Concordia University

Project report in partial fulfilment of:

ENGR 6191

Introduction to Biomedical Engineering

Surface Electromyography: Use, Design & Technological Overview

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1 INTRODUCTION

It is simply remarkable how the pace of science and technology has advanced so rapidly over the past 300 years. It is particularly astonishing to bear in mind that a whole fundamental branch of physics (electrical) has developed in this time. To see this stark contrast in relation to our present day developments in the applied sciences, specifically my topic of electromyography, we need only to consider these following historical breakthroughs.

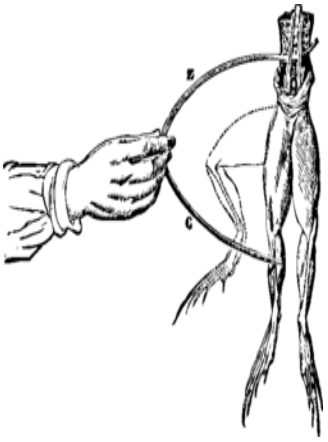
The origin of human understanding on the subject of electricity can be traced back to antiquity beginning with the observation that amber could be rubbed with fur to attract a small feather. Thales of Miletus 624 BC–ca. 546 BC of the ancient Greeks is credited with this discovery[1].

Perhaps more interesting is that the use of electro-stimulation may have predated the Greek discovery of electrostatic attraction. Historical evidence suggests that the ancient Egyptians in 2500 BC used electrogenic fish in the treatment of ailments[2]. An Arab physician of the 12th century provided an account the electric properties of the Nile fish (an electric catfish)[3]. However it was the Roman physician Scribonius Largus who is credited for being the first to document the use of electrogenic fish for medicinal purposes in 46 AD[4].

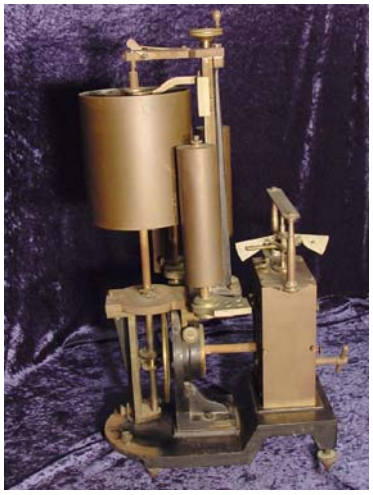
About two milleniums passed by without any deep scientific questioning about the nature of electricity, but in 1663 Otto von Guericke's invention of the electrostatic generator would soon change everything. Subsequent refinements of this apparatus provided scientists with a tool for conducting electrical experiments including Galvani's accidental discovery of animal electricity over a century later.

In 1750 Benjamin Franklin proposed his famous kite experiment. In an attempt to prove that lightning is electricity, he proposed to collect the electrical charges from a storm cloud. The result of this and various other experiments jolted the scientific community of his day regarding the nature of electrical fluids. He was the first to propose that "vitreous" and "resinous" electricity were not different types of "electrical fluid", but in fact the same electrical fluid under different pressures. He labeled them positive and negative, and discovered the principle of charge conservation[5].

In 1783, Luigi Galvani dissected a frog on a table top where he had previously been performing experiments involving static electricity. His assistant touched an exposed sciatic nerve on the frog leg with a metal scalpel and sparks were observed in the "electricity machine" just as the dead frog leg kicked to life. The term *animal electricity* was coined to describe this newly observed phenomon responsible for the muscle twitching in his dead specimens[6].



Within two years, Allesandro Volta demonstrated that muscle twitching was also possible through the application of his own invention the Voltaic cell (the first battery consisting of two disimilar metals and an electrolyte) to the exposed nerves of the dead frog leg. He argued that the basis for the observed "animation" was not bioelectricity, but rather metallic electricity.



Intrigued by the works of Galvani and Volta, Carlo Matteucci in 1830 began a series of experiments which allowed him to prove that injured muscle tissues generated direct electrical currents using a sensitive galvanometer (current meter). In 1846 he invented the kymograph (shown right), which is a mechanical device used to record physical displacment resulting from muscle contractions[7].

Emil du Bois-Reymond (1818-1896), influenced by Matteuci's observations and through determined effort strived to explain "the electrical phenomenas presented by living beings" invented new techniques and improved existing methods for studying bioelectric phenomenas. He is credited with theorizing what we now call the nerve action potential and is considered to be the father of experimental electrophysiology[8].

Advances in contemporary medical science and electrical engineering would now persist at an incredibly intense rate. My report will focus on these later developments by providing an overview of the historical developments leading up to present day EMG equipment, provide a discussion on the physiological basis of this technique, its use, applications and benefits, followed by a discussion on present day design challenges and considerations, and finally include a commentary about some present research and future applications.

2 OVERVIEW OF TECHNOLOGICAL DEVELOPMENTS

2.1 FIRST ELECTROMYOGRAPHY READINGS

In 1849, Du Bois-Reymond, regarded as the father of experimental electrophysiology, performed his classic experiment of placing blotting cloths on his subject's hands and forearm and immersed each of them in separate vats of saline solution in electrical contact with electrodes. The electrodes were connected to a galvanometer (current meter) whereupon the subject's arm flexing, consistent and predictable deflections was observed. He deduced that the magnitude of the readings was diminished by the impedance of skin. After removing a portion of the subject's skin and applying the electrodes he saw a large increase in signal magnitude during the wrist flexion.

In the early 1900s, Pratt F.H. demonstrated that the magnitude of energy related in a given muscle contraction was a result of individual muscle fibre recruitment rather than the magnitude of the neural impulse.

In the 1920s, Gasser, Newcomer and Erlanger developed a triode vacuum tube amplifier for use with the newly invented cathode ray oscilloscope. The amplified signals from a pair of electrodes connected to muscle, EMG signals could now be displayed. To store these readings, photographic film was held up against the cathode tube instead of anything resembling today's storage media.

"Often we'd work all day and wind up at five o'clock at night with one good record. And that record was obtained not with a camera – the tube wasn't bright enough to photograph – so we held up a big piece of film up against the end of the oscilloscope and we'd get a blurred line there that we could interpret approximately, defining the waves of the compound action current."

Archives Collection Oral History Number 4, recorded on November 24, 1969 with Dr. George Bishop concerning his collaboration with Dr. Joseph Erlanger on nerve action potential research during the 1920s. Dr. Erlanger later received the 1944 Nobel Prize in physiology for this research[9].

2.2 ANALOG EMG SYSTEMS: 1950–1973

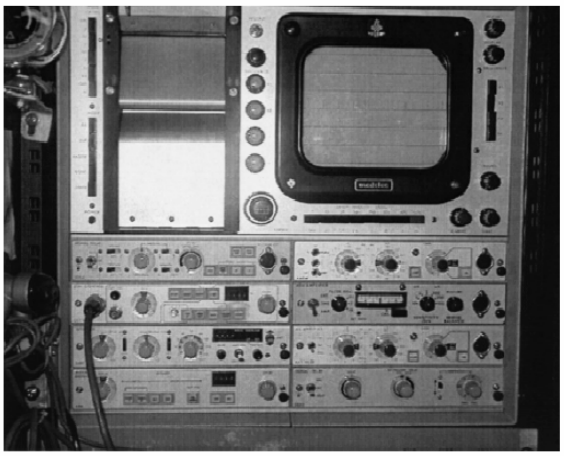
In 1950, DISA A/S (Denmark) introduced a three channel EMG system capable of displaying and recording waveforms from each channel. It was called model 13A67. Each channel had amplifiers and filters to process the EMG signals to individual cathode ray tubes (CRT) used as the visual displays. A channel selectable audio amplifier and loudspeaker was used for auditory presentation of the signals, and paper film recorder was used for permanent storage of any acquired waveform. Electro-stimulation was provided by a separate timing device attached to the system. There was no synchronization between the stim device and the free-running display. If an electromyographer needed to evaluate a recording in detail he would take the exposed film out of the machine and into the darkroom to be developed and processed. DISA 13A67 was considered a success. Over 400 systems were used worldwide.

DISA 13A67 EMG System

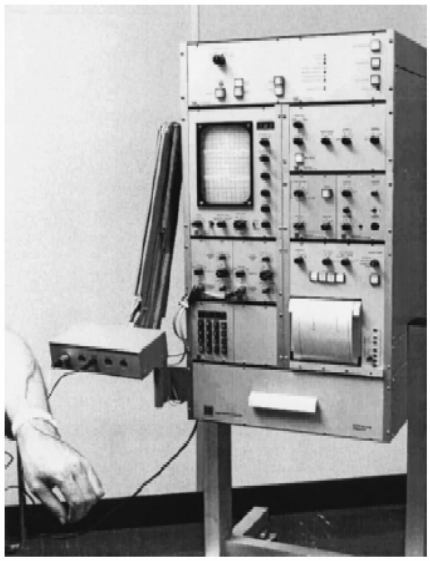
With the invention of the first transistor in 1947, production of commercial transistors made them readily available by 1954 for a mere $49.95 (the equivalent of about $361 in year-2005 dollars)[10]. By the early 1960s, Medelec Ltd. (UK) and DISA introduced transistorized EMG systems that were developed on printed circuit boards. This meant a significant increase in equipment reliability. Standard on these newer EMG systems were analog delay lines for synchronization of signals, signal trigger functions and time cursor functions. In the later part of the 1960s, CRTs had longer persistence functions which allowed the user to take averaged readings of a given sensory action potentials. While paper film recorders were improved to allow raster types of recording, the actual development of the film was time consuming and so a standard Polaroid camera was attached to the CRT display and screen shots of an EMG signal were simply taken using a camera.

