of the signal. The MA filter can be applied on the sEMG signal using Eq. (7).

$$y[i] = \frac{1}{M} \sum_{j=0}^{M-1} x[i+j] \tag{7}$$

7.3.3 Low pass filter

Another common technique for smoothing of the sEMG signal is to use a low pass filter that blocks all the higher frequencies of the signal. For this purpose, usually, a low pass filter with a cutoff frequency between 2 and 5 Hz is used.

8. Conclusions

The biomechanics is basically divided into four major areas: kinetics, kinematics, anthropometery, and electromyography. To understand the biomechanics, one must have clear understanding of all the four major areas especially the EMG. Since, the main application of the biomechanics is to observe the problem and improve the diagnosis and fixation of any disease or lacking identified during the analysis. Researchers

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have developed a number of techniques to monitor the behavior of human mechanics using 3D cameras, motion sensors, reflector markers but none of the technique gave the essential analysis which can be obtained through EMG. Therefore, this chapter covers the essential knowledge required to build a knowledge base for the reader for the better understanding of the Biomechanics of human body.

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