CHAPTER 2: LITERATURE SURVEY

2.1. INTRODUCTION

A question that emerged from the introduction chapter is how to manage research in a multidisciplinary field and to find connections to solve the biomechatronic problem. This section deals with the multidisciplinary issue. A general investigation of HMI is done to understand how HMI function, and to create a mind-map of the HMI's available for powered prosthesis. The EMG concept is introduced and the reasons are given why this HMI is chosen. An overview of how EMG systems function is investigated. This is followed by the way antagonist muscles inside a joint function. This is required to ensure the problem is approached correctly to find an effective solution for future research. This chapter concludes with a discussion of the limits of existing EMG systems in terms of proportional control, to ensure that the sEMG sensing platform developed will have proportional control capabilities. The final section deals with the ethical issues around HMI research.

2.2. BIOMECHATRONIC RESEARCH

Firstly, the issue of multi-disciplinary field of biomechatronics is dealt with, as biomechatronics is a mixture of electronic and mechanical engineering as well as the medical field. Biological systems are seen as “biological black boxes”, and by following a systems approach, design specifications are revealed by the analyses of biometric and biomimetic properties of any biological system [9]. It is believed that the extent of biomechatronic designs is a reflection of the designer's interest in biology and his/her keenness to consult biologists for information [16-17].

The idea to “learn from nature” is understood and proven continuously, but it seems that there is a constant deviation from this idea. Motivation for an engineer lies in the personal satisfaction in the successful realisation of a solely personal effort. Satisfaction should be gained through taking credit for the correct questions asked to persons (e.g. biologists) involved in the study. This is the mind-shift engineers have to make to manage biomechatronic studies (as well as any other multidisciplinary project) correctly [16].

It must be established exactly how much biological detail is required to be able to create an HMI for control prostheses. The information interface requirements must be established in terms of transfer rate between systems. The communication type, for example single-way or two-way communication is also important to cater for the application [17].

Systems engineering is a tool used to manage the analysis and design of systems [18] that fits into any engineering development life-cycle [19]. This process follows a “black box approach” as it focuses on the analysis of the system, before any design process takes place, since solution finding requires understanding of problems. The bio-inspired field of biomechatronics implies that the study starts with biometrics and biomimetics, moving towards engineering techniques with the knowledge gained from the biological study.

2.2.1. BIOMETRICS

Biometrics is the science of gathering, measuring and statistically analysing biological data. It includes studies of facial patterns, hand measurements, fingerprints, voice patterns, and retina and iris measurements [20]. Biometric studies have a list of important parameters to describe any function or feature inside the human body [21-22]. The important features used to describe human features used for prosthesis control are discussed in this section.

Universality is the quality present in every human being and proves identical without exception. An example of universality is the fact that every person has a nervous system, and EMG produced in healthy muscles.

Any feature that could be used to distinguish persons, such as fingerprints is described by the uniqueness quality. This quality is not favourable in this study, as variability in body type affects sEMG signal quality.

Collectability is the description of how easy it is to gather information on a feature/function on a person, e.g. how difficult it is to take a thumb print vs. how difficult it is to read thoughts of a person. Fewer issues are associated with sEMG than iEMG, therefore more preferable.

Performance refers to the accuracy, precision or power of any human feature/function such as running speed. Typical human hand performance would be described by movement, softness and imprecision.

2.2.2. BIOMIMETICS (BIOMIMICRY)

Biomimetics is any man-made process, substance, device, algorithm or system that uses techniques from nature to replace nature, or to perform any non-nature-related function [22-23]. A good example would be an artificial neural network (ANN) which is a functional mimic of a human-brain, or the design of an artificial hand to mimic a natural hand and cover an amputation. The measures used to rate the success of biomimetic devices/processes are discussed in this section.

The accuracy of the prosthesis refers to the success of the device has to interpret the patient’s intended gesture correctly.

The term “precision” is a relative term to describe people’s gestures, as people are imprecise. It is expected from a device to function with exact precision. The question is rather: Does the device mimic these imprecise movements exactly?

The Robustness of technology used refers to the durability and performance. Robustness describes how long will the device last, and how well does the device tolerate any environmental factors such as electromagnetic interference (EMI).

Acceptability is the psychological degree of approval of a technological device. Circumvention is the measure that indicates the substitute’s user-friendliness compared to the natural version of the body.

2.3. BIO-INSPIRED DESIGNS: ADVANTAGES AND DISADVANTAGES

Biological systems cannot be seen as single-function systems, since in nature, an organism’s survival depends on its multi-functionality. Consequently, it is important to understand the system as a whole [23]. Nature evolves to solve biological problems in a certain environment; therefore the generalisation of solutions might not be the best approach in the effort to “learn from nature”.

Biology has its strength and weakness. Identifying the problem correctly from an engineering viewpoint, before seeking for any solutions from nature, will ensure that the correct choices are made in biological inspired projects. To benefit from the strength from various biological techniques (including the existing synthesized techniques) is also good practice. Biomechatronic research follows a repetitive cycle in which principles are taken from nature and transformed into engineering solutions. The problem is that biological inspiration does not automatically imply that the biological side of biomechatronics is understood.

2.4. BIOMECHATRONIC PROBLEM SOLVING

Although biological organisms differ from engineering designs, the common ground between the two domains is the abstraction of functions and interfaces within each domain. Any biology-inspired engineering design, with the function of imitating nature, is referred to as biomimetic design or biomimicry [24].

The biomimicry process starts with a biological need/problem. The inspiration emerges from observation of nature and the systematic processing of information gathered from biologists. A different approach would be to see the biological system from an engineer's perspective as a functional black-box. A black-box approach means that the designer does not focus on the detail inside the process box, but rather on the relationship between inputs and outputs. This method allows a problem to be simplified by breaking it down into manageable sub-problems.

The second step is to perform a functional decomposition of the biological system to identify the characteristics, which need to be imitated using engineering techniques. This is done by identifying the interfaces that exist between each block, before looking for parallels in the engineering domain to solve the problem.

As illustrated in figure 4, two design approaches are identified, namely the direct approach, and the analogous approach. In the direct approach the functions of the biology domain are mapped to functions within the engineering domain. This is the less preferable approach as it may result in functional duplication in some cases. The analogous approach is the process in which the abstraction of functions is done, using analogous reasoning to optimise the solution by looking at the overall biomimetic goal, rather than treating the functions individually.

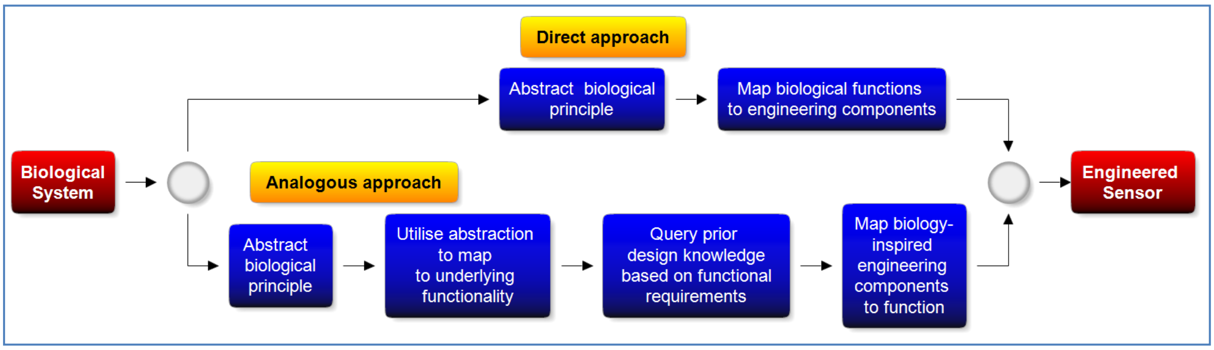

Figure 4: Approaches to biology-inspired design [24]

2.5. HUMAN-MACHINE INTERFACE (HMI) RESEARCH

The human-machine interface (HMI), also called Brain-computer interface (BCI), is a communication channel made available for a prosthetic device to gain information from human nerve and/or muscle activity.

Two main HMI methods exist. The first is the invasive methods, which means that some sort of surgery is involved to implant sensors, while the second non-invasive method group requires no medical procedure. As invasive methods involve the implant of devices underneath the skin, the material selections for these devices are important as not to react with tissue [25]. Non-invasive sensors are easily attached or removed from a patient as they are attached to the skin of the patient which requires no surgery.

Although non-invasive methods seem to be the logic option for non-medical researchers, currently, invasive methods are still superior as they provide more information. Invasive sensors function more accurately, as they are less affected by external noise than non-invasive methods [26]. The available HMI technologies are explained in detail in Appendix A.

No method is superior in all aspects, but the latest trends in HMI involve research mostly on invasive methods [27]. The reason is that invasive methods remain superior to non-invasive methods in terms of functionality and aesthetics [28].

The muscle control system is similar to engineering control systems. It has input, process, output and a feedback component. The feedback loop communicates information back to the process section to control the muscle movement. Prosthesis control design is based on an analogous approach of this biological muscle control system.

2.6 HUMAN ANATOMY IN MUSCLE CONTROL

The anatomy in muscle control involves the nervous system, and the muscle system. The nervous system includes two sub-systems, namely the Central Nervous System (CNS) and Peripheral Nervous System (PNS). The anatomy of a nerve cell is described, followed by a description of the CNS and PNS. The muscles work in antagonist muscle pairs, and the HMI has to be able to sense both muscles' activity to extract information about a single joint.

2.6.1. NERVE CELLS

Nerve cells consist of inputs (Dendrites) and an output (Terminal branch). The nucleus is the largest part of the cell. The axon is the longest part of the nerve cell, and is an electrical extension, connecting the nucleus to another remote part of the human body. Figure 5 shows a diagram of a nerve cell and the terminology [29].