2.3 DIGITAL EMG SYSTEMS: 1973–1982

The birth of digital electronics and the invention of memory devices added many new possibilities to EMG system designs. These systems increased in size and complexity compared to previous generation. Typical systems of this period include the MS6 (from Medelec) and the DISA 1500. These were highly modular in design to accommodate future expandable modules. The MS6 was an analog EMG system introduced in 1969, was an analog system but with the development of an averager in 1973, digital modules were offered for the analog system. Introduced in 1975, the DISA 1500 EMG system was considered to be the first completely digital EMG system as all modules were equipped with digital components.



Medelec MS6 with Integrated Averager



DISA 1500, Digital EMG System 1976

In a simple bus arrangement, communication between analog signals and digital setting information was facilitated to and from amplifiers, stimulators, CRTs, digital delay lines, averagers and data storage modules. Analog EMG signals were digitized and printed out with all relevant user set information on a real-time array printer. Dedicated modules developed for analysis of EMG signals included the Willison analyzer from Medelec in 1972 (turns/amplitude analysis). DISA introduced in 1979, a module for analysis of jitter which had dual triggers and dual time-based features. “From 1975 to 1982, nearly 30 different modules were developed for both the Medelec MS6 system and the DISA 1500 system.”[11]

Many researchers started interfacing their EMG systems to computers. Combining EMG system with the standard computer opened up the possibility of an even more powerful analysis tool for EMG signals. In particular, research into

methods for extracting and analyzing motor unit potentials was being done in many laboratories. Other research included nearly computerized EMG systems with software programs for decrement analysis, jitter analysis, turns/amplitude analysis, motor unit analysis, and scanning EMG were under development in the research setting.[12]

However, the increasing complexity and cost of producing digital EMG systems gleamed towards the introduction of microprocessors into EMG systems.

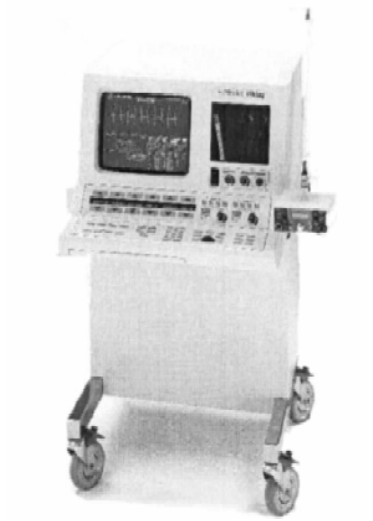
2.4 MICROPROCESSOR-CONTROLLED EMG SYSTEMS: 1982-1993

In the early 1980s, a new generation of microprocessor-controlled EMG was introduced to reduce production cost and increase clinician ease of use. Early microprocessors still lacked the power to perform data acquisition and processing, and so were limited to control applications such as data routing of EMG signals from amplifiers to averagers, control over displays and the user interface equipment such as monitors, control panels, and the keyboard. These systems had graphical displays that showed EMG signals with user setting information and measurement data. These systems were typically menu driven with test settings that could be stored in memory.

Typical application of these microprocessor-controlled EMG systems included conduction of sensory nerve and motor tests, decrement analysis, needle EMG exams, and various evoked potential modalities (“time locked” electrical signal in response to some stimulus).

However, the computing power of these early systems were considered too slow to perform advanced signal processing and analysis as required in motor unit analysis (analysis of one motor neuron and all of the muscle fibers it innervates). To bypass these early computational limitations, many systems were digitally interfaced to an external computer. Enhanced functionality interested companies to explore the new commercial opportunity where PCs could be programmed to run EMG systems. The first companies to do this was Intersoft (Sweden) and Medelec.

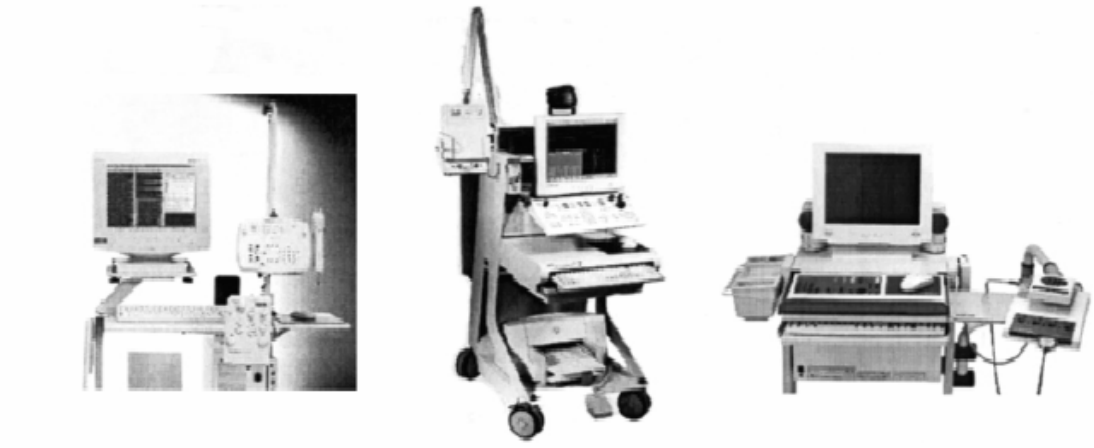
By 1982, Intersoft unveiled a complete software package which included nerve conduction testing with automatic latency markers, decrement analysis, motor unit analysis, interference pattern analysis, and various other software analysis modules. Intersoft introduced the first computerized EMG system. These same programs were later implemented on an IBM PC that came with the DISA Neuromatic 2000.



Nicolet Viking EMG System, 1985

By 1985, microprocessor hardware/firmware had reached a level where the computational power and graphics capabilities could perform most EMG signal analysis. The Nicolet Viking EMG system shown above is an example of dedicated analog and digital hardware combined with system software that performed advanced forms of signal analysis. It was unique from previous systems in that the display had multiple tracing windows. It had continuous display of amplitude measurements and latencies in nerve conduction programs. Another unique feature was template matching for motor unit analysis.

2.5 PC-BASE EMG SYSTEMS: 1993–2001



Advances in computer hardware and software made it possible to make the PC perform all the processing related function required in EMG recording and analysis. Benefits of a PC-based EMG system included powerful signal processing, flexible graphical representation, larger data storage capabilities, and shorter latencies. “All EMG systems introduced after 1993 are PC-based[11]” except for some introduced after 2001 which are micro-controller based.

Typical PC-based EMG systems used standard word-processing programs for generating reports and the data could be stored over a network, or directly to a CD-ROM. Some systems included a workstation desk where the clinician could write a report and archive recorded data (too advanced!).

Introduced in 1993, the Keypoint EMG system from Dantec Medical (formerly DISA) had a range of features which included automatic scoring of EMG readings, online comparison with reference values, and networking capabilities for review and reanalysis on another PC. Another model, the Nicolet Viking IV also introduced in 1993 had networking capabilities.

Available from the early 1990s, the MyoVision 8000 (MyoVision, USA) shown below, was a static dual channel SEMG system developed with commercial electronics and manufactured with popular technologies of this era. Surface-mount components (miniature resistors, capacitors and other components) had become widely used in some sectors of electronic manufacturing (computers, VCRs, other consumer electronics devices) where reliability and miniature size was desired. Both through-hole and surface-mount parts was used in the MyoVision 8000. RS-232 serial data protocol provided a means of transferring data to and from the PC. The white boxes shown on top of the data acquisition unit are electrode probes consisting of three electrodes solidly mounted into a plastic enclosure. These probes are used for static EMG measurements because subject movement would greatly affected readings.

MyoVision 8000, early 1990s

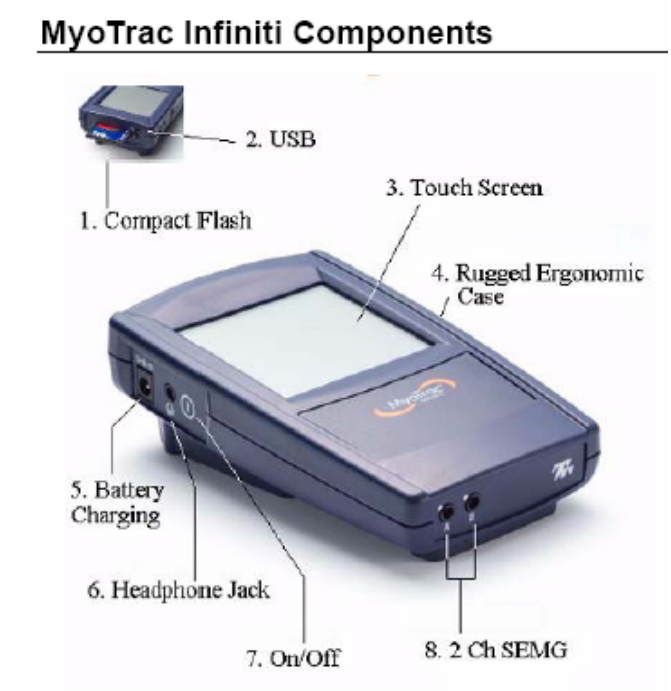
2.6 HANDHELD & WIRELESS EMG SYSTEMS: 2001-PRESENT DAY

Biomedical engineers work with all the commercially available technologies to provide EMG equipment with added versatility and mobility. EMG is now routinely used in therapy, training, and biofeedback for patients.

Recent developments in all fields of electronic technologies have pushed EMG equipment into the present state. The old RS-232 serial data transfer protocol previously used in the PC-based generation would be replaced by the Universal

Serial Bus 2.0 which provided faster data exchange rates and even a means of supplying power to the EMG handheld device to recharge the device. Increased storage capacity of data recordings on digital storage media became a common place. Hardware memory and computing power increased even further making it possible for small and powerful microprocessors to run entire training suites and store all user recorded stats to the handheld device. The user can then upload their recordings to a PC at a later time, eliminating the need for a bulky workstation.

An example of a typical handheld EMG system is the MYOTRAC INFINITI introduced in 2003 (Thought Technology Ltd). This unit is a dual channel, handheld portable EMG device with three distinct operating modalities: Surface Electromyography (SEMG), Neuromuscular Electro-stimulation (NMES) and SEMG-triggered Stimulation (ETS). This is uncommon compared to other EMG devices in that it reads SEMG and provides electro-stimulation. It features many of the recent commercial technologies such as software developed monitoring and training suites, and is currently being sold worldwide to hospitals, rehabilitation clinics, therapists, physicians, dentists, researchers, and prescribed patients.



MyoTrac Infiniti, Handheld EMG 2003

Wireless technologies such as Wi-Fi and Bluetooth have also been incorporated into today's existing EMG equipment to provide the user with extended mobility from the PC on PC-based systems. Acquired EMG signals can now be picked up on the body and sent wirelessly to a PC where it is recorded, processed and analyzed.

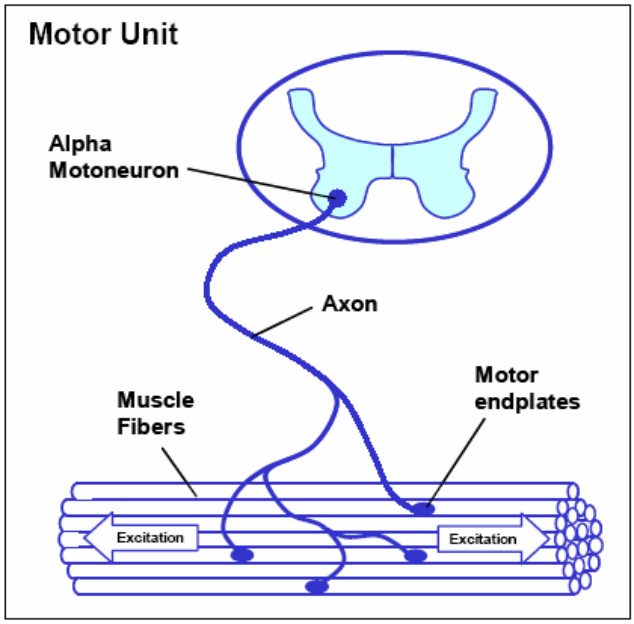
In 2008, Thought Technology will introduce a wireless telemetry module for PC-based data acquisition systems. This module will insert into the compact flash slot on ProComp Infiniti and FlexComp Infiniti. Bluetooth technology has been selected and incorporated based on its ability to outperform Wi-Fi under most wireless traffic load conditions. These wireless data acquisition systems monitor EMG along with a wide selection of other biosignals. They are currently being tested by researchers at NASA who want to monitor raw EMG (raw EMG is more demanding on the telemetry system than processed EMG), and various sports therapists who want to monitor top athletes in the field. The range of this module will cover 100 meters (typical Class 2 Bluetooth dongle) and has a battery life of 4-16 hours (depending on how many sensors are in use).

3 PHYSIOLOGICAL BASIS OF EMG

3.1 PHYSIOLOGICAL MECHANISM

In the study of muscle physiology, neural control of excitable muscle fibres is explained on the basis of the action potential mechanism. The electrical model for the motor action potential reveals how EMG signals provide us with a quantitative, reliable, and objective means of accessing muscular information.

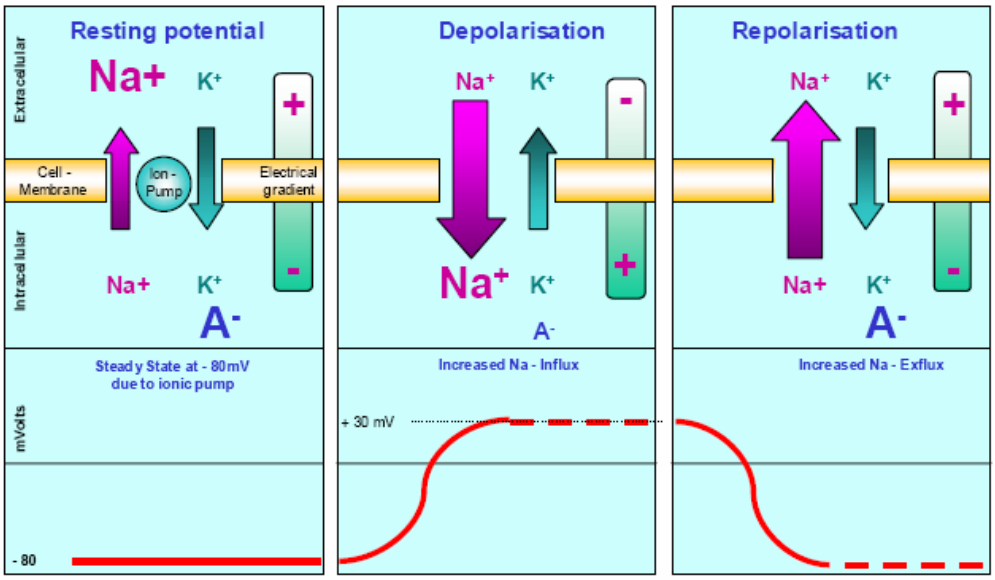
When an alpha motoneuron cell is activated (induced by the central nervous system or as a result of a reflex action), the conduction of this excitation travels along the motor nerve's axon and neurotransmitters are released at the motor endplates. An endplate potential is formed at the muscle fibres and innervates the motor unit (the smallest functional unit where neural control over muscular contraction occurs).

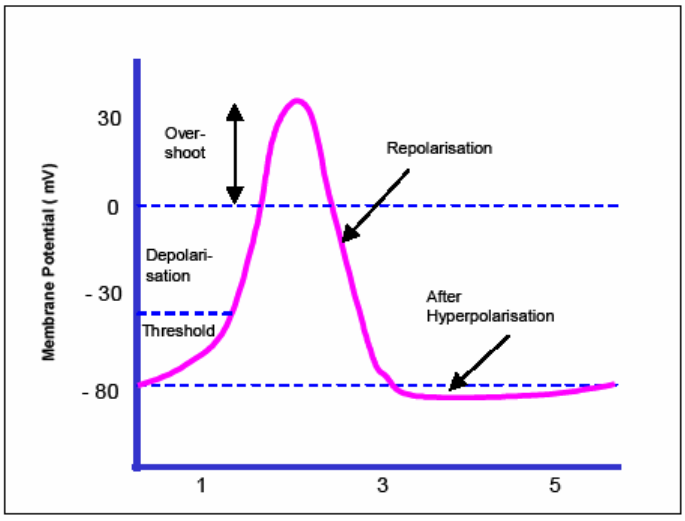


Muscle fibres are composed of muscle cells that are in constant ionic equilibrium and also ionic flux. The semi-permeable membrane of each muscle cell forms a

physical barrier between intracellular (typically negatively charged compared to external surface) and extracellular fluids, over which an ionic equilibrium is maintained. These ionic equilibriums form a resting potential at the muscle fibre membrane (sarcolemma), typically -80 to -90mV (when not contracted). This potential difference in maintained by physiological processes found within the cell membrane and are called ion pumps. Ion pumps passively and actively regulate the flow of ions within the cell membrane.

When muscle fibres become innervated, the diffusion characteristics on the muscle fibre membrane are briefly modified, and Na^+ flows into muscle cell membranes resulting in depolarization. Active ion pumps in the muscle cells immediately restore the ionic equilibrium through the repolarization process which lasts typically 2-3ms.

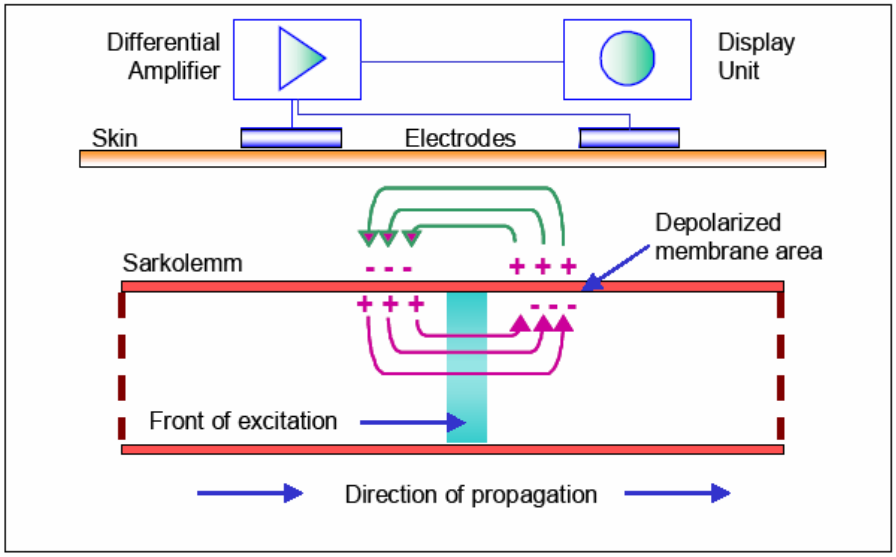


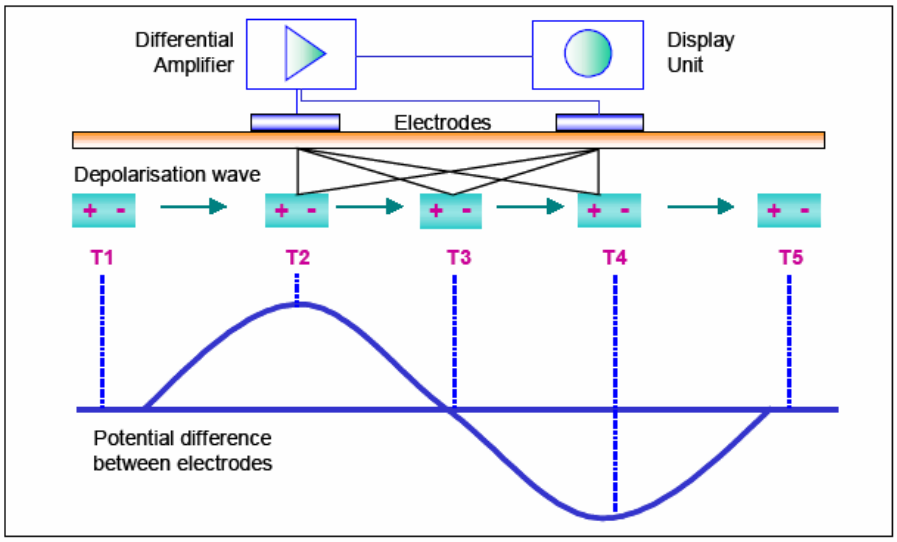


When a certain threshold level is exceeded by the influx of Na^+ resulting in a depolarization of the cellular membrane, an action potential is developed and is characterized by a quick change from -80mV to +30mV. This monopolar

electrical burst is restored in the repolarization phase and is followed by a hyperpolarization period.

Beginning from the motor end plates, the action potential spreads across the muscle fibres in both directions at a propagation speed of 2-6m/s. The action potential leads to a release of calcium ions in the intracellular fluid and produces a chemical response resulting in a shortening of the contractile elements of the muscle cells.

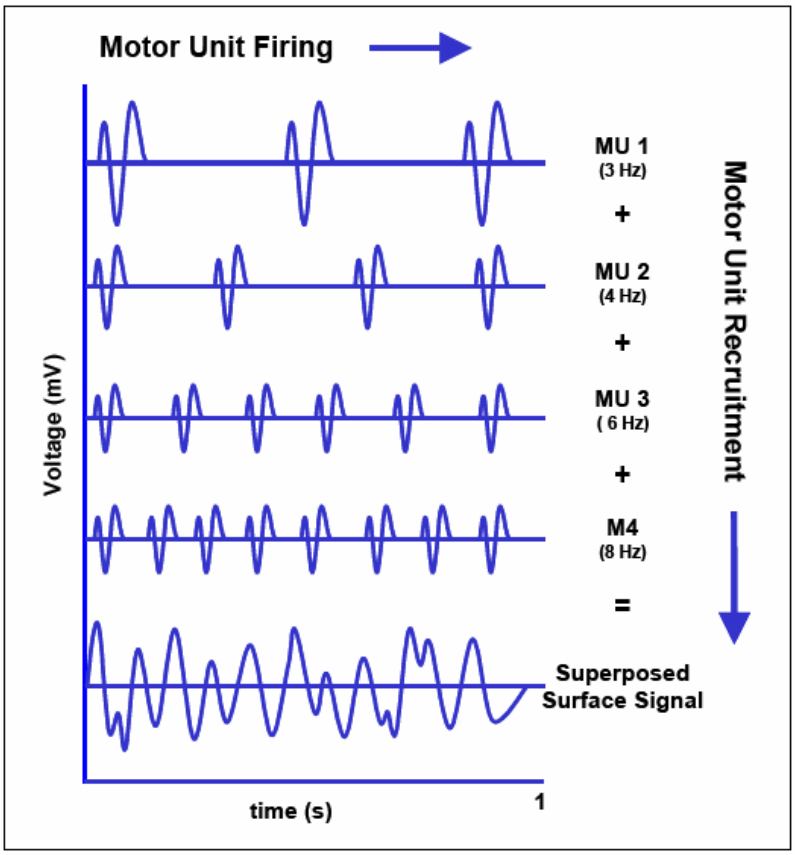




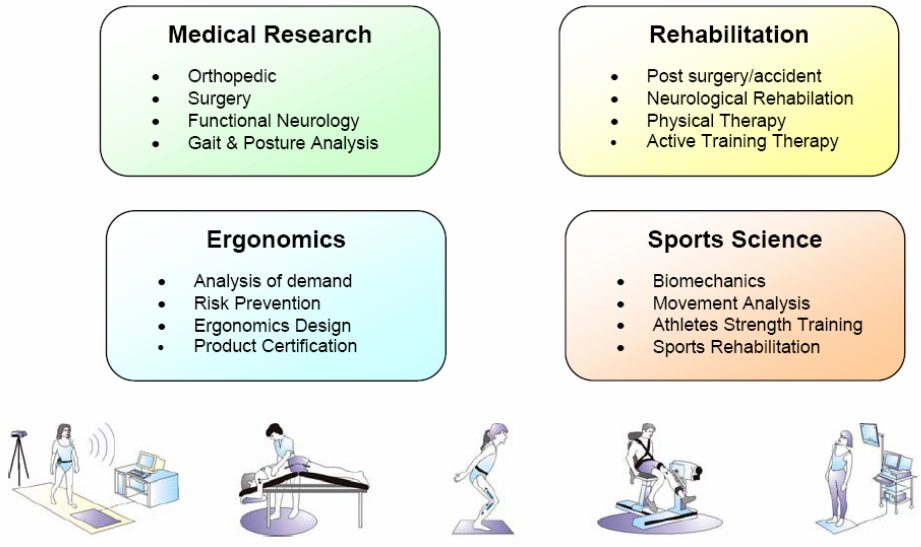
The depolarization-repolarization process described is a monopolar action potential that travels across the surface of the muscle fibre. Electrodes in contact with this wave front present a bipolar signal to the EMG differential

amplifiers because the electrodes are measuring the difference between two points along the direction of propagation of the wave front.

EMG signals provide us with a viewing window into the electrical signals presented by multiple muscle fibres and are in fact a superposition of multiple action potentials.



3.2 APPLICATIONS & BENEFITS OF EMG



Whenever the basic question of “what are the muscles doing?” arises, the benefits of EMG become apparent. EMG allows us to look at the electrical activity responsible for muscle contractions and allows us to measure muscular performance. Extending beyond the traditional use of EMG in physiological and biomechanical research, EMG has well established value as an evaluation tool used in applied research, physiotherapy, rehabilitation, sports medicine and training, biofeedback, and ergonomics research.

Practical medical applications involves EMG use in pre/post surgical assessment and treatment, prevention or retardation of muscle atrophy, increasing local blood circulation, relaxation of muscle spasms, maintaining or increasing range of motion, and muscle re-education and rehabilitation through biofeedback.

Stroke victims and individuals diagnosed with incontinence (lack of voluntary control of excretory functions) typically undergo training regimens that enable them to regain functional control over specific muscles. The electrical activity normally present during a patient’s muscle contraction and relaxation cycle is often characteristically different or much weaker and harder to detect on damaged muscle sites. Through careful and skilled placement of certain electrodes onto specific electrode sites, biofeedback provides the patient and therapist with objective information about the subject’s muscle activity in real-time. The EMG user directly benefits from the instant feedback increasing his/her self-awareness of the muscular activity under direct conscious control, and accelerates the therapist’s instruction to the patient to improve the patient’s ability to complete specific movements.

4 EMG BASICS

4.1 TYPES OF ELECTROMYOGRAPHY

4.1.1 SURFACE ELECTROMYOGRAPHY (SEMG)

Non-invasive technique for measuring muscle electrical activity resulting from contraction and relaxation exercises.

4.1.2 FINE WIRE ELECTROMYOGRAPHY (INTRAMUSCULAR EMG)

Invasive technique for measuring muscle electrical activity resulting from contraction and relaxation exercises.

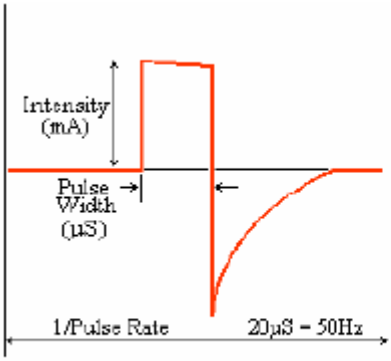
4.1.3 NEUROMUSCULAR ELECTRICAL STIMULATION (NMES)

Burst of electrical pulses stimulate muscle contractions in targeted muscles via electrodes.

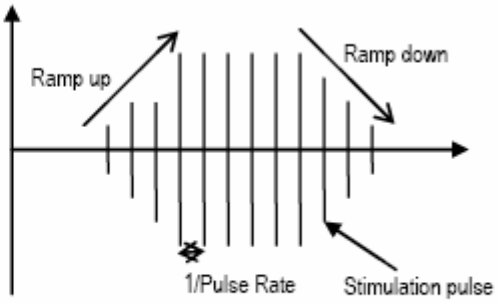
Parameters of NMES are:

1) Pulse width: duration of individual pulses
2) Pulse rate: rate at which a number of pulses is delivered
3) Intensity: intensity of current delivered by each pulse. NMES type electrodes must be used for this application as electrode power density is an important safety concern. Using SEMG electrodes can result in severe electrical burns.
4) Ramp: time it takes the intensity of successive pulses to reach a maximum preset value or to decrease back to zero.

Shown below is a typical pulse waveform used in NMES. The stimulation pulses occur in successive fashion ramping up, maintains a preset intensity, and then ramps down. A burst of pulses is always followed by a rest period to allow the muscle to recover and avoid fatigue.



stimulation pulse



Burst of pulses

4.1.4 EMG-TRIGGERED STIMULATION (ETS)

ETS is a combination of two complementary EMG modalities: SEMG and NMES. The user's SEMG serves as a guide in determining the onset of electrical stimulation. The patient initiates the muscle contraction and when a specific EMG threshold is reached an electrical stimulation burst is delivered and the muscle and the patient is stimulated to complete the contraction. This technique provides the possibility of "getting the best of both worlds" in that it utilizes both passive and active rehabilitation techniques to aid and motivate the patient.

4.2 SKIN PREPARATIONS, ELECTRODE TYPES & ELECTRODE PLACEMENT

4.2.1 SKIN PREPARATION AND CONSIDERATIONS

Proper skin preparation and electrode positioning are essential elements in acquiring quality EMG measurements. Two key strategies govern electrode preparations:

1) electrode contact must be stable
2) skin impedance must be minimized

While there are no general rules for skin preparations, the type of application and signal quality sought usually determines the extent of the skin preparation. For example, given a targeted test condition if the movement is somewhat static or slow moving and only qualitative reading are desired, a simple alcohol swab around the area of interest is sufficient. However, if dynamic conditions present risk of the introduction of movement artifacts like in walking, running or other planned accelerated movements, a thorough preparation is required.

Skin preparation for surface electrodes usually involves removing the patient's hair around the electrode site to improve electrode adhesion. Cleaning the skin then involve one of the following methods:

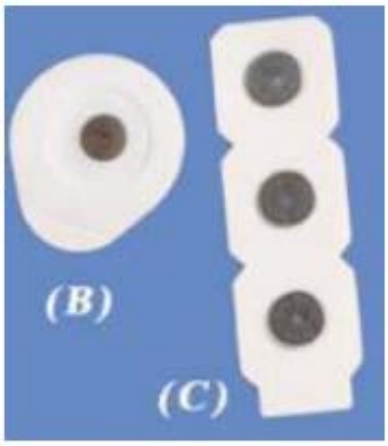
1) Use of special abrasive and conductive pastes to remove dead skin and lower skin impedance.
2) Use of fine sandpaper to abrade the skin surface combined with alcohol swabbing to clean the dead skin, oil and or dirt to lower skin impedance.
3) Strict use of alcohol swabs to clean the skin surface which is often sufficient in static EMG measurements.

Most modern EMG differential amplifiers are designed to work with skin impedances ranging from 5 – 50kΩ. Some EMG systems have built in impedance checking circuit that sends an imperceptible burst of current through the electrodes and controlled measurements are correlated to a known impedance levels to indicate the quality of the electrode contacts.

4.2.2 EMG ELECTRODE TYPES

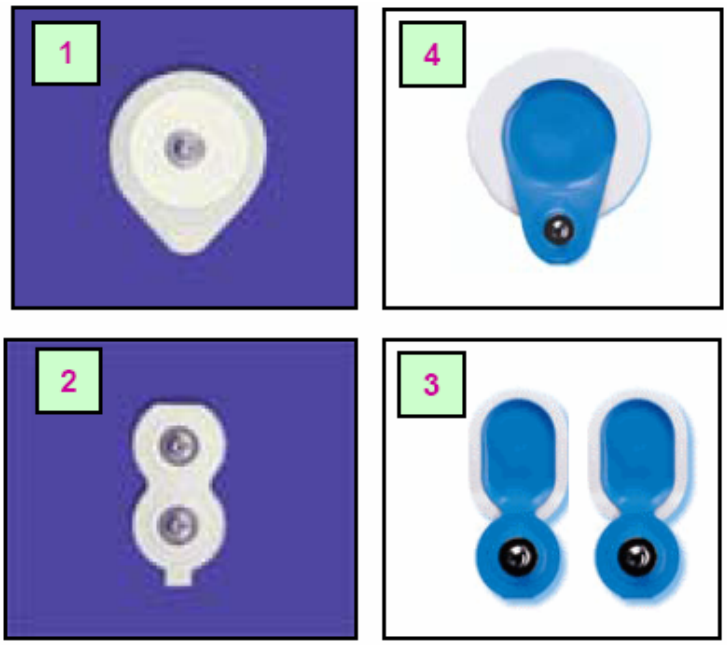
Most major limb and trunk muscle activity can be measured using surface electrode techniques. For deeper, smaller, or overlaid muscles fine wire electrodes need to be used to acquire intramuscular activities.

For surface electrodes, simple platinum or silver disc electrodes, pre-gelled Ag-AgCl electrodes, and wet-gel electrodes are commonly used. The disc electrodes are reusable while the gel electrodes are single use. Distinction exists between electrodes used for SEMG and those used for NMES and ETS. Whenever an electrical stimulation is applied, the electrodes used must be properly designed to deliver such electrical stimulations otherwise the power density generated at the skin contact can result in patient injury. Also, for the evaluation and treatment of incontinence, special vaginal and anal probes are used to measure the pelvic floor muscle activities.



Thought Technology's SEMG
Metallic disc electrodes: UniGel (B), and Strip (C)

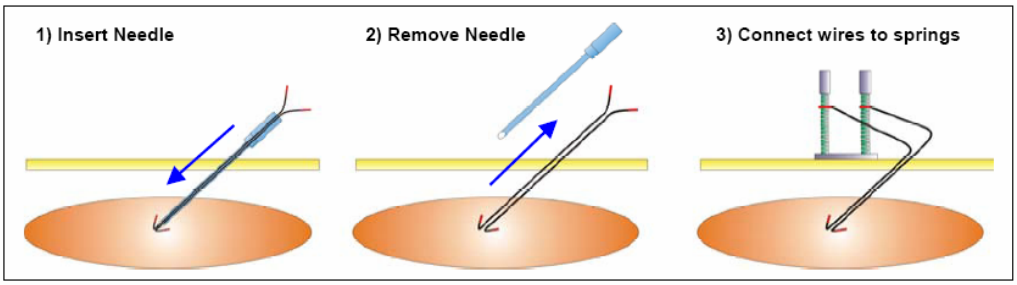
Thought Technology's NMES electrodes:
Mylar substrate with AgCl paste

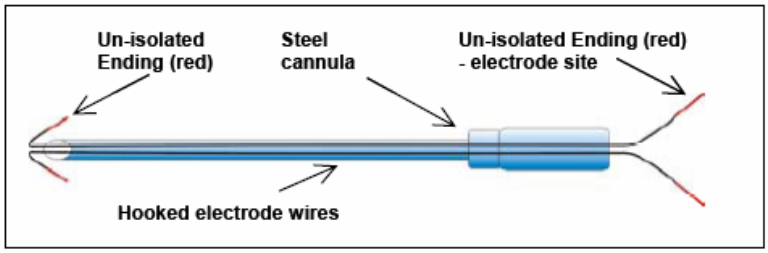


Noraxon's gel electrodes: pre-gelled AgCl (1, 2) and wet-gels (3, 4)

Perry probes: Vaginal probe (left), Anal probe (right)

When intramuscular EMG is required to look into the electrical activity of deeper or overlaid muscles, thin and flexible fine wire electrodes are used. The fine wire electrode is inserted into the muscle site of interest. The needle or steel cannula is removed, and the electrode wires are connected to the steel spring adapters to minimize movement artifacts.





Medelec's fine-wire electrode

For all electrode types, additional measures can be taken to affix the electrode cabling to the patient body to minimize movement artifacts. Regular adhesive tape, hook and loop fasteners, and elastic straps are commonly used to secure cabling onto the body, but never the electrodes as this will affect the readings.

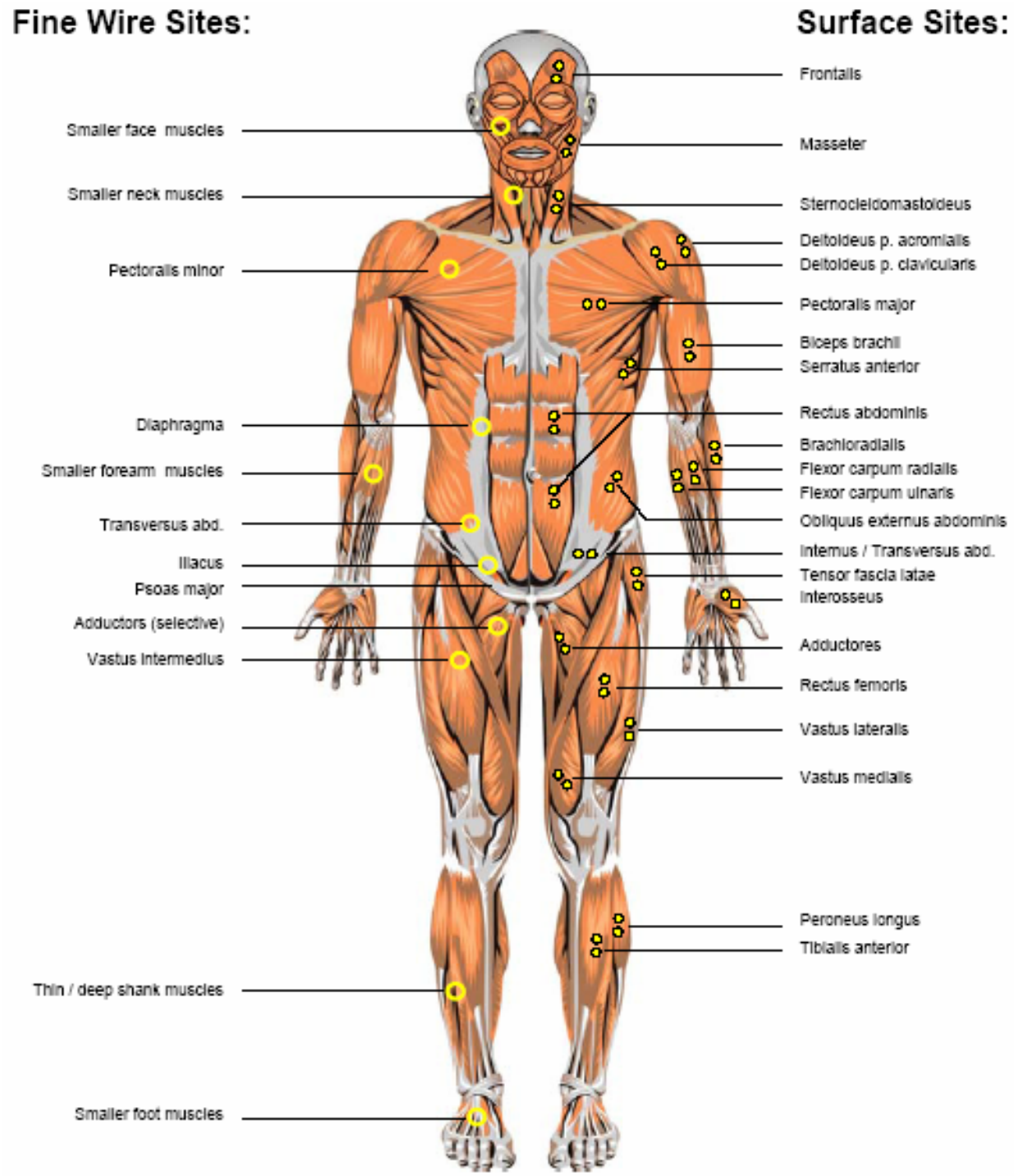
4.2.3 General Electrode Placement Sites & Reference Electrode

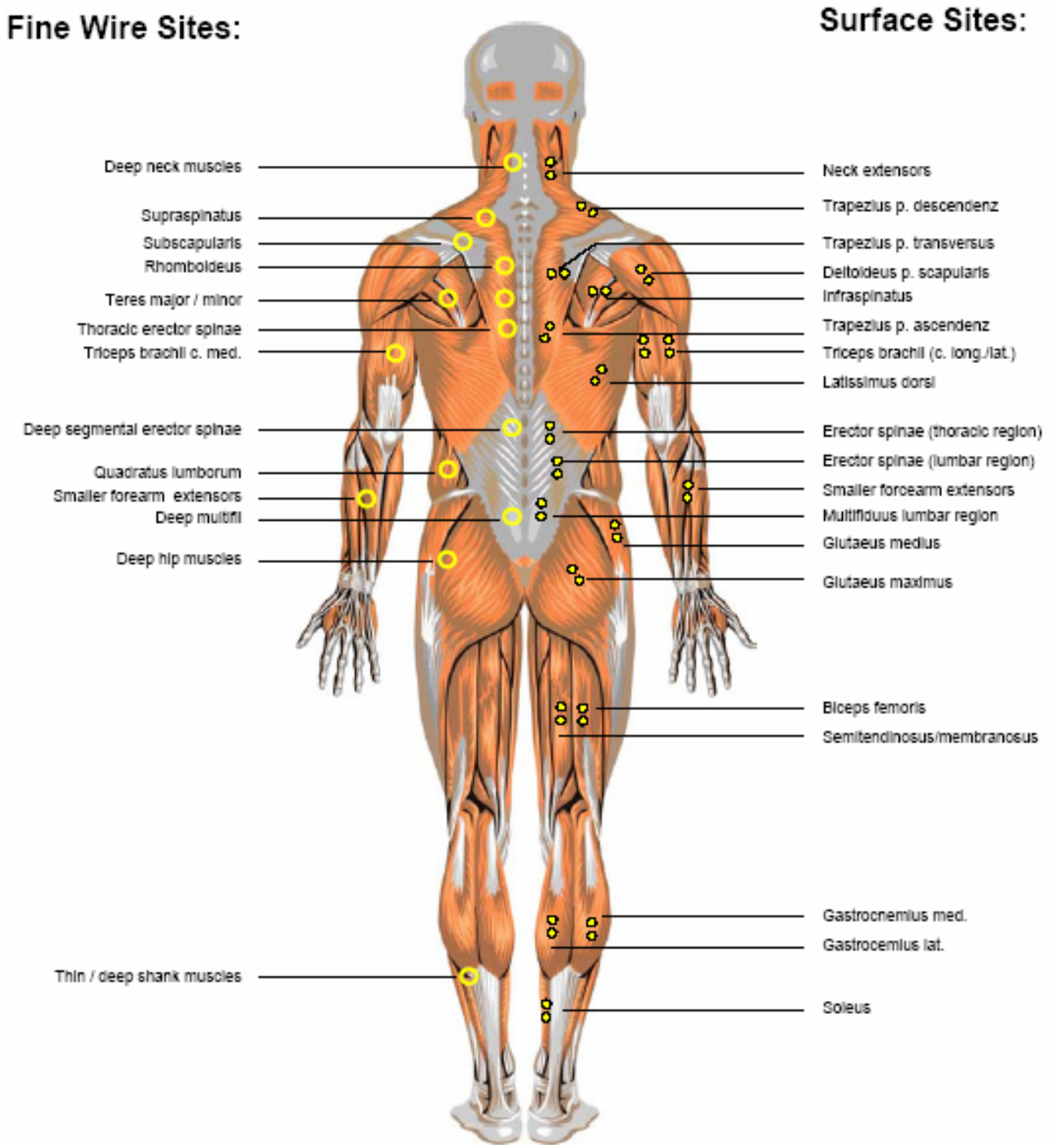
The following shows recommended differential electrode placement sites for both fine wire and surface EMG. These sites are well defined and are known as anatomical landmark sites. Notice that the placements of these differential electrode pairs are always along the direction of the muscle fibres under study.

Along with the differential electrode pair, a reference electrode is used in SEMG and ETS to provide a reference to the differential amplifier and to limit the range of any common mode signals (50-60Hz power line interference and its harmonics). NMES does not require use of reference electrodes as this technique only provides electrical stimulation to the patient and no readings are being acquired.

When required, placement of the reference electrode is typically more proximal and away from the differential electrodes, preferably on electrically neutral tissue (say over a bony joint).

Some EMG systems have an active patient drive circuit connected to the reference electrode This is a specialized circuit designed to send a portion of the unwanted 50 - 60Hz power line interference back into the patient at 180^{o} phase to cancel this interference.


Fine Wire Sites:
Surface Sites:
Frontalis
Smaller face muscles
Masseter
Smaller neck muscles
Sternocleidomastoideus
Deltoideus p. acromialis
Pectoralis minor
Deltoideus p. clavicularis
Pectoralis major
Biceps brachii
Serratus anterior
Diaphragma
Rectus abdominis
Brachioradialis
Smaller forearm muscles
Flexor carpum radialis
Flexor carpum ulnaris
Transversus abd.
Obliquus externus abdominis
Internus / Transversus abd.
Iliacus
Tensor fascia latae
Psoas major
Interosseus
Adductors (selective)
Adductores
Vastus intermedius
Rectus femoris
Vastus lateralis
Vastus medialis
Peroneus longus
Tibialis anterior
Thin / deep shank muscles
Smaller foot muscles

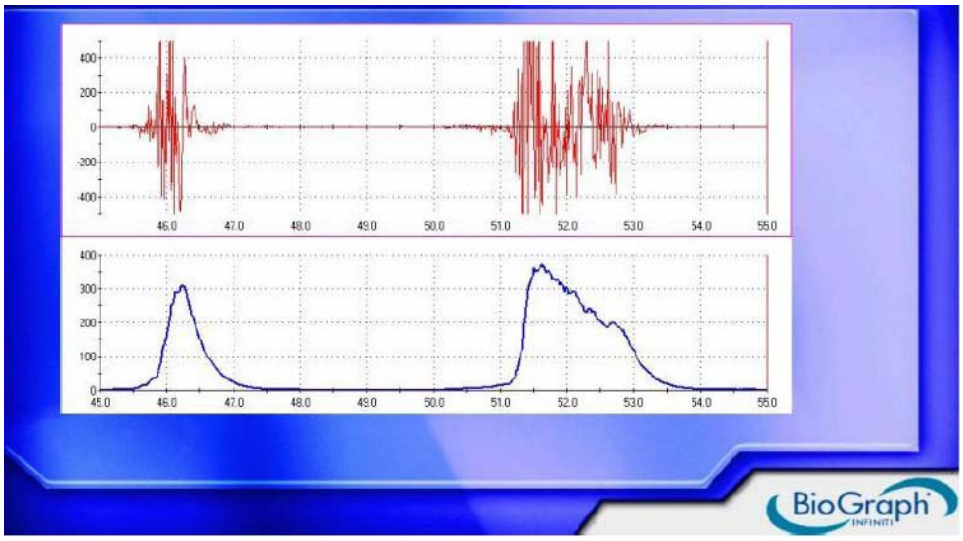

Fine Wire Sites:
Surface Sites:
Deep neck muscles
Supraspinatus
Subscapularis
Rhomboideus
Teres major / minor
Thoracic erector spinae
Triceps brachii c. med.
Deep segmental erector spinae
Quadratus lumborum
Smaller forearm extensors
Deep multifi
Deep hip muscles
Thin / deep shank muscles
Neck extensors
Trapezius p. descendenz
Trapezius p. transversus
Deltoideus p. scapularis
Infraspinatus
Trapezius p. ascendenz
Triceps brachii (c. long./lat.)
Latissimus dorsi
Erector spinae (thoracic region)
Erector spinae (lumbar region)
Smaller forearm extensors
Multifiduus lumbar region
Glutaeus medius
Glutaeus maximus
Biceps femoris
Semitendinosus/membranosus
Gastrocnemius med.
Gastrocemius lat.
Soleus

4.3 EMG SIGNALS & USES

Raw EMG (red) is the unprocessed signal characterized by positive and negative peaks. The amplitudes and frequency content of this signals provides information about the contraction or resting state of the muscle under study. It is useful when studying the activation timing of a muscle, or for verifying the quality of the signal and detecting signal artifacts.

RMS EMG (blue) is the root mean squared form of the raw signal and represents the mean power of the signal. The amplitude envelope makes it easier to view. It is useful when studying the activation timing of a muscle, and for measuring the level of activation of a muscle such as the resting level or quantifying the force generated by a muscle.

Both raw and RMS EMG signals display the electrical activities under study in the time domain.

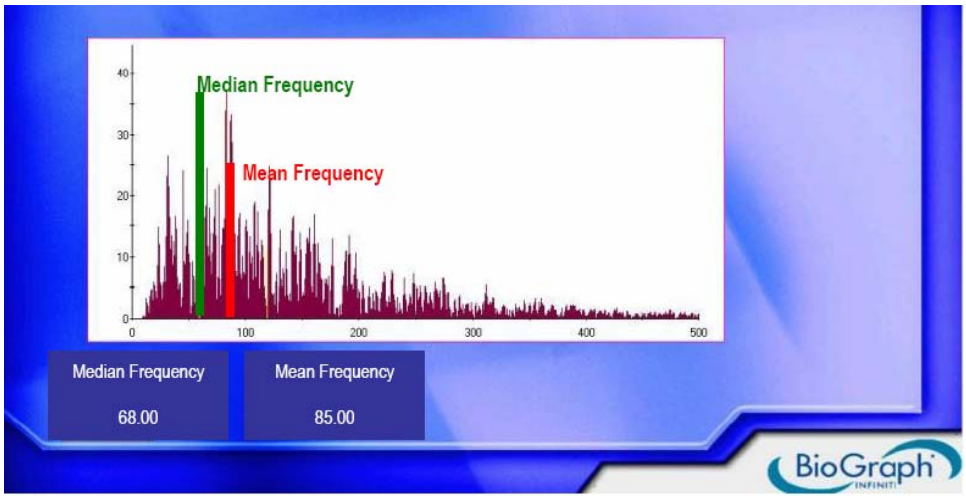


RAW (red) and RMS (blue) EMG Signals

Frequency Spectrum of EMG is the raw EMG that has been converted into the frequency domain by performing a Fast Fourier Transform (FFT) calculation using all available data points. The frequency spectrum reveals the frequency content of the electrical firings within the muscle. It is commonly accepted that the relevant SEMG frequencies range is between 20 - 500Hz. Looking at the frequency spectrum can also provide information not readily available in the time domain such as muscle fatigue.

As muscle fatigues, the frequency of the firing decreases but the mean amplitude may remain the same. Therefore looking for indications of muscle fatigue in the time domain is not so easy. Two important measures of muscle fatigue is the median frequency (shown below with the green bar) and the mean frequency (red bar). As muscles fatigue, both mean and median frequencies

decreases. However, these indicators are relevant only for isometric contractions (sustained contraction with no movement).

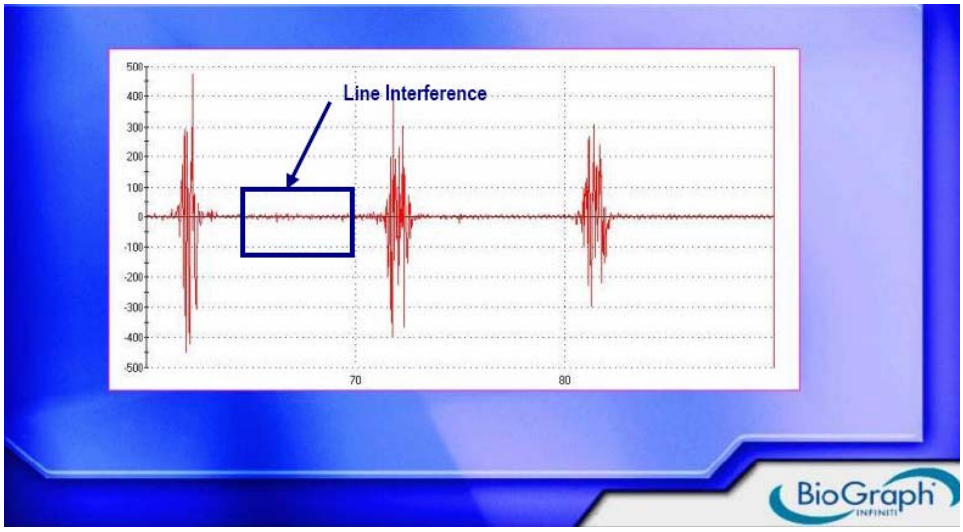


EMG Signals in Frequency Domain

Furthermore, by looking at the individual frequencies, it is also possible to separate the activity of the slow-twitch fibres (20 – 90Hz) from the fast-twitch fibres (90 - 500Hz).

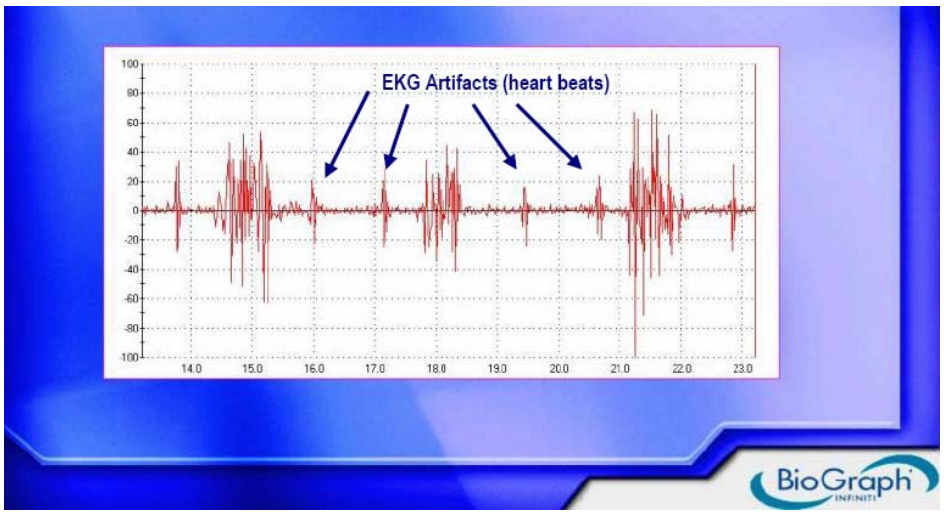
4.4 Signal Quality: Artifacts & DC Offset

50-60Hz power line interference is the most common artifact. It is transmitted by up electrical devices (e.g. computers used around the EMG equipment), and even though EMG equipments are typically isolated from line power, this line interference finds its way into the acquired EMG signal. Typically a notch filter implemented in software is used to remove this interference.



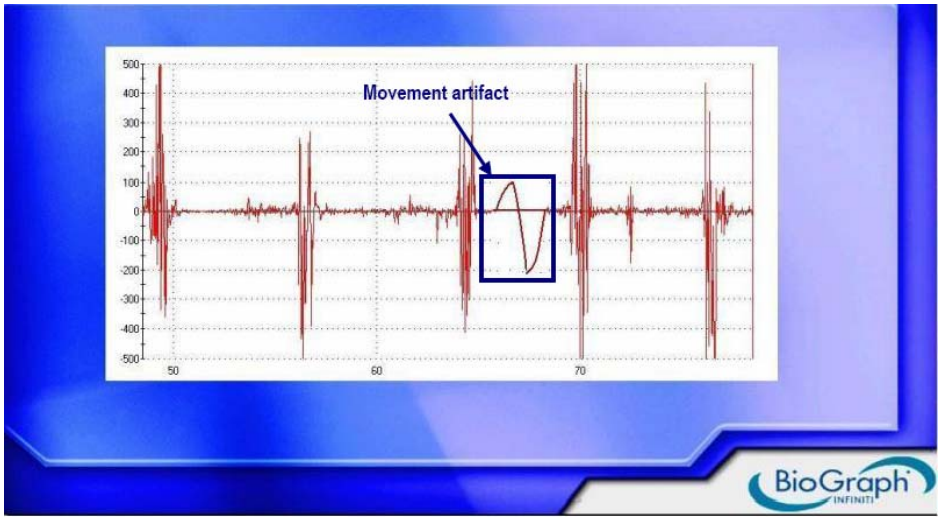
50-60Hz Power Line Interference

EKG artifacts are a result of the electrical signals generated by the heart muscle and can also be picked up in EMG signals. These artifacts are often very difficult to remove, but can be avoided by placing the electrodes off axis from the heart activity. Also, placing the electrode on the same side of the body typically reduces or removes this artifact. As a last resort, a high-pass filter at 100Hz implemented in hardware or software may be used to attenuate or remove all the signal frequencies below the cut-off frequency, which also may remove the signals of interest.



EKG Artifacts

Movement artifacts occur whenever a patient moves and the electrodes are disturbed or the cables are pulled. Electrodes must be placed in firm contact with the skin and electrode cables must be fastened so as to prevent such artifacts. Filters (hardware or software) can also be applied to remove residual artifacts. But when all else fails, these artifacts may be removed manually based on the statistics of a certain movement artifact.



Movement Artifacts

DC offset results from a difference in the electrical impedances between the skin and electrodes. RMS EMG readings will give misleading information about resting and activation levels if this offset is not attended to. The raw EMG signal (normally center on 0) is used to detect DC offsets. With proper skin preparations and firm placement of electrodes, this problem can be prevented. When all else fails, conductive gels can be added to reduce skin impedance.

Muscle crosstalk results from the electrical signals generated by muscles other than the one under investigation. Crosstalk is minimized through the appropriate placement of the electrodes on the middle of the muscle belly. The recommended inter-electrode distance (from one differential electrode to the other) is about 2 cm.

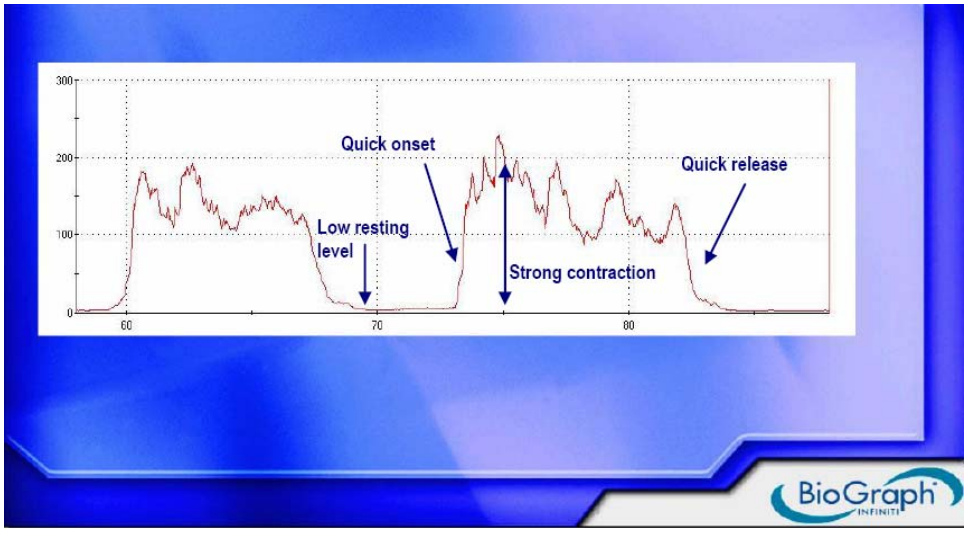
4.5 SIGNAL ANALYSIS & COMPARISON METHODS

The goal of any signal analysis is to provide objective, accurate, reliable and measurable data. To that end, amplitude analysis, temporal analysis, bilateral comparisons and MVC-normalizations are some common methods used when looking at SEMG signals.

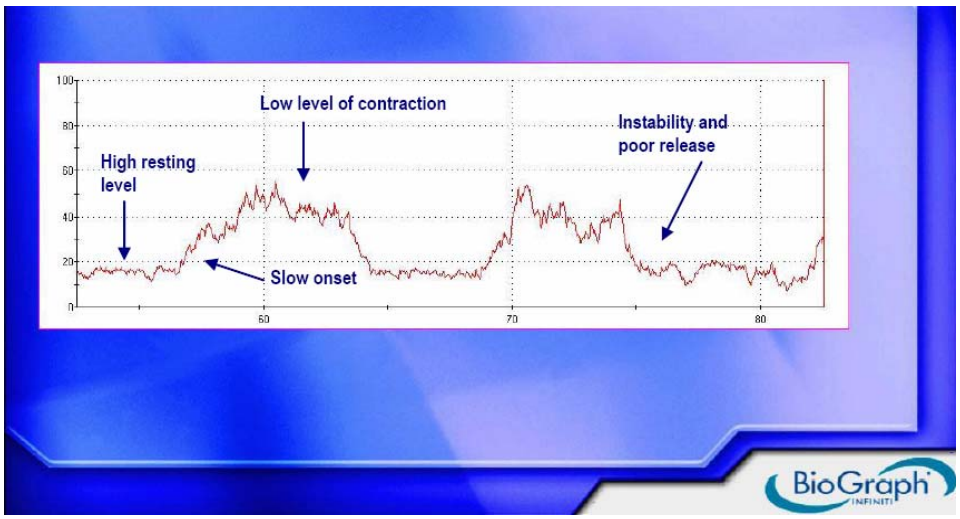
Amplitude analysis looks at the activation levels during rest and contractions. The **resting level** of totally relaxed muscles should be less than 5μV otherwise this indicates poor muscle relaxation, or that a DC offset is present due to poor skin preparations. The **averaged contraction** is the mean level of the muscle's electrical activity during a contraction period, and is considered to be a good indicator of the level of muscular strength and endurance. **Variability** in the activation levels indicates neuromuscular stability.

Temporal analysis looks at the time it takes for a muscle contract or release. The **onset time** defines the time for a muscle going from the resting state to a full contraction. The **release time** defines the time for a muscle to recover from a contraction back to the resting state.

In healthy muscles, the typical resting level is low, onset and release times are short, and the contractions are high. Unhealthy muscles have characteristically high resting levels, lower contraction levels, and greater variability.



Amplitude & Temporal Analysis Parameters of Healthy Muscles



Amplitude & Temporal Analysis Parameters of Unhealthy Muscles

A drawback of SEMG measurements is the inherent variability in the readings. It can vary significantly between subject, muscles, electrode placement on a given muscle, and even from one day to the next. Several normalization methods exist to provide better reference points for comparing measurement results.

Two common methods for comparing measurements are:

1) **Bilateral comparison** which compares the readings from the involved site to an uninvolved site.
2) **MVC-normalization** (maximum voluntary contraction) compares the amplitude of a given contraction as a percentage of the MVC. The MVC value is the averaged maximum value obtained over several isometric contractions.

5 DESIGN CONSIDERATIONS FOR EMG EQUIPMENT

5.1 TYPICAL DESIGN CONSIDERATIONS

Understanding the operational requirements actually represents the most critical design aspect in EMG equipment development today. With all the available technologies (what has actually allowed us to acquire the knowledge that we do have as of today) the future of EMG equipment development is rooted in finding new applications and redefining the requirements of present day EMG equipment.

In the meantime, present day design considerations for the development of EMG equipment will be outlined. The **signal resolution, accuracy, distortion, CMMR, signal range, and sampling rate** ultimately define the quality of an EMG signal.

Differential amplification is a technique commonly used whenever signals are picked up from the body. In order to eliminate the unwanted common mode signals say from power line interference, differential amplifiers are used to reject the common signals at the amplifier's inputs and amplify any detectable differences. This is called Common Mode Rejection. The ability of an amplifier to amplify differential signals over common signals is characterized by the common mode rejection ratio (**CMMR**). Fortunately, modern differential amplifiers have very high CMMR (90 – 140dB) which is typically considered adequate for suppressing extraneous electrical interference. Furthermore, any residual 50-60Hz power line interference can still be removed in software.

Input impedance of an EMG system front-end must be as high as possible since the source impedance at the skin-electrode contact is variable between a few kilo-ohms to several mega-ohms. In order to maintain good signal pickup, thus preventing **signal distortion** or attenuation, the inputs at the differential amplifier must have high impedance. Present day differential amplifiers have input impedances in the order of 10^{12} ohms with 5 pF capacitance and are not considered to be a great implementation challenge.

ADC (analog-to-digital converters) allows the amplified differential signals to be converted into digital signals that are processed by a microprocessor or a PC. The quality of an EMG signal is therefore largely dependent on the **resolution, accuracy** and **sampling rate** of the ADC used. This single component is in fact of primary concern in the design of modern EMG equipment since these performance parameters are directly related to the cost of the equipment. Present day ADCs used in EMG equipment ranges from 10 - 24 bit systems. However, the resolution, accuracy and signal range of the overall system is largely dependant on how the overall hardware is implemented. The sampling rate used in any EMG system must at least obey Nyquist's theorem whereby the minimum sampling rate must be twice that of the signal frequency in question. Once again, modern electronics has provided commercial ADCs with sampling rates of upwards to 300 MSPS (mega samples per second). In all present day

EMG applications including research, the upper limit on the frequency of interest is around 500Hz, and so there is no need to go beyond 1 KSPS.

With all these great technologies, the main concerns for a design engineer when faced with developing an EMG system remains fixed on accuracy and cost. To this end, the design challenge at present is not a technological one, but an implementation and manufacturing challenge.

Expertise in analog and digital electronics, firmware (microprocessor) programming, RF (for electromagnetic compatibility testing of the device), system software (programming user applications), product development (defining the requirements of a product in conjunction with the users/clinician), along with manufacturing expertise are all prerequisite to the realization of quality equipment. Manufacturing techniques utilizing automated pick-and-place machine to assemble the components are now a common place. Use of these machines virtually eliminates all human error associated with soldering the components on the PCB (if there is an error, the error will be detected in product testing). Further PC automated testing verifies all the important specifications of the product efficiently, and test logs for each unit are generated for future reference. Quality systems generally are implemented in the manufacturing process to ensure conformance of device specifications and user returns.

5.2 TYPICAL DEVICE SPECIFICATIONS

Here is a comparison of two typical device specifications for EMG sensors. Of particular interest are the following specifications:

1) Accuracy: an overall specification related to the implementation of the differential amplifier, ADC, and several other components, as well as noise inherent to the components used. The design engineer typically spends a great deal of time optimizing each component used to minimize noise to ensure accuracy.
2) Sensitivity: resolution of the ADC and how it is implemented governs the overall resolution of the system. This spec allows the clinician to understand the limits of his/her reading, and not to over analyze a signal.
3) CMRR: ability of the differential amplifier to reject common mode signals, and important in avoiding 50-60Hz power line interference.
4) Input Impedance: differential amplifier selection and implementation optimizes this operating margin for various user skin types and electrode interfaces.
5) Input range: a result of hardware implementation and ADC used. It specifies the range of the EMG that can be picked up without saturating the amplifier. The larger the range the better, but this typically comes at the expense of signal resolution.

Thought Technology Sensor Specifications

MyoScan EMG Sensor (SA9503M)
Size (Approx.) 37mm x 37mm x