CHAPTER 3: LITERATURE STUDY

3.1. INTRODUCTION

This chapter gathers and prepares the information required for the conceptual design chapter. A detailed investigation is done to understand how EMG systems are described using equations. This includes how transfer functions are derived for the skin-electrode interface and muscle functionality, using on mathematical models. This is required to ensure the problem is approached correctly to find an effective solution to aid in future research on proportional control. The chapter concludes with a description of the interface possibilities between the sensing platform and the Matlab®/Simulink® environment.

3.2. SYSTEM MODELLING AND PARAMETER ESTIMATION

Two biomechatronic design approaches described in the introduction chapter exist and the analogous approach is the chosen method. The analogous approach is the process in which the abstraction of functions is done using analogous reasoning to optimize the solution by looking at the overall goal of the biomimicry, rather than the individual functions.

The two biomechatronic models required for this project include the muscle model and the skin electrode impedance model. The muscle model is the biological system in engineering terms, and the skin-electrode model is the HMI. The electrodes are connected to an instrumentation amplifier and the rest of the system, which occur inside the engineering domain. The last section is dedicated to an introduction to EMI modeling

3.2.1. MUSCLE MODELLING

Hill [38] proposed a three-element muscle model in 1938. Figure 29 is the illustration with the contractile element (CE), the serial elastic element (SE), and the parallel elastic element (PE). This model is used to derive an antagonist muscle model.

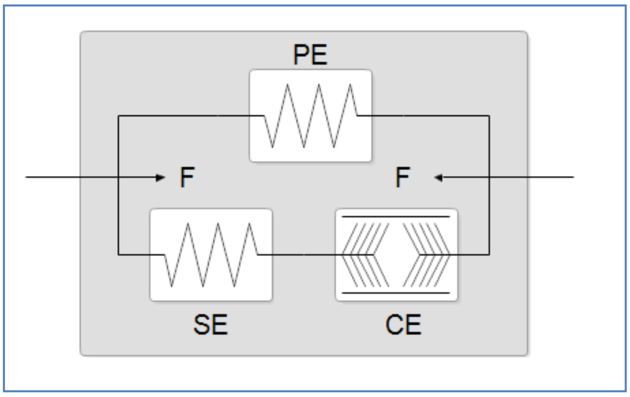

Figure 29: Hill's three-element muscle model [38]

Both the parallel and series elastic elements (PE and SE) are spring elements. It depends from the type of muscle group whether these elastic elements are linear or not [38]. The contractile element CE generates the force, *F*. Dynamic systems, such as the human muscle, are described mathematically by differential equations (DEs) All the various muscle models developed are based on the Hill's muscle model, with variations that ranges from a second order to an eighth order DE [38].

3.2.2. HILL'S MUSCLE MODEL AND THE PNS

Hill's muscle model contains the CE, the SE, and the PE [38]. The PNS contains the parallel muscle spindle and the serial Golgi tendon organ. Table 1 shows the relationship between the two models as well as the naming of the afferent nerves. Figure 30 is an illustration of the human muscle and the muscle model.

Table 1: Relationship between muscle model and PNS [39]

Type of muscle nerve	Group number	Element Symbol	Position	Location in muscle
Primary muscle-spindle afferent	Group Ia	SE	x_2	Central bag region of spindle (non-contractile)
Secondary muscle-spindle afferent	Group II	PE	x_1	Pole region of spindle (contractile and innervated)