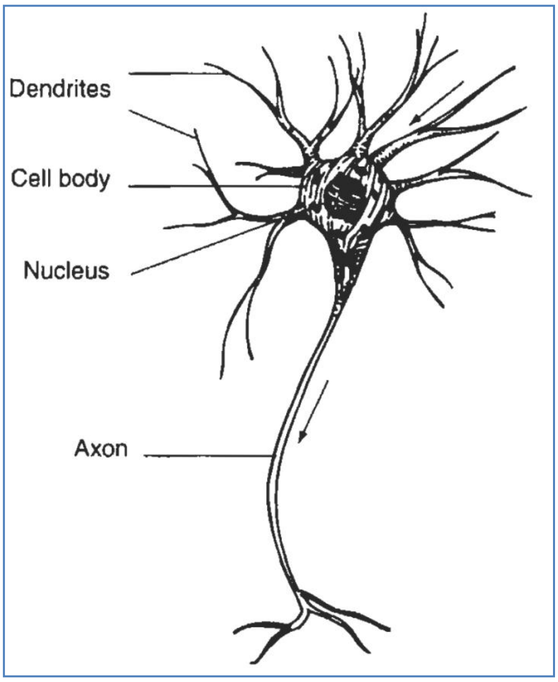

Figure 5: Basic nerve cell terminology [30]

2.6.2. CENTRAL NERVOUS SYSTEM (CNS):

The CNS includes the brain and spinal cord, with their location illustrated in figure 6. Any desire to perform voluntary muscle action originates in the brain and is sent into the spinal cord (the CNS pass input through spinal cord to the PNS). The brain not only controls muscle motor behaviour, but receive feedback from sensory organs (feedback is sent from PNS to CNS via the spinal cord). The spinal cord is the principle route all nerves follow to and from the brain [29].

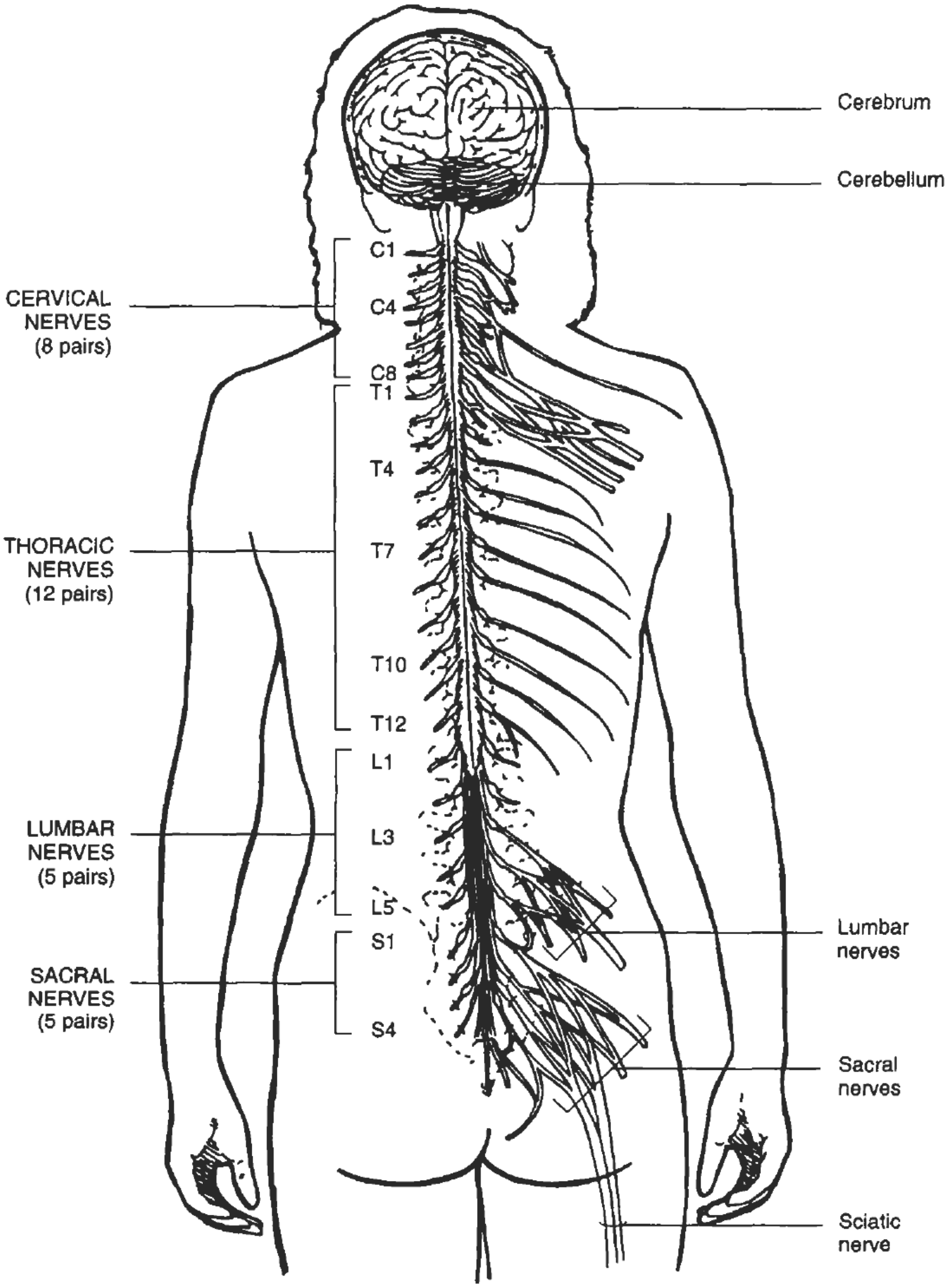

Figure 6: Parts of the Central Nervous System (CNS) [30]

2.6.3. PERIPHERAL NERVOUS SYSTEM (PNS)

The PNS is located in the spinal cord, and forms a closed loop with sensory (afferent) axons and motor (efferent) axons and the interneurons found inside the spinal cord [29]. An example to demonstrate the fact that the CNS receives feedback without being part of the processing of muscle movement is the classic "reflex arc" demonstration, shown in figure 7 [30].

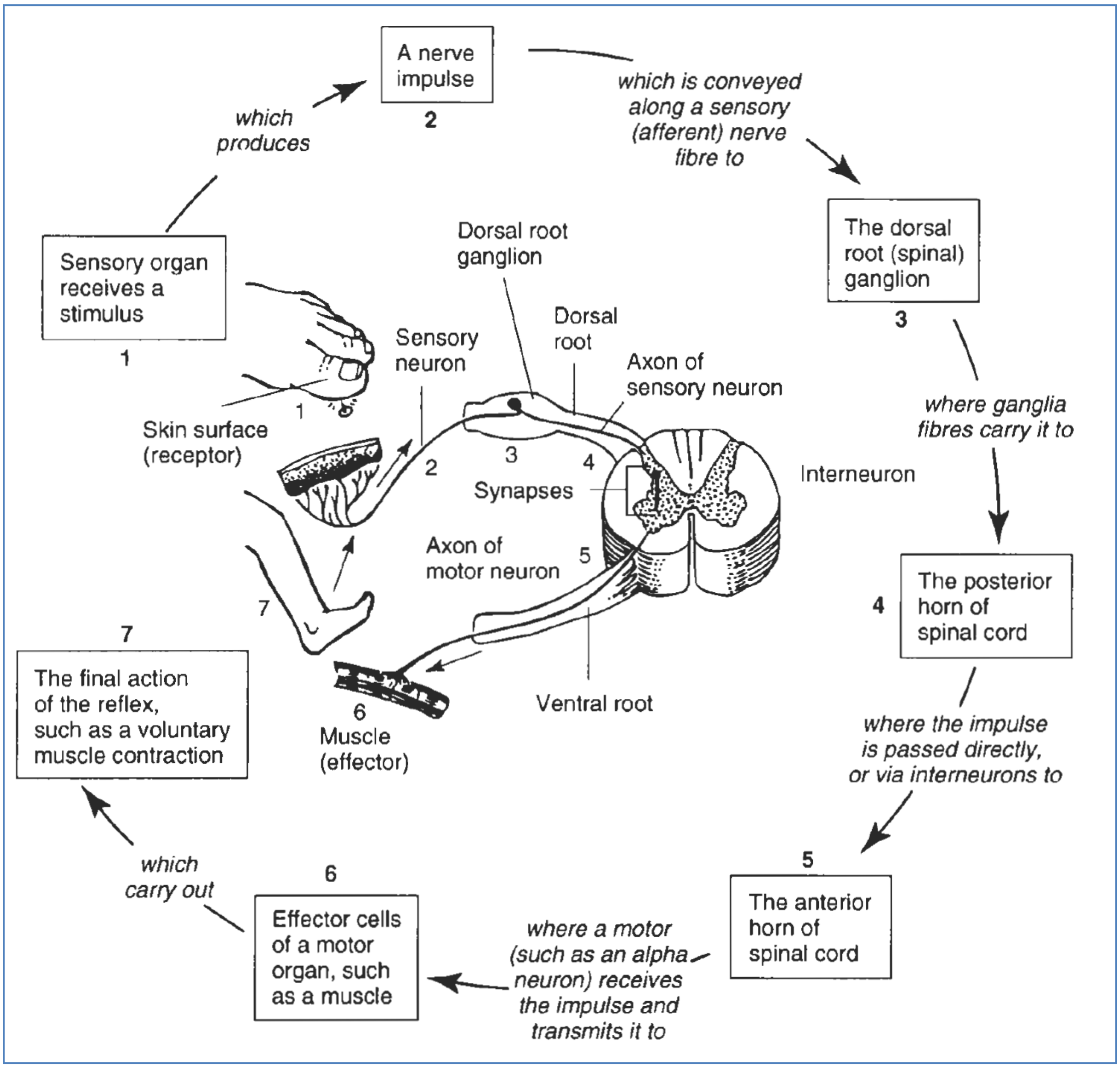

Figure 7: Reflex arc demonstration of the PNS [30]

To conclude, a functional block diagram in figure 8 shows the nervous system functional layout [29]. A two-way communication channel connects the CNS and PNS. The CNS overrides the PNS with voluntary movements, which means that the PNS are required to respond to the given instruction. The PNS is the natural nervous control loop that processes input and output, but communicates to the CNS the feedback from sensory nerves.

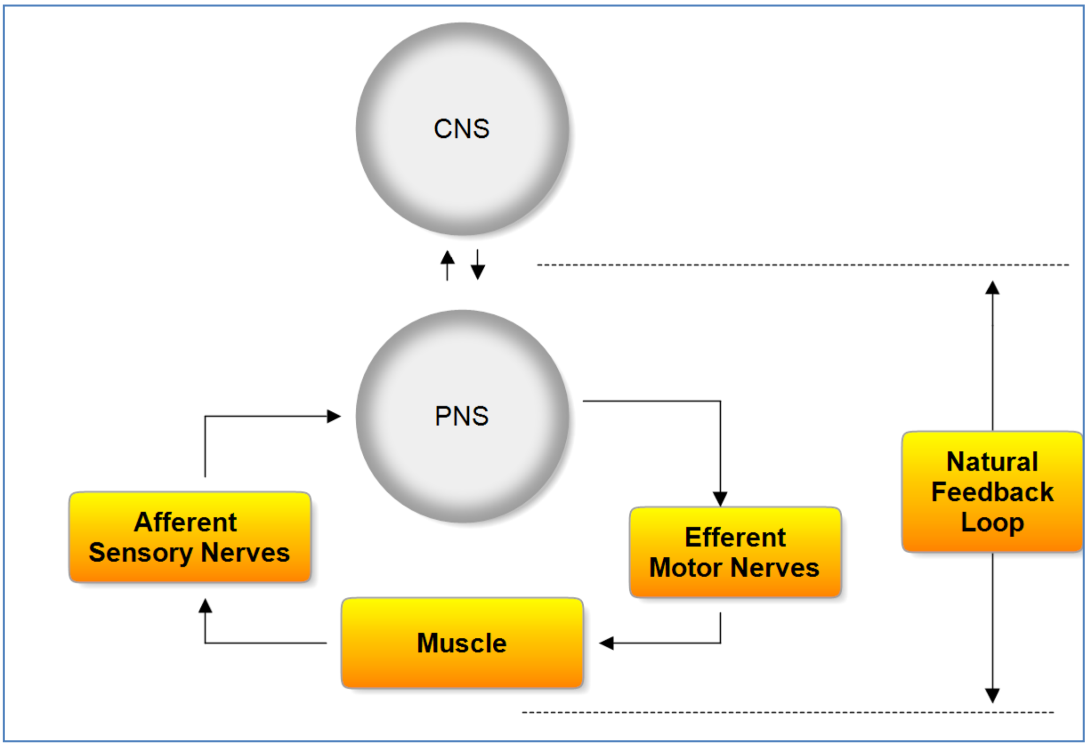

Figure 8: Interaction between CNS and PNS

2.7. NATURAL INPUT METHODS INSIDE THE HUMAN BODY

As the project title suggests, the project involves a sensor device. The biomimicry method is used to design a sensor. The first step is to abstract the functional blocks of the input sensors involved in muscle control.

The main sensory nerve groups and their purposes are listed below [24]:

- Extroreceptors (Sense) - all sensors able to sense surroundings, such as vision, smell, taste, hearing and touch.
- Proprioceptors - the name given to all voluntary feeling inside the body such as muscle tension.
- Interoceptors – The sensory organs required to manage other involuntary processing such is intestine function or heart rate, without the person knowing of the sensors.

It is believed that engineers are more familiar with bio-sensors than they think. Bio-sensors have a transducing capability, similar to that of an electronic transducer. The sensor sends a coded version of the position, change in position or tension to the nervous system. The nervous system then decodes, recognises and responds to the specific input.

Most extroceptors are already studied by engineers, and are described as chemo-, electro-, magneto-, mechano-, photo-, and thermo-receptor types, named after their transducing functionality [24]. The Proprioceptors found inside muscles are Golgi tendon organs and muscle spindles, and are used in the muscle feedback loop by the PNS. Figure 9 presents the sensory nerves found in muscles. Golgi tendon organs are in series with muscles to measure tension. Muscle spindles are parallel to muscles to measure muscle length and changing rate in length. Therefore a person can perform basic actions without visual feedback [29].

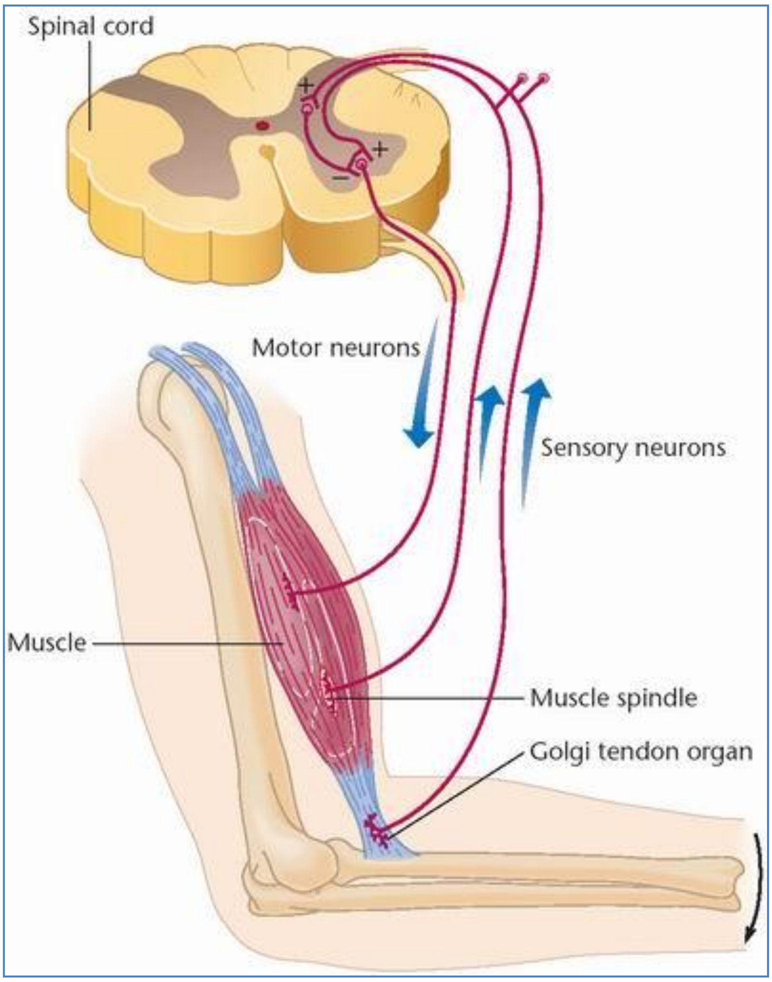

Figure 9: Sensors found in the PNS muscle control loop [31]

2.8. ARTIFICIAL INPUT METHODS

From figure 9, it is clear that the possibility for an HMI is restricted by the ability to measure either muscle activity (how much effort a muscle exerts), or a combination of the motory and sensory nerves (the information communicated through the natural feedback loop).

Figure 10 shows previous work conducted in terms of prosthesis control, and illustrates the functional blocks of the artificial system's interaction with the amputee. Also included in the figure is a summary of the various HMI technologies available for prosthesis control.

In figure 10, the human brain and spinal cord blocks resembles the natural CNS loop. The spinal cord together with the motory and sensory nerve blocks completes the natural PNS loop. The input, process output and feedback blocks resemble the artificial components used to complete the natural loop damaged by the amputation. The HMI techniques are divided into invasive and non-invasive techniques, with a description of each method in the figure.

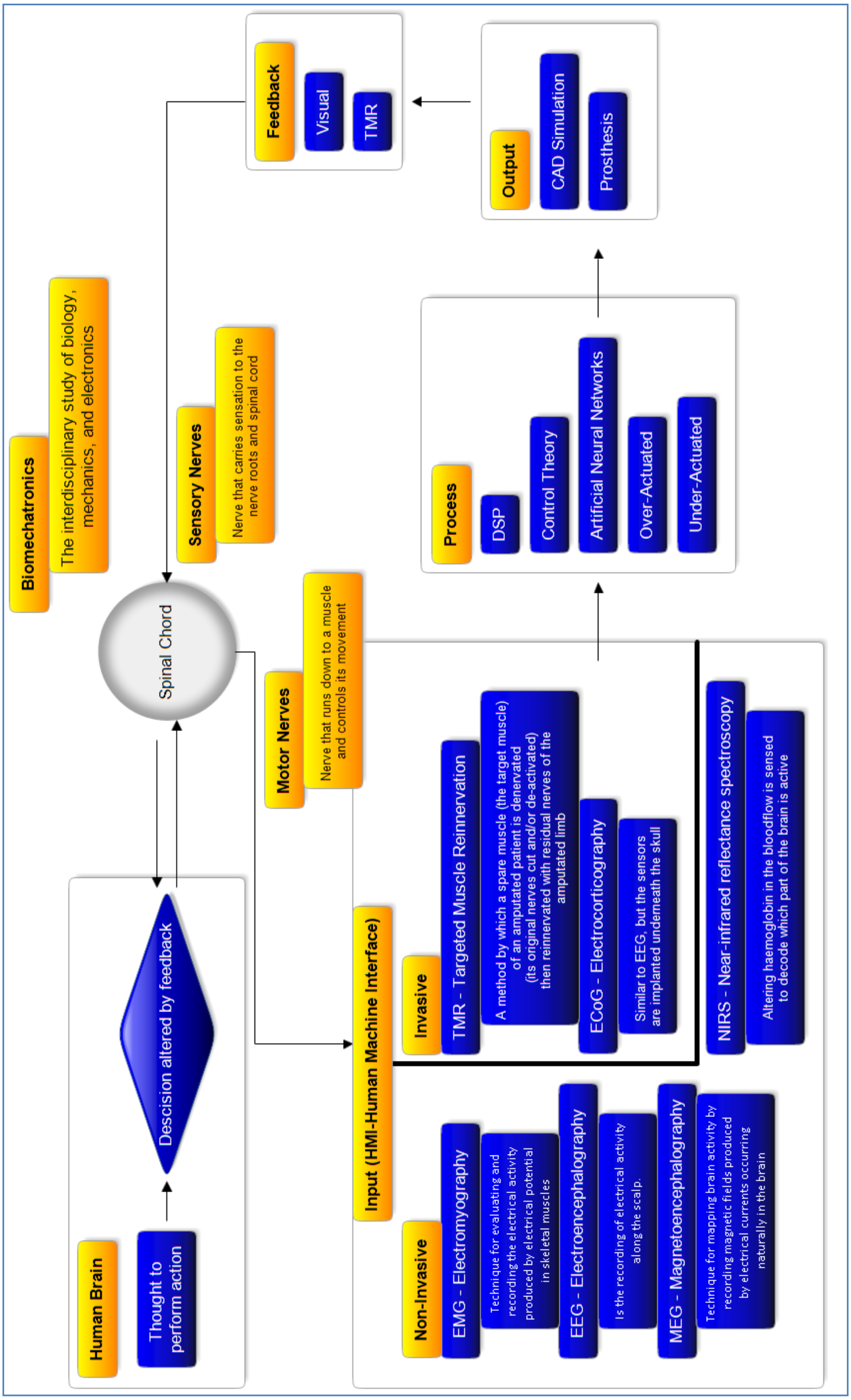

Figure 10: Prosthesis control research summary

2.9. SEMG CHOICE FOR HMI

According to literature EMG-based sensors are preferred for upper limb prosthetic control applications. The prior incentive for this project is academic purposes, and the possibilities of developing a complete usable hand that has the ability to mimic the movement and actions of a natural hand, as well as a resemblance to a human hand is considered.

EMG-based control allows the amputee to use original gesture control thoughts to control the prosthesis. This means that the same way the patients used to control their original limb (desire to move their limb with their brain) remains, as the EMG senses the remaining muscle actions.

Figure 11 illustrates the parts of the natural system which are removed by the amputation, and where the EMG-controlled prosthesis can assist. It is also an illustration that the missing body part is replaced by the EMG-controlled prosthesis. The EMG-sensor senses muscle activity and decodes the signals into recognisable control information for the controller to use. Three main configurations exist. The first is amplitude-coded control, the second is rate-coded control, and the last is a feature extraction based control [25].

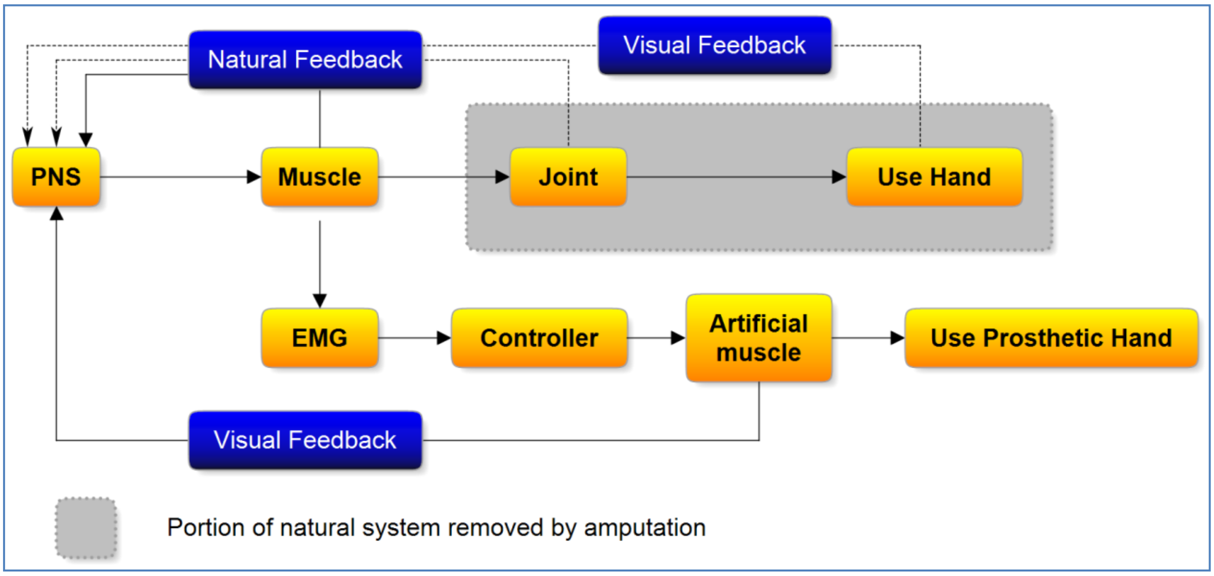

Figure 11: Natural and EMG-based control

When selecting an appropriate input sensor technology, aesthetics (appearance) and ergonomics (how the design unites and interacts with human body dimensions and movements) will influence the selection process.

2.9.1. NON-INVASIVE SENSOR CHOICE

Non-invasive sensors require no medical specialists to perform experiments. Technology improves at a rapid rate, resulting in frequent device upgrades. Invasive methods are avoided as upgrades would mean surgery or the implant of a sensor. People are scared of needles and surgery, and would avoid any method that involves these, as far as possible. The choice to proceed with research in a non-invasive input sensor technology is based on these facts.

2.9.2. MOTIVATION FOR A SEMG SENSOR

The motivation for this study is driven by the possibility to improve the quality of life for people with amputations. The sEMG technique is chosen above the remaining non-invasive techniques is due to aesthetic reasons, and the ease of implementing the technique.

AESTHETIC AND ERGONOMIC REASONS

sEMG, EEG, MEG are currently the matured non-invasive techniques to sense brain, or muscle activity. EEG and MEG are methods that involve sensors being placed on a patient's scalp, which is aesthetically unpleasant. From Maslow's' theory of human motivation, a person's self-esteem is not controlled solely by his/her independence and freedom, but also by their recognition and acceptance by society [2].

Figure 12 is an example of an EEG cap. Although it may look futuristic, patients don't want to wear the electrode cap on their scalp. sEMG sensors are only placed in the area of the patient's muscles where the prosthesis is already fixed to.

Figure 12: Example of an EEG cap

IMPLEMENTATION

Smith [26] promotes the use of EMG as HMI, rather than other methods, due to the ease of implementation and the required time to implement the HMI. Neural sensing is not possible through non-invasive methods close to muscles, as muscle artifacts are usually large (EMG signal level amplitudes are around 1000 times larger than EEG signals'). This is the reason why EEG could only be performed on a patient's scalp, and not on a patients arm.

2.10. EMG CONCEPTS

Before a sEMG platform could be developed, a study of the sEMG HMI method is initiated to create an understanding of the requirements.

2.10.1 NERVE FUNCTION

The human body transmits signals by means of electric current. Neither going into elementary electromagnetic theory, nor physiology, the basic idea around the human CNS will be discussed. Thoughts originate in the brain, and the signals are transported via the axon (from the spinal cord) to the target muscle. The nerve axons consist of Sodium-Potassium ion chains (called a Sodium-Potassium pump) to pass the electrical signal to the target muscle [29]. The rise (depolarisation) and fall (repolarisation) of electrical potential inside any cell, called the action potential, results in a rapid ion exchange which occurs across the cell membranes. Figure 13 illustrates the waveform generated in an action potential. This action potential may last from 1 ms to a few hundred ms [26].

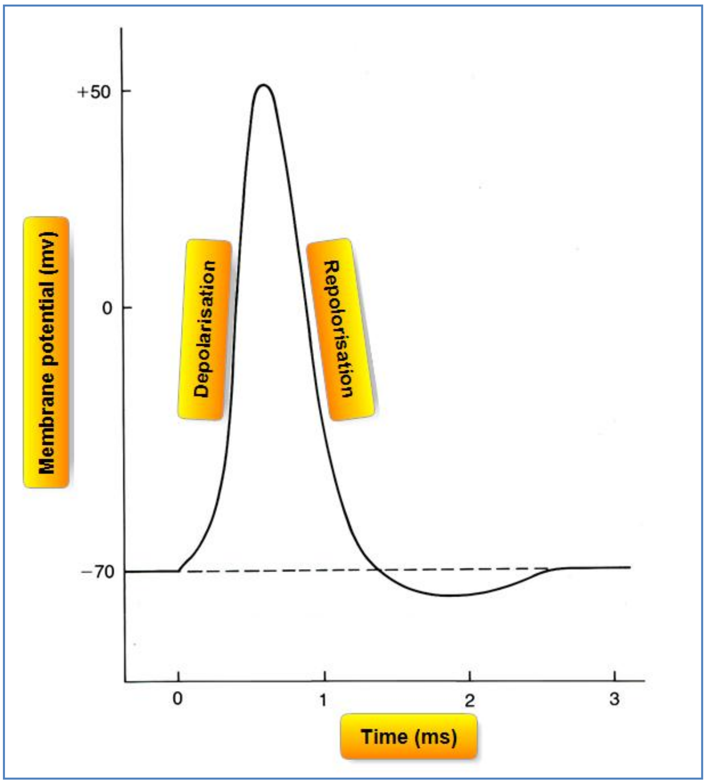

Figure 13: Typical action potential waveform [26]

The Somatic Nervous System (SNS), which is involved in voluntary muscle control, has nerve cells that originate at the spine, and ends up at muscle fibers inside a muscle. The moment an instruction (action potential) reaches the muscle fibre the muscle fibre contracts, resulting in a potential difference across the muscle fiber. The anatomy of the human muscle is shown in detail in figure 14. A muscle fiber is a single strand inside the muscle group.

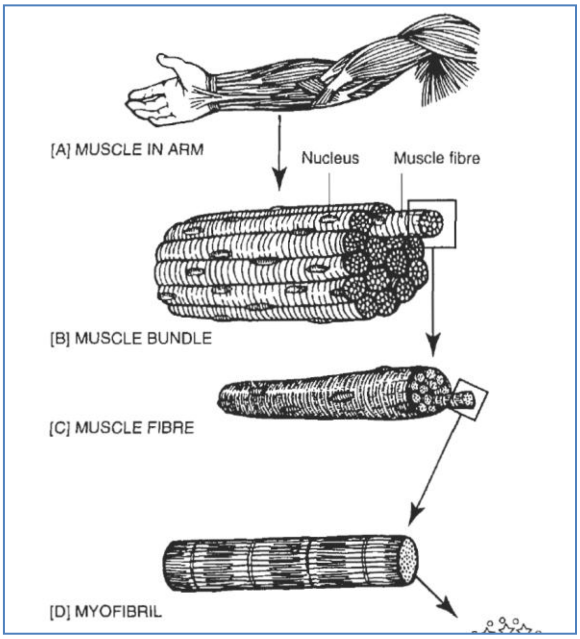

Figure 14: The anatomy of the human muscle [30]

An EMG signal measures the multiple potential differences from the group of muscle fibers. The sEMG sensor has to sense this potential difference through the patient's skin. Referring to figure 15, the potential differences that appear across the muscle when the muscle contracts, is measured, using an instrumentation amplifier.

$$V_{out} = V_{E1_e} - V_{E2_e}, \tag{3-1}$$

Where V_{out} is the instrumentation amplifier's output, V_{E1e} and V_{E2e} are the voltages measured across each of the pair of electrodes ($E1_e$ and $E2_e$) and the ground reference.

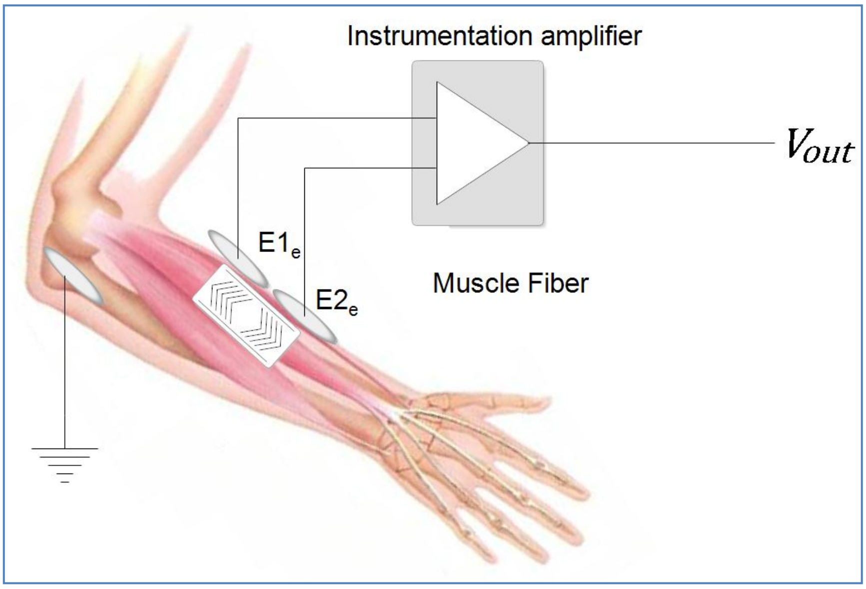

Figure 15: The principle of EMG signal sensing

The differential amplifier's output would typically show the tri-phase responses of a single MUAPT in an iEMG electrode measurement, as shown in figure 16. This response is sensed as the MUAPT travels along each of the muscle fibers. The actual voltage for a group of muscle fibers would appear differently, and is discussed in the next section.

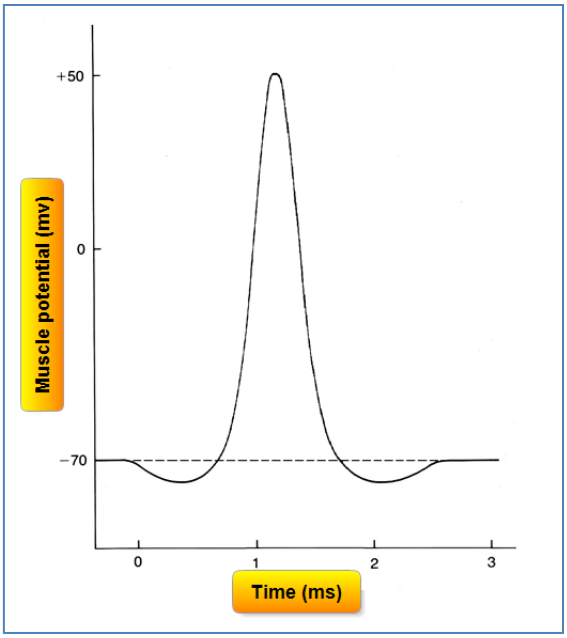

Figure 16: Response of a single MUAPT [26]

2.10.2. VOLTAGE RANGE OF SEMG SIGNALS

The EMG signal ranges in frequency from 1 to 2000 Hz. The human body acts as a low-pass filter, passing only frequencies between 5 Hz and 500 Hz to the skin. It is impossible to sense nerve signals with non-invasive methods close to muscles. The muscles produce noise at amplitudes a 1000 times larger than the nerve signal amplitude [26]. The sEMG signal range is between 1uV-5uV [26], [29]. As the muscle fibers' MUAPTs occur randomly, the actual EMG doesn't look like the tri-phase response of a single MUAPT. Figure 17 illustrates a typical EMG recording.

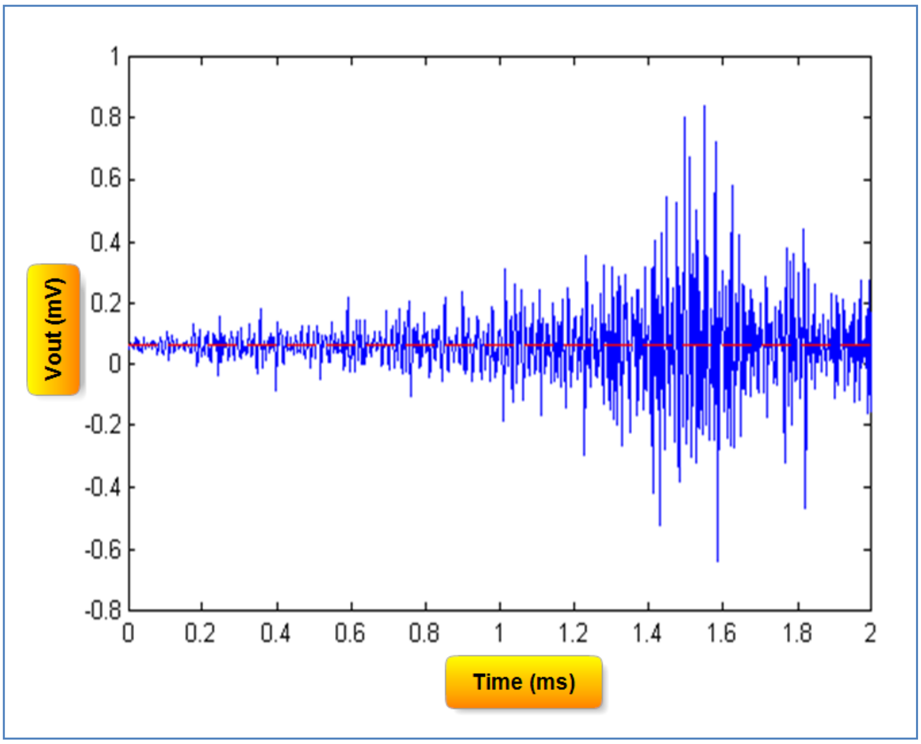

Figure 17: Typical EMG recording example

2.10.3. SENSING OF EMG SIGNALS

To process this small signal into a usable signal, it has to be amplified a few thousand times. Instrumentation amplifiers (also called differential amplifiers) are used to detect EMG signals and consist of dual-input amplifiers. Instrumentation amplifiers amplify only the difference between the two inputs, but rejects signals common to both inputs. This measure used to describe the instrumentation amplifier's performance is called common mode rejection ratio (CMRR) [7], [32]. Instrumentation amplifier choices are therefore limited especially those with good CMRR, the correct band-width and input resistance specifications.

The electrodes used to sense the sEMG and iEMG are connected to the instrumentation amplifier's input. Most of the existing sEMG systems use two sets of sEMG sensing electrodes, connected to a dual-channel EMG signal amplifier and conditioning circuit. The need for a two-channel system is to measure the muscle activity of antagonist muscle groups to decode a single joint movement.

2.10.4. ELECTRODES USED

The electrodes are disk-shaped. It is made of any metal that is non-reactive and non-irritable to the human skin, for example stainless-steel, silver or gold-plated. Electrode fastening methods include self-adhesive, strapped and suction types [29].

The most effective electrodes used are made from AgCl, and very expensive to produce. The AgCl electrodes are specialised sensors as they serve as a high pass filter with very low impedance between the patient's skin and the EMG amplifier [26]. This decreases noise in the EMG system.

2.11. SEMG-BASED PROSTHESIS COMPONENTS

Firstly the components found in a typical EMG recording system are described, followed by the additions required for EMG-based prosthesis control. A typical EMG recording system consists of the component shown in figure 18 and a description of each component follows in this section.

The muscle is the biological part in a patient by which activity will be sensed as input. The muscle generates a small voltage which appears on the patient's skin close to the muscle. The voltages generated by the muscle are in the mV range, but the tissue around the skin has high impedance, resulting in sEMG signals in the µV range.

A set of electrodes (at least three) is placed across a muscle on the skin to sense its activity. Two electrodes sense the voltage generated by the muscle. The third electrode serves as a reference and is connected to any bony joint on the patient, for example the elbow joint.

The sEMG amplifier is an instrumentation amplifier, used to amplify the potential difference across a muscle, but eliminates common noise sensed by both electrodes. The muscle's sEMG signal of a few uV is amplified to a voltage the processor can interpret (typically 3V to 5V).

In most systems, a band-pass filter is used to eliminate any DC-offsets in the amplified sEMG measurements, and serves as an anti-aliasing filter, required for the analog to digital converter (ADC). sEMG signal frequency ranges from a few Hz up to 500Hz. The anti-aliasing filter is chosen to have a cut-off at 500 Hz, as higher frequencies are regarded as noise.

The analog to digital converter (ADC) converts the amplified and filtered analog sEMG measurement into digital format. According to the Nyquist sample frequency theorem for the ADC, the minimum sampling frequency should be at least 1 KHz.

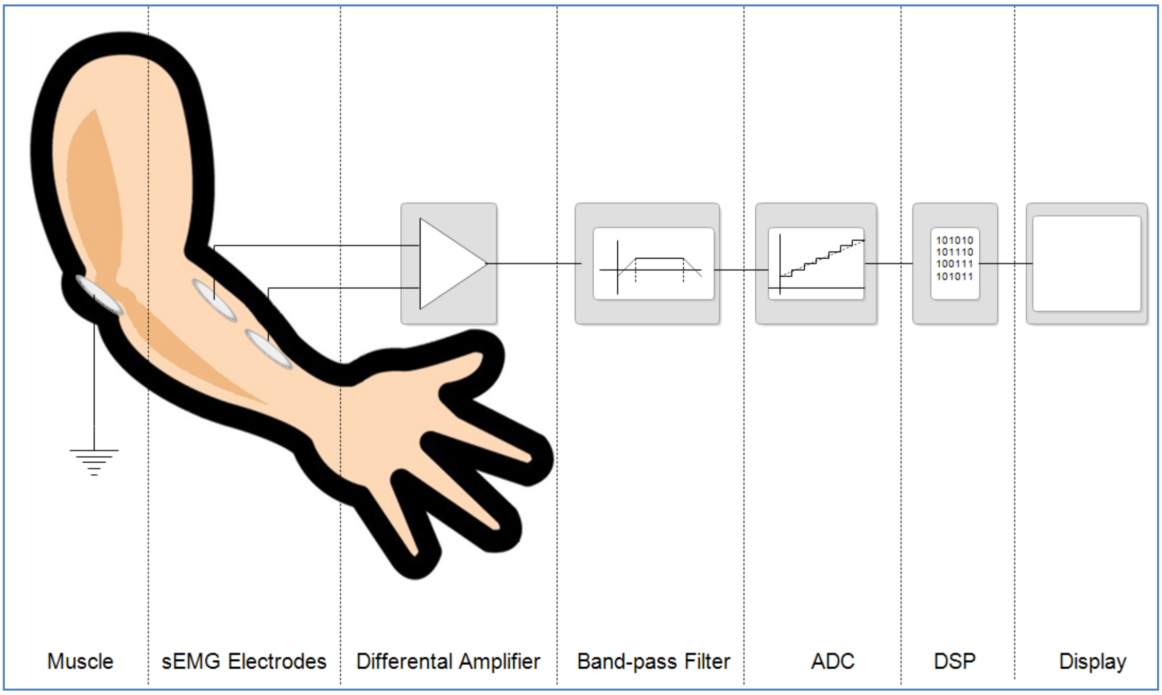

Figure 18: Typical sEMG recording system

The digital signal is processed by the processor. The raw signal is converted into a signal that portrays information such as instantaneous muscle activity or net muscle into useful information, such as instantaneous muscle activity or net muscle activity. The initial use for sEMG was to perform nerve conduction tests used by neurologists to detect diseases in muscles and nerves [26].

In terms of prosthesis control, an sEMG prosthesis control system consists of similar components, with the addition of artificial muscle controller and feedback circuitry. Figure 19 shows a typical layout for a complete sEMG-based prosthesis hand's functional block diagram.

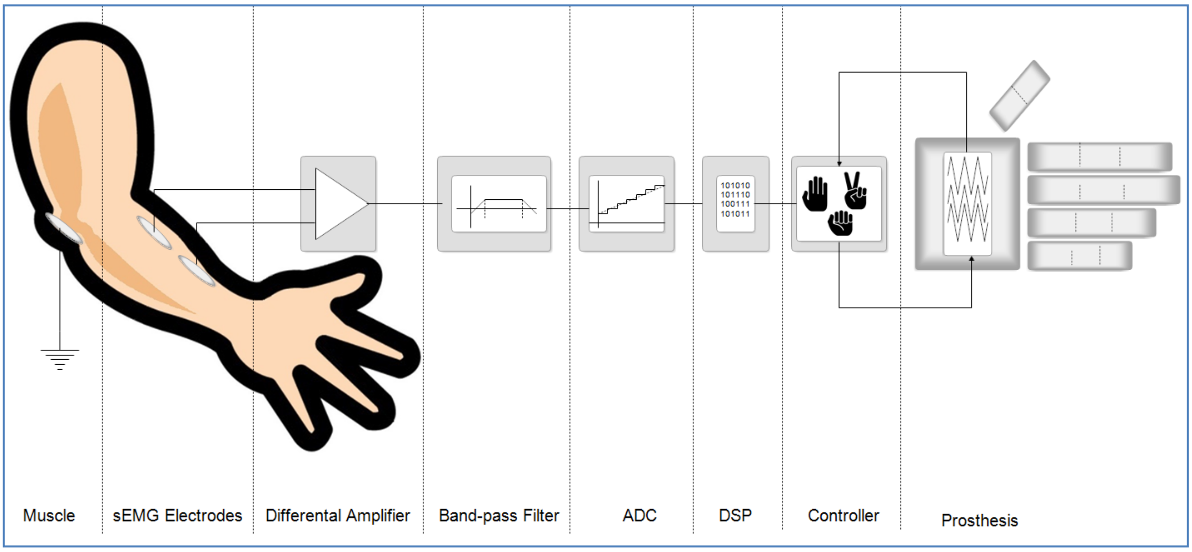

Figure 19: Typical EMG based prosthetic control

2.12. PREVIOUS RESEARCH ON PROPORTIONAL CONTROL ALGORITHMS

As mentioned before, although the proportional control algorithm is not within the scope of the study, the system must have the capability of extracting the correct information from a patient to allow proportional control of a powered prosthesis. To create an understanding of what the control algorithm would require in terms of hardware functionality, ideas around proportional control are studied.

The commercial name for EMG-based control systems is "myoelectric" systems. In the simplest form a myoelectric prosthetic hand/arm consists of a motorised hand powered by a battery and controlled by muscle EMG signals to either open or close the hand. This is usually called digital control since the hand can either be open or closed (1 or 0) as shown in figure 20.

Motion control of prosthetic arms was originally established in 1974 by a group of faculty members and researchers at the University of Utah, led by Dr. Stephen Jacobsen, to commercialise the medical technology developed at the University's Center for Engineering Design. As a result of this University/Industry partnership, the world's most advanced prosthetic elbow/hand combination was developed, the Utah Artificial Arm.

The industry partner is a company called Motion Control, Inc. Motion Control's current president is Harold H. Sears, Ph.D., an alumnus of Dr. Jacobsen's group at the University of Utah [33]. There were a number of developments over the past years that will be briefly discussed in section 2.13.

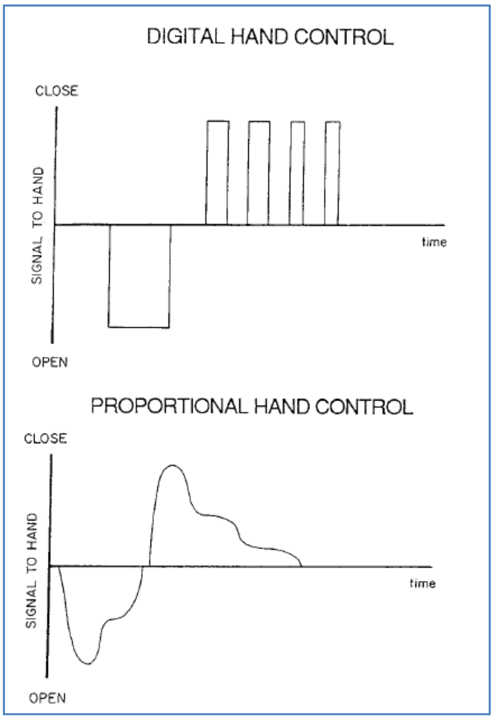

Figure 20:Comparison of control signals generated by "digital" and proportional control

This following section describes the functional capability of various sEMG systems. The three main topologies include amplitude-coded, rate-coded and feature-extraction controllers.

AMPLITUDE-CODED ALGORITHM

Amplitude-coded controllers rely on the existence of a relationship between muscle activity and EMG signal amplitude. The prosthetic controller is designed to perform actions according to decision boundaries mapped in the amplitude level of the EMG signal. A one-channel amplitude-coded EMG-controlled prosthetic is where three regions are defined in the amplitude level of the EMG signal. Figure 21 illustrates the decision boundaries (S1 and S2) for a single EMG-sensor controller.

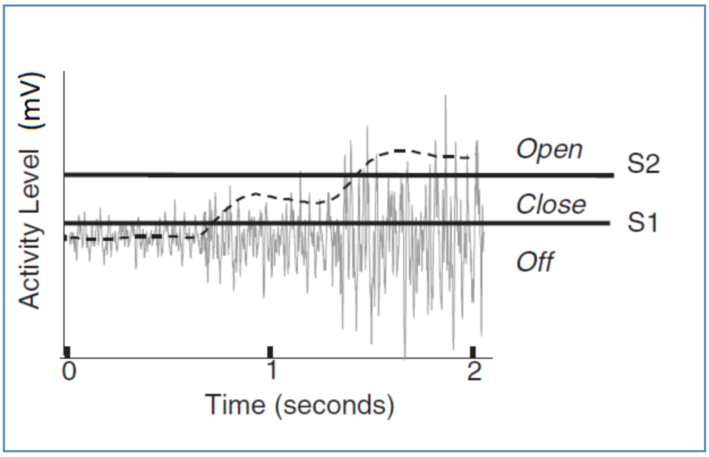

Figure 21: One-channel Amplitude-coded control [25]

In a different configuration, two EMG-sensors are attached to antagonist muscles (i.e. extensor and flexor muscles of the hand in the forearm) to use the natural impulses to open/close the prosthesis. Figure 22 shows the dual-channel EMG signals with the decision regions thresholds (S1 and S2) for the prosthesis control. This controller configuration is more intuitive to use than the previous configuration.

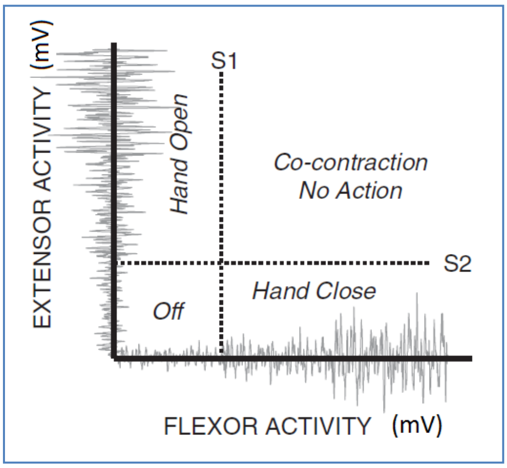

Figure 22: Two-channel amplitude-coded control [16]

RATE-CODED ALGORITHM

This controller uses a single EMG-sensor, and the decision boundaries are defined according to the derivative of the EMG signal. Figure 23 illustrates the method where the change in EMG signal's amplitude is used to perform a predefined action.

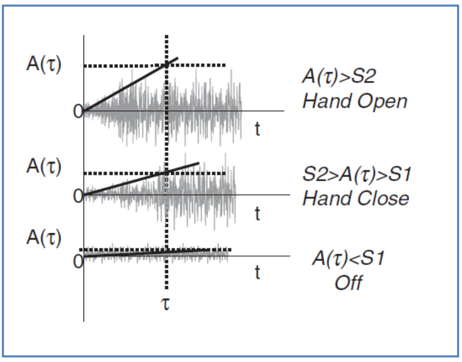

Figure 23: Single-channel Rate coded control [25]

The symbol A is the EMG recording, and τ is the time interval in which the absolute value of the EMG signal is compared to the thresholds S1 and S2.

FEATURE EXTRACTION ALGORITHM

All limbs in the human body require two opposing muscles for control. These opposing muscles are called agonist-antagonist (or antagonist) muscles. Patterns of agonist-antagonist muscles suggest certain gestures.

Gesture patterns are visible in tri-phase responses where the agonist muscle pulls the limb in the desired direction, the antagonist muscle brakes the limb at the desired position and the agonist muscle gives a final pull, similar to the typical oscillation in an under-damped control system [29].

A library of patterns is compiled for the prosthesis' control system to decode and interpret the desired gesture.

Features are extracted from the recorded EMG signal, by comparing the raw sEMG signal to a pattern library. An artificial neural network (ANN) is a popular technique used to recognise patterns from the pattern library and control prosthesis [25]. The pattern library is not always preferable, due to its computational intensity.

2.13. PREVIOUS RESEARCH ON SENSOR CALIBRATION AND CONDITIONING

The raw EMG signal is of little use, and needs to be process into useable information for the control of a powered prosthesis.

2.13.1. UTAH ARTIFICIAL ARM (1981)

The Utah proportional hand control system is shown in **Error! Reference source not found.**. As can be seen the motor voltage varies in direct proportion to the EMG command signal, which is the difference between the two muscle EMG inputs. However dead-bands (notch filters) have been included in the circuit to cope with noise issues. Due to these dead-bands the sensor is not entirely proportional. An adaptive filter is also added after the differential gain. This filter adds a very long time constant of 500 ms lag to the system. This takes care of “jitter” induced by noise, but may cause time delay unacceptable to the user.

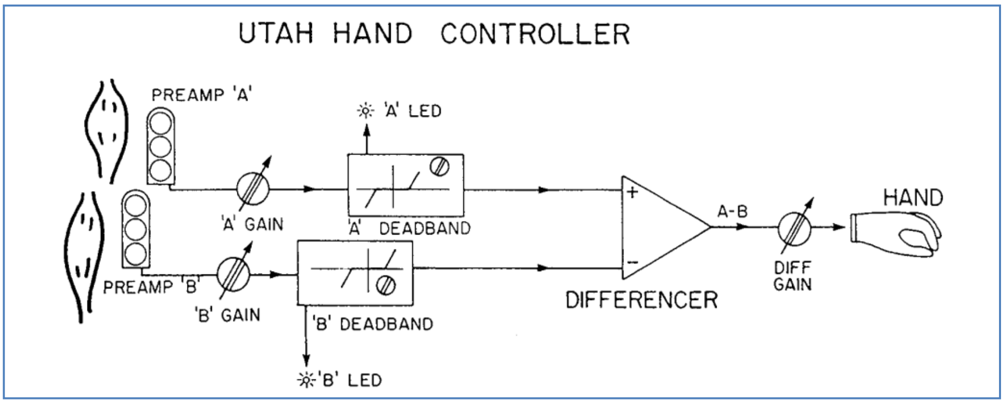

Figure 24:Proportional control circuit of the Utah arm [15]

2.13.2. UTAH ARTIFICIAL ARM 2 (1997)

The second generation of the Utah Arm, called the Utah Arm 2 or U2, replaced the original, with major improvements in the electronics, motor and transmission. However, not much were changed in terms of control [54].

2.13.3. UTAH ARTIFICIAL ARM 3 (2004)

Two microcontrollers are programmed for the elbow and hand, thus allowing separate inputs and therefore simultaneous control of both. In addition, the U3 uses a computer interface which greatly simplifies fine tuning of the elbow and hand controls. This interface is called *AutoCal*® [34].

2.13.4. OTTO BOCK® DEVELOPMENT – THE MICHELANGELO HAND (2010)

Currently Otto Bock®, one the leading prosthesis manufacturers in the world, have an EMG-based prosthesis available [35-37], called the “Michelangelo hand”.

The Michelangelo hand has 7 modes of operation that includes wrist rotation, thumb movement, precision and power grips. Again, two sets of sEMG sensing electrodes, connected to a dual-channel EMG signal amplifier and conditioning circuit. The single wrist movement of the patient existing muscles is used to control the hand and to select the various modes. The patient steers the prosthetic hand into the desired position using the antagonist muscle groups in his/her forearm using the built-in a forward-off-backward controller.

Proportional control is defined as one in which the amplitude of the hand motor voltage, and thus its speed and force, varies in direct proportion to the amplitude of the EMG signal generated by the wearer [14-15]. This means that the Michelangelo hand is not a true proportional sEMG system.

2.14. CONTROL POSSIBILITIES THROUGH SEMG

The section that follows this section describes the limitations of current systems. To create an understanding for the limitations and the areas of improvement, the possibilities of sEMG must be given. The human hand has around 22 degrees of freedom, 39 muscles and 36 joints [37]. The possibilities of creating a usable hand to mimic the movements and actions of a natural hand, depends on the functional capabilities of the sEMG HMI method.

Fortunately the EMG signal amplitude varies closely with the actual tension generated by the muscles. This allows the possibility for proportional control algorithms. Recall that “Proportional control” is defined as one in which the amplitude of the hand motor voltage, and thus its speed and force, varies in direct proportion to the amplitude of the EMG signal generated by the wearer [14-15].

In case of wrist amputation, a patient still has the extensor and flexor muscles of its amputated hand left in his/her forearm. Opposing extensor and flexor muscle groups are referred to as antagonist muscles. These antagonist muscles are suitable for prosthesis hand control. Figure 25 shows the flexor and extensor muscles mechanics. The function of antagonist muscles is to contract and relax (open and close) all five fingers. If the sEMG signals of these muscles could be isolated, single finger control could be made possible.

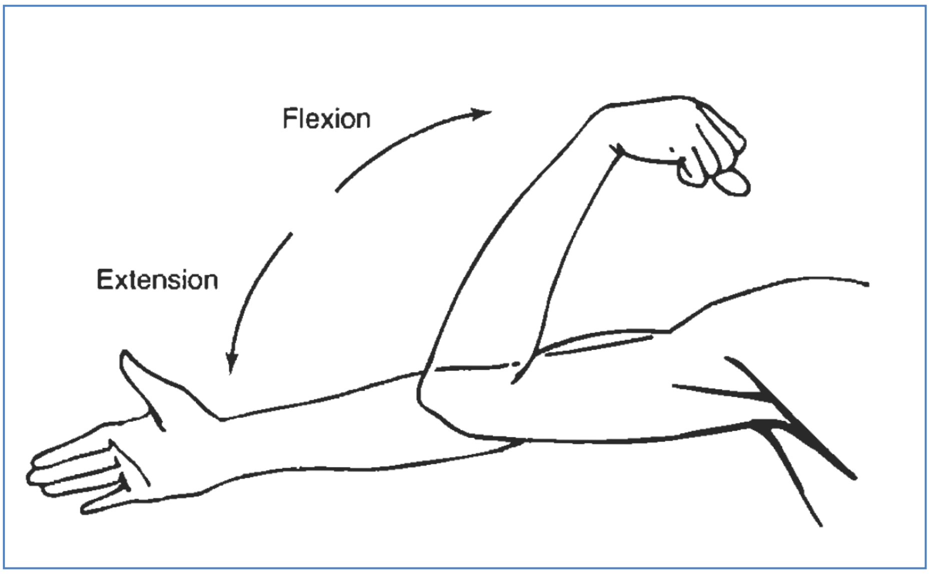

Figure 25: Flexor and extensor muscle mechanics [22]

The major drawback of amputations is muscle damage [37]. sEMG depends on healthy muscle function. From the 22 degrees of freedom in the hand, 7 are possible through muscles that are located in the hand itself. These degrees of freedom include the moving fingers from side to side. Figure 26 shows the degree of freedom associated with muscles located inside the hand. Unfortunately the muscles responsible for the side to side finger and thumb motion will be lost.

Natural two-way communication is lost as sEMG has no feedback to the PNS. Fortunately for patients with vision, their visual feedback remains, because they are able to see how the prosthesis reacts to their instructions.

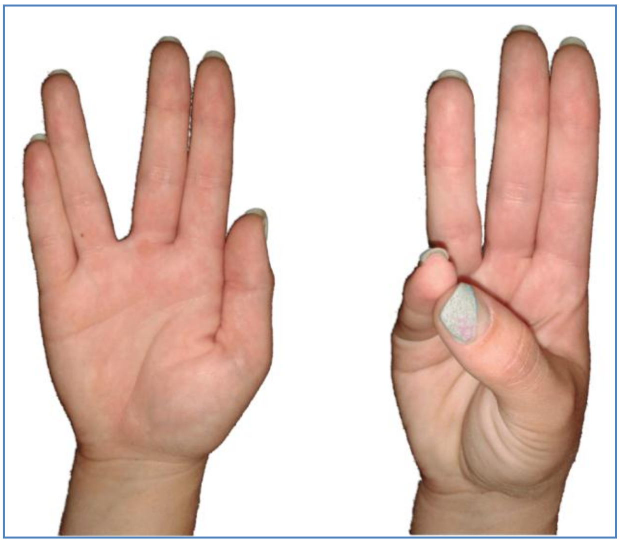

Figure 26: Side to side finger movement

Another limitation of EMG is the fact that there is no afferent sensory nerve feedback. Figure 27 is a diagram showing the natural feedback loop and EMG without any feedback to the natural loop. Afferent nerves are the sensors found in the feedback path from the sensory nerves to the spinal cord [29]. Afferent sensory feedback is the phenomenon of a person being able to walk without having to look at his/her foot placement. When making use of a powered prosthesis, the remaining visual feedback might be adequate for prosthesis control. In case of blindness, a person doesn't any longer have the sense of hand position. Without the afferent sensory nerve feedback (lost by amputation), he/she does not have visual feedback of their prosthesis hand's actions.

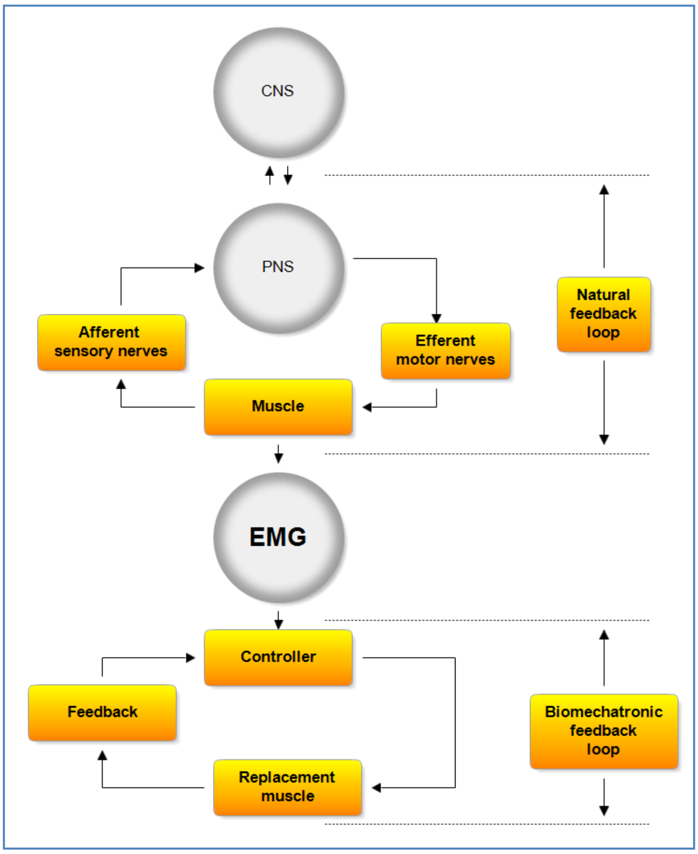

Figure 27: Natural feedback loop and the biomechatronic circuit

To conclude, although some of the hand's functionality is located inside the hand itself, most of the hands functionality is located inside the forearm. This means that the possibilities of sEMG could be expanded further.

2.15. LIMITS OF EXISTING EMG-BASED SYSTEMS

The limits of existing EMG-based systems are described by the functionality offered by the systems, based on functional capabilities, precision and responsiveness.

2.15.1. FUNCTIONALITY

Currently, the most advanced method has three states in prosthesis control (i.e. open-off-close). Current research focuses on proportional control, which means that the prosthesis follows a linear motion exactly as a natural hand functions. Multiple finger control is still under development.

2.15.1. PRECISION

The hardware of the Utah Arm contains dead-bands, used to eliminate noise effects. This may cause the amplifiers not to be perfectly proportional/linear.

2.15.1. RESPONISIVENESS

Adaptive filter are added to the conditioning circuit in EMG systems. These filters add very long time constants (of around 500 ms) lag to the system. This takes care of "jitter" induced by noise in the systems, the time delay caused by the filters are unacceptable to the patient.

2.16. AREAS OF IMPROVEMENTS

The following example should inspire, due to the fact that biomechatronics can change lives. Biomechatronics can achieve more than the existing technology, especially on hand prosthesis control.

2.16.1. HUGH HERR'S POWERFOOT®

In the past, prosthetic feet were manufactured at a fixed 90 degree angle to allow patients to have the ability to stand, but they had difficulty to walk. The PowerFoot® in figure 28 is a prosthetic foot with an ankle that knows when to bend forward and backwards, when to relax and when to support. The PowerFoot® utilises three processors and 12 sensors to measure force, inertia and position. The prosthesis automatically adjusts for slopes, stairs and walking on flat surfaces [1].

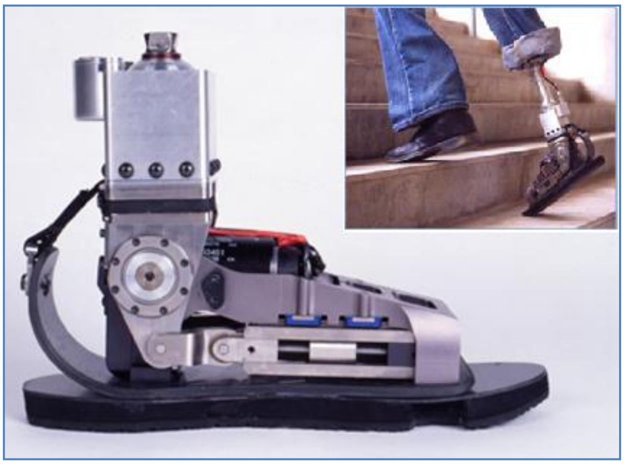

Figure 28: Images of the PowerFoot [1]

2.16.2. NON-INVASIVE HMI METHODS

The perception of non-invasive HMI methods must be recontemplated. Non-invasive HMI methods must be encouraged. The multiple benefits include easier material selection, easier testing on patients, without having costly medical procedures and specialists to perform these medical procedures. Consider the rate of technology advancements and the continuous upgrades, as technology improves. The disadvantages of non-invasive HMI methods, namely the lack of aesthetics and the functionality, should be eliminated to favour non-invasive HMI methods.

2.16.3. SEMG IN PROSTHESIS CONTROL

The PowerFoot shown in figure 28 mimics the angle, stiffness level and damping of a natural foot, imitating the biological feedback loop inside a person's nervous system with its library of known patterns. Although EMG and sEMG are both matured technologies in the medical field, there might be more technological growth potential for EMG and sEMG in the biomechatronics field, as input method for prosthesis control.

2.16.4. SEMG SYSTEM DESIGN

The variability that exists in humans such as the fat-layer thickness underneath the patient's skin influences sEMG signal quality [26]. The healthiness of muscle and the electrode placement on the patient also plays a role in the signal quality [26]. Quach [7] believes that some commercially available EMG sensor systems lack their claimed performance, and makes recommendations on the possible improvement in quality of an EMG signal recording, by evaluation of the signal resolution, accuracy, distortion, CMRR, signal range, and sampling rate.

An artefact is any unwanted signal that contaminates the sEMG signal. The patient's heart beat or electrocardiograph (ECG) is minimised when the electrodes are placed close to one another, and on the same side of the patient's body [7]. 50Hz power line interference is minimised by using a differential amplifier with a good CMRR (90-140dB), and to connect an active drive circuit connected to the patient's reference electrode [7]. A notch filter could be added to the sEMG circuit, or filtered digitally [7].

DC-offsets in data are minimised by preparing the skin by sanding dead skin with sandpaper, or abrasive paste before cleaning with an alcohol swab. The swab disinfects the area and removes oil to lower skin impedance [7]. These methods to remove DC-offsets in data are rejected. The possibility to eliminate DC-offsets in data using a calibration algorithm is proposed.

2.16.5. CONTROL ALGORITHMS

This is not within the scope of the study, but important to realise where the future studies focus on control algorithms' is, to design the correct hardware.

To derive information, pattern libraries are compiled. It is therefore vital to extract the information accurately. The elimination of any variability would result in the effective implementing of a pattern library. Inherent variability in the readings may be improved by reviewing circuit design and control algorithm approaches. In the removal of artefacts, the DC-offset can be minimised using other techniques than skin preparation methods currently used [29].

The PNS found in the human body is a natural feedback system. By using the sEMG method to control prosthesis, the sEMG sensor has to sense the natural feedback loop's output. Then the control algorithm has to decode sufficient information for the biomechatronic circuit to mimic the natural feedback loop. Figure 27 shows the natural muscle control loop, the biomechatronic control loop, with EMG in between.

There are two cases in which a feedback loop could possibly mimic another feedback loop. The first case is when the sEMG sensor can extract sufficient information within the natural feedback loop, and mimic the function directly. In the second case insufficient information is sensed within the natural feedback loop, the required information sent to the biomechatronic feedback loop must first be derived using a pattern library.

Existing products and research prove that prosthesis control is possible through EMG. Experiments with on-off control are achieved, but the next step in prosthesis control is proportional control, which means that the prosthesis follows a linear motion exactly as a natural hand does.

2.17. ETHICAL CONSIDERATIONS

Personal and technological success mainly relies on reputation. Ethics are always taken into consideration for its influence on reputation. The ethical issues around HMI methods emerge because surgery always becomes a personal matter. Insecurity arises because the aesthetics of prosthesis influences patient’s appearance and social acceptance. Suspicion occurs regarding privacy issues with mind reading. The current ethical issues with HMI are mainly focused on invasive methods, as it could have a permanent effect on a patient [29]. These issues are discussed in the following sections.

2.17.1 RISK/BENEFIT ANALYSIS

Non-invasive HMI methods imply no risk as non-invasive sensors are detachable. Invasive HMI methods prove to be a concern because they imply permanent impact on the patient’s tissue. The materials used in invasive HMI methods could have side effects, or perhaps react to the patient’s tissue, and cause permanent damage to the patient’s tissue. Surgery and continuous probe insertion could also decrease tissue functionality. Medical procedures involved in invasive HMI methods could cause a decline in the patient’s condition if anything in the procedures goes wrong. HMI system designs imply group involvement, from various disciplines. Consequently it is important to rely on a responsible decision making group where transparency is adamant.

2.17.2. SOCIAL ISSUES

It is important to deliver a reliable and aesthetic appealing prosthesis, because it affects the quality of life of patients and their families, as well as the patient’s personality and self-esteem. Affordability must always be considered, as people are from different socio-economic groups, which will affect their ability to fund their disability. Animal testing for human benefit has always been a sensitive issue and the stage to move from animals to patients are highly sensitive issues (especially invasive methods). Regard of privacy should be promoted and propagated by the media, justifying the methods used.

2.18. CONCLUSION

The basic human anatomy creates an understanding of what the design of a HMI entitles. Latest trends in HMI research suggest that invasive HMI methods are favoured due to their improved performance in accuracy and reliability. From the HMI methods available, it is shown that the non-invasive methods have the lowest risk and the least ethical issues. The area of improvement for non-invasive methods is their functional capabilities, which validates the need for this study. The functional capability of powered prosthesis control is shown to be limited, and is considered another opportunity for research. The literature suggests that an artificial feedback loop could also be implemented in prosthesis, and could be recommended for future studies.