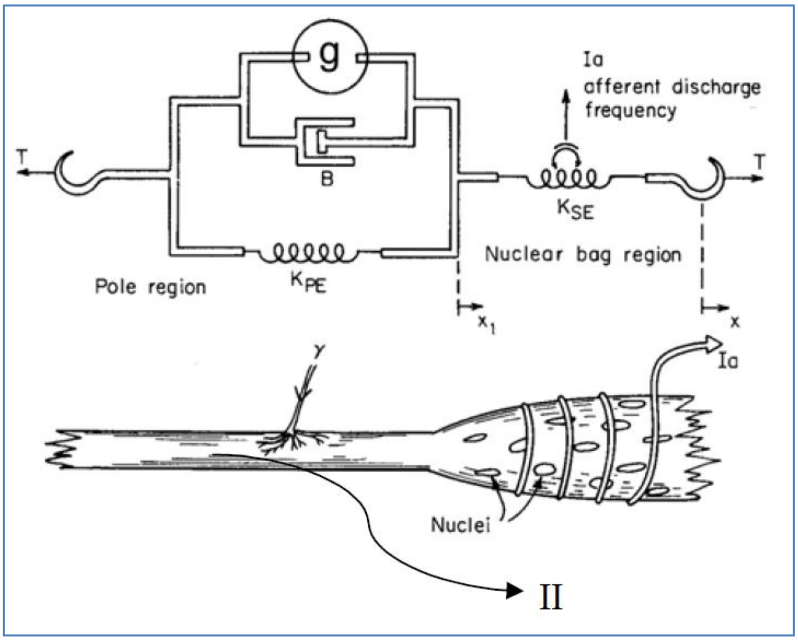

Figure 30: The natural muscle and the muscle model [39]

3.2.3. MUSCLE MODEL AND EMG RELATIONSHIP

There are various studies done on the relationship between the muscle model elements and EMG, with various results. The amplitude of the EMG recording and the contractile element (CE) is linear in some cases, but it varies with different muscles. It is not always clear which type of muscle contraction was used in the muscle contraction tests.

There are different types of muscle contractions. The different types of muscle contractions that can be performed include concentric, eccentric, isometric and isotonic muscle contractions. In concentric contraction the force of the muscle is sufficient to move the joint, and is the type of contraction most people regard as being a "muscle contraction". Eccentric contraction is when an object is too heavy to carry, and it is decelerated towards the ground without free falling. An isometric contraction occurs when a muscle exerts a force but can't change in length, such as tree hugging. Isotonic contraction is performed when a load is picked up and the muscle changes in length without the muscle tension increasing. The information about the various muscle contractions is important to determine the relationship between the muscle model's elements to derive a transfer function.

3.2.4. LINEAR AND NON-LINEAR SYSTEMS TRANFER FUNCTIONS

If the muscle model used to derive the antagonist muscle model in the detailed design chapter is linear, the Laplace transform could be used in the simplification of the DE [40]. For the proportional control of the sEMG to be linear, it depends on linear activity of the CE, recorded by the sEMG sensing technique. Each muscle inside the human body consists of a large number of motor units. EMG senses the overall motor unit activity inside a muscle. Researchers assume that the EMG recording is the sum of all the motor units i.e. the principle of superposition, but according to the superposition principle, this is only true if the muscle model is linear [40].

However, non-linear systems can be treated as linear systems with the correct assumptions made. If a model has a linear region and the operation point remains within this region, a linear approximation could be as accurate as the assumptions made to suggest the conditions in which the model would behave as a linear model. Figure 31 illustrates how a non-linear spring's behavior is turned into a linear transfer function using linear approximation. The spring has a quadratic function describing the relationship between the spring's length and the force applied. By carefully selecting the operating point on the relationship graph and ensure that the change in the independent variable is within certain limits, a linear function is fitted to the relationship to determine the linear approximation [40].

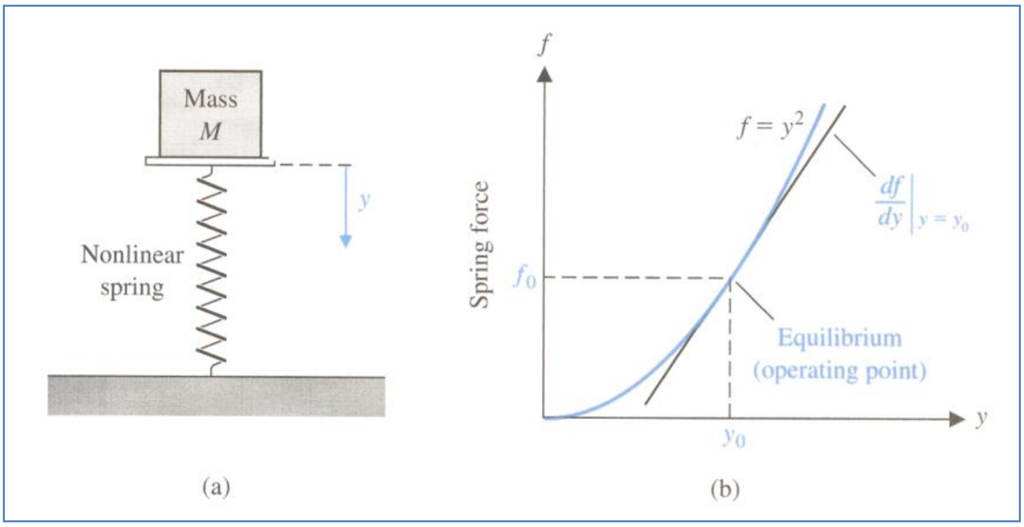

Figure 31: Linear approximation of a non-linear model [40]

The elastic elements found in the muscle model (PE and SE) could be treated as linear spring elements by assuming that concentric muscle contraction occurs.

3.2.5. THE MUSCLE MODEL TRANSFER FUNCTION

Transfer functions reveal the property through components, or across the components. A through-variable example is the variable that passes through components, such as electrical current through electrical components, and mechanical force that passes through mechanical components. An across-variable is the property measured across a component, such as the voltage across an electrical component, or the pressure difference across a mechanical component. The types of component elements found in models are inductive and capacitive storage elements, and energy dissipators [40].

To derive the transfer function, the first step is to determine the following types of variables found in the in the muscle model [40]. The across-variable found is the force generated by the CE. The through-variable is the current that flows through the CE. The translational stiffness of the muscle spring elements (SE and PE) each are approximated as a linear spring and are defined as linear inductive storage elements.

As the human hand is lightweight it is assumed that the mass of the fingers is insignificant small and could be excluded from the model. This means that there is no capacitive storage elements included in the muscle model approximation. The human joints are assumed to be frictionless, resulting in no energy dissipator elements present in the muscle model. This is seen as the simplest form of muscle model. Although not recommended as generalisation of the characterisation of muscles [38], a first order DE is easily implemented to demonstrate the functionality of the sensing platform.

These elements are used to derive the antagonist muscle model in the detailed design chapter.

3.2.6. SKIN-ELECTRODE IMPEDANCE MODEL

The HMI in this project is represented by a few electrodes. The human skin is a poor conductor, but the use of natural sweat or electrolytic gel enables the possibility for biological input for prosthesis control circuitry. A skin-electrode model and its equivalent small signal circuit are given in figure 32 [41].

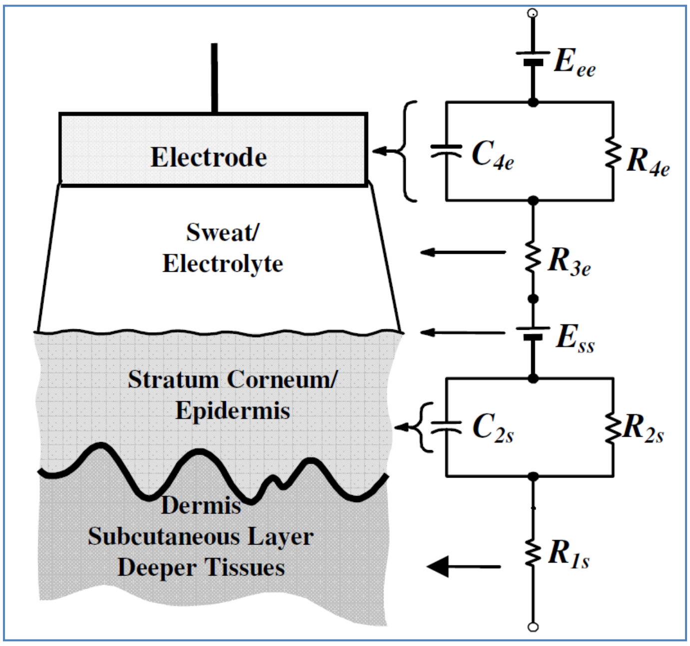

Figure 32: Skin-electrode interface and its electrical equivalent circuit [41]

The skin impedance is represented by the three passive components C_{2s}, R_{2s}, and R_{1s}. R_{1s} is the deeper tissue layer resistance, and R_{2s} is the outer skin layer resistance. C_{2s} exist because of the layered structure of the skin. E_{ss} is the voltage seen on the skin surface. E_{ee} should be a resemblance of E_{ss}, as E_{ee} enters the sEMG amplifier. C_{4e}, R_{3e} and R_{4e} are the characteristic impedance components of the electrode. Without the electrolyte, the resistance value of R_{3e} would increase, and therefore increase the total electrode impedance, as seen by the sEMG amplifier.

3.3. VARIANCE IN PARAMETERS IN HUMANS

The human body is capacitive, resulting in EMG signal that is filtered by a natural low-pass filter. This means that a distorted frequency spectrum of an EMG signal is sensed by sEMG. This implies that frequency modulation (FM) is considered as an unreliable method of decoding sEMG signals, as some signal information is lost, compared to the iEMG method [18]. Amplitude modulation (AM) techniques are considered as these methods are not frequency dependant. The problem associated with

AM is the fact that a large signal to noise ratio (SNR) produces dc-offsets in data. This may induce issues in the scaling of signal for decision boundaries of prosthesis control.

Variance in EMG data that exists from person to person includes body fat percentage, which affects SNR and scaling of sEMG signals. Variance in muscle development affects scaling of sEMG signals.

3.4. NOISE AND INTERFERENCE ISSUES

EMI and EMC is a wide field of study, and this project focuses on the hardware design in terms of functionality. Subsequently only the crucial noise and interference issues are covered in this section. Noise or interference is sensed by passive, active and parasitic components within the circuit

3.4.1. PASSIVE COMPONENTS

Resistors, capacitors and inductors are the passive components in a circuit. Resistors generate thermal noise. Formulas are available to calculate the thermal noise power generated by the passive components [42].

3.4.2. ACTIVE COMPONENTS

All types of amplifiers are active components. Important factors when choosing amplifiers are noise gain, slew rate and power bandwidth (for distortion) and internal noise found in amplifiers [42]. Noisy power sources used to power amplifier circuits also contaminates amplifiers' outputs [43].

3.4.3. PARASITIC COMPONENTS

Parasitic components are the unwanted characteristics added by imperfect components and circuit layout. Resistance is found in capacitors and inductors and contributes to noise in the circuit [42]. Parasitic inductance and capacitance are added to a circuit where tracks on a PCB contain large loops or large copper planes [43].

Noise and interference can be random or repetitive, and result in unwanted voltages or currents at any frequencies inside a circuit [42]. This poses a threat if repeatability and reliability in results are important. The reader is referred to [8-11] for more detail on advanced concepts of EMC and medical electronic design.

3.5. INFORMATION DERIVED FROM SEMG

The information that can be extracted from an EMG signal is the net activity of a muscle to perform an action. n the following paragraphs the method for deriving muscle activity will be discussed. Refer to the four graphs in figure 25 for illustration of the net muscle activity calculation.

3.5.1. REMOVE DC-OFFSET

Remove the signal's DC-offset by subtracting the average value of the complete signal (figure 24) from the original signal. The answer is given by

$$V_{Out}(i) = V_{in}(i) - Offset\,, \tag{3-1}$$

$$Offset = \frac{\sum_{j=1}^{n} V_{in}(j)}{n}, \tag{3-2}$$

where V_{out} is the recorded EMG signal as a 1xn array, n is the length of the input array and i is the i'th element of the input and output arrays. Figure 25 (a) illustrates the result.

3.5.2. RECTIFY SIGNAL

Next step, the signal is rectified by taking the absolute value of the data. This step is required because sEMG signals are AC signals and the average value of the original signal would result in zero. The output is given by

$$V_{rec} = |V_{out}(i)| \qquad 3\text{-}3$$

The first graph in figure 33 (a) shows a sample signal, with figure 33 (b) showing the rectified signal.

3.5.3. LOW-PASS FILTER

Next the data being filtered with a low-pass filter using a moving average filter:

$$V_{LPfilter}(i) = \frac{\sum_{j=i}^{i-k} V_{rec}(j)}{n}, \qquad 3\text{-}4$$

where *i* is the i'th element of the output array and *k* is the length of the moving average filter. Figure 33 (c) illustrates how a sample signal would appear after it has been processed by a low-pass filter.

3.5.4. TOTAL MUSCLE EFFORT

The final step is the calculation of the total muscle effort by taking the discrete integral of the data over the complete sampling period. The integral of the signal obtained from the filter is given by

$$V_{Out}(i) = \frac{1}{T}\sum_{i=0}^{n} V_{In}(i), \qquad 3\text{-}5$$

where *n* is the length of the recording (number of samples) and *T* is the sampling period. Figure 33 (d) is the result of the total muscle effort processed from a raw EMG sample signal.

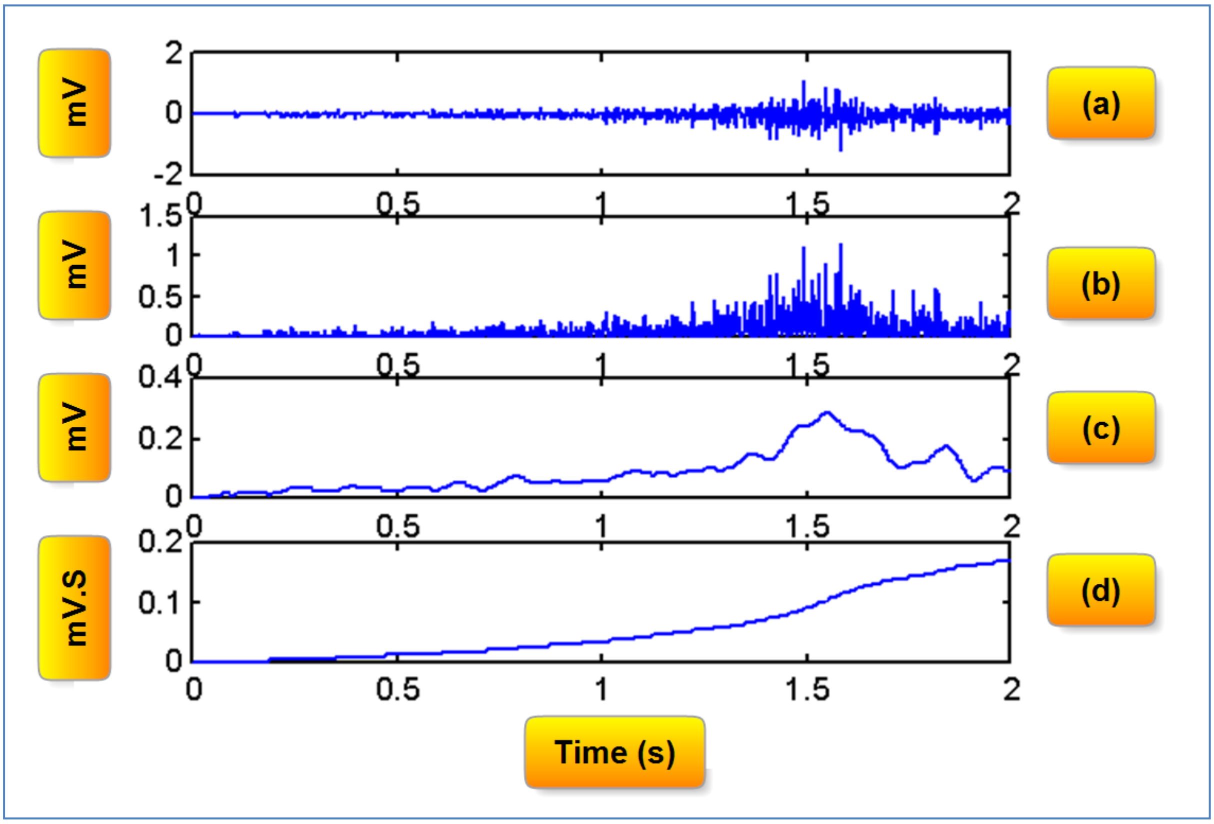

Figure 33: sEMG DSP example

3.6. SEMG ELECTRODES

The material selection for the electrodes is important for impedance matching. The number of electrodes will also be discussed, as well as the placement of the electrodes based on the application. sEMG electrodes function similar to ECG and EEG electrodes.

3.6.1. ELECTRODE TYPES

Electrodes are disk-shaped metal alloy plates supported by a flexible plastic patch. The electrode itself is around 6 mm in diameter and is covered by an electrolytic gel to ensure proper contact to the skin. The plastic support has a sticky surface to stick to the patient's skin. There are also multi-electrode patches available. The types of electrodes include passive and active electrodes [29].

Passive electrodes have a long cable to connect the electrode to an external amplifier [29]. Figure 34 is an example of a single passive ECG/sEMG patch. The cable clips onto the electrode. Active electrodes are similar to passive electrodes, but the amplifier is built into the electrodes' support. Active sensors are popular, as there is a short path between the electrode and the first amplification stage, minimizing noise sensed by the connection between the electrode and the amplifier [29].

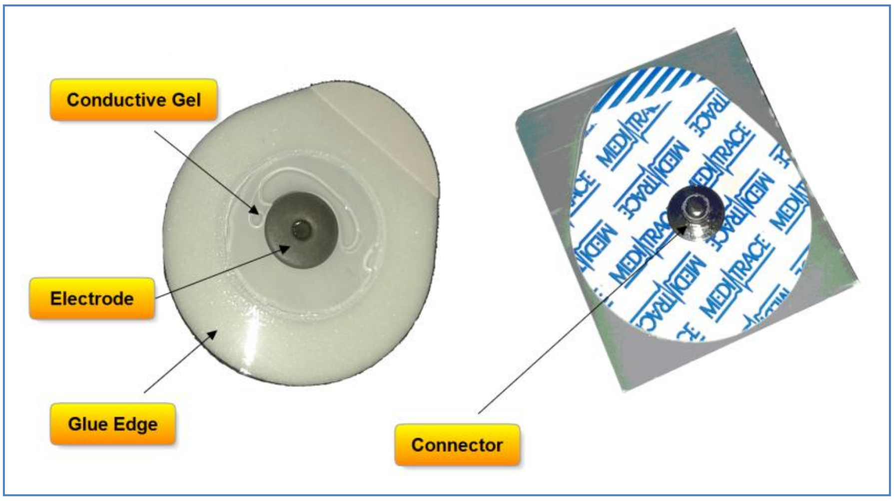

Figure 34: Example of a passive EMG/ECG electrode

3.6.2. ELECTRODE MATERIAL SELECTION

The most popular material selected for surface electrodes is Silver/Silver-Chloride (Ag/AgCl) electrodes [26]. The idea behind the layered electrode is to lower the impedance of the electrode for AC voltages. These electrodes have an impedance of around 5 kΩ at sEMG frequencies (50 - 500 Hz) [44]. Figure 35 illustrates the small signal equivalent circuit of the Ag/AgCl electrode.

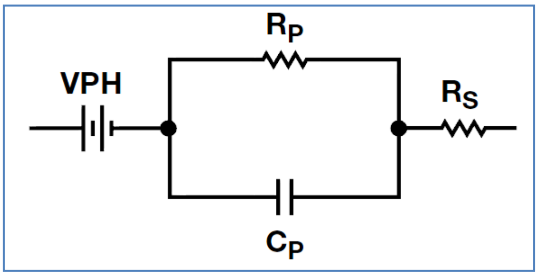

Figure 35: Circuit model for bio-potential electrode [44]

The VPH component resembles the voltage that appears on a patient's skin due to muscle activity. The electrode circuit model is represented by three passive components. The Cp component refers to the capacitive nature of the layered electrode. This component favours the electrode functionality as a capacitor acts as a DC-block, but allows AC sEMG signal to pass through [18]. The Rp component is the parallel leakage resistance through the junctions inside the layered electrode. The Rs is the serial impedance of the electrode.

The total output impedance of the electrode is given by

$$Z_{electrode} = Z_{Rs} + \frac{Z_{Rp} * Z_{Cp}}{Z_{Rp} + Z_{Cp}}, \quad 3\text{-}6$$

where Z_{Rp} is the impedance of the R_p component, Z_{Cp} is the impedance of the capacitor component C_p, and Z_{Rs} is the impedance of the R_s component.

Other electrode variations include flexible electrodes made from conducting polymers and carbon-filled silicone [29].

3.6.3. NUMBER OF ELECTRODES

The external electrodes are placed on a muscle to measure the motor unit action potential trains (MUAPTs) inside the muscle. By placing one set of electrodes on a muscle group, the general MUAPTs inside the muscle are recorded, which is sufficient, as the muscle fibers inside a muscle group are connected in parallel.

In some cases, multiple electrodes are used to capture an EMG signal. This signal is decomposable into individual MUAPTs, which is useful in medical studies to detect diseases. Figure 36 illustrates how an electrode array of four sEMG electrodes is used to capture and decompose individual MUAPTs. Figure 37 explains the internal circuitry of an electrode array, showing the differential measurements taken between each of the four electrodes [45]. The differential inputs are used to decompose single MUAPTs.

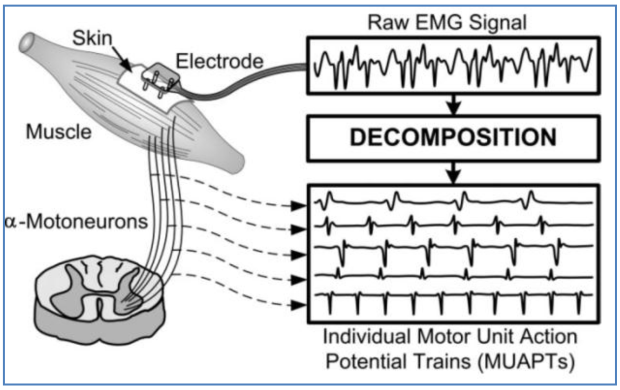

Figure 36: Pictorial outline of the decomposition [45]

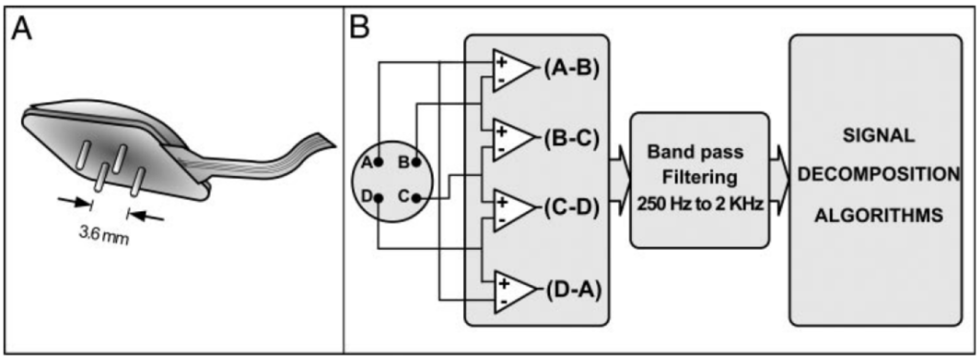

Figure 37: sEMG sensor 4-pin array [45].

3.6.4. PLACEMENT OF ELECTRODES

The most basic set of electrodes consists of at least three electrodes. Refer to figure 38 for the electrode placements.

DIFFERENTIAL ELECTRODES - The potential difference occurs over the length of a muscle. A set of two electrodes should be placed over the length of the muscle for a single muscle group measurement, as illustrated in figure 38. Note the frequency dependency of the electrode placement.

REFERENCE ELECTRODE - Any bony joint contains minimum noise, as these regions in the human body have the minimum muscle and nerve activity. Any bony joint in the human body is therefore a suitable region for a ground reference electrode placement (GND_{ref}).

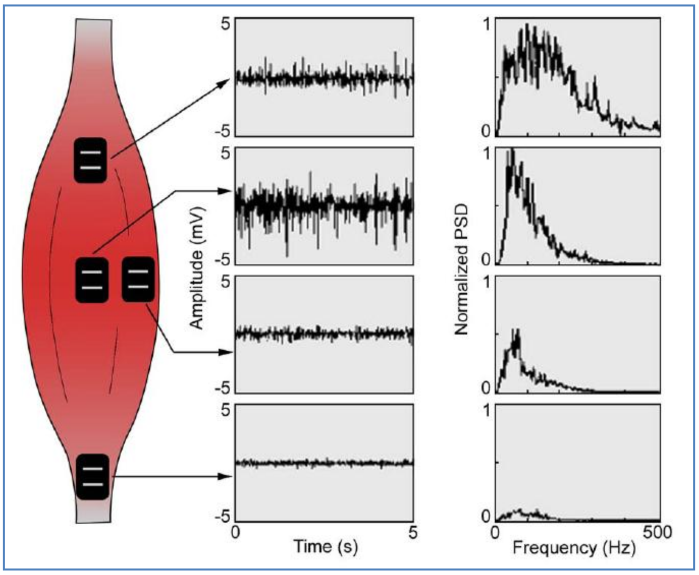

Figure 38: Frequency dependency on the differential electrode placement [46]

3.7. THE MATLAB®/SIMULINK® INTERFACE

The first decision that is needed to be made is whether an analog or digital connection will be made between the PC and the sensing platform. The Matlab®/Simulink® environment contains the following as standard analog input and output functional blocks:

- Analog Audio - The "audio in" and "audio out" functional block utilize the PC's sound card to convert the analog signal into digital format.

The Matlab®/Simulink® environment contains the following as standard digital input and output functional blocks

- Serial communication – The "serial send" and "serial receive" functional blocks utilize the serial port of the PC (also known as a COM port or RS-232 port)
- Transmission Control Protocol (TCP) – The "TCP send" and "TCP receive" functional blocks offers UDP communication between various PCs.
- User Datagram Protocol (UDP) – The "UDP send" and "UDP receive" functional blocks offers UDP communication between various PCs
- Controller Area Network (CAN) – This protocol is mainly used in vehicles.

The analog audio interface is not a preferable choice because the quality of the digital signal inside the Matlab®/Simulink® environment is dependent on the quality of the sound card inside the PC. Because audio levels and quality differs between various sound cards, any of the digital interfaces are preferred.

Between the digital interfaces, the serial communication would be the simplest and least expensive interface to implement. All peripheral devices are designed to be “plug-and-play”. To simplify the design in terms of connections and cost of a power supply for the sensing platform, USB powered sensing platform will be designed, with a built-in serial-to-USB converter.

Microcontrollers with USB functionality might look expensive, but the addition of a microcontroller to the design allows the platform to be used in future as a standalone unit. As an example, should the developer/researcher want to implement the control algorithm directly on the sensing platform, and move away from using a PC in the control loop, this could be a possibility. The USB design would cater for Notebook computers, as they do not have RS-232 ports (DB-9 connectors).

3.8. CONCLUSION

The muscle model could be useful with the assumption that concentric muscle contractions are used and the elastic elements are treated as linear spring elements. The electrode model and muscle model could be combined with the existing sEMG system components to finalise the hardware sensing platform. Care is taken when the hardware design is finalised and implemented, taking these factors into consideration when selecting components for the circuit design and PCB layout to minimise noise and interference. This is necessary for the reliability of the sEMG sensing platform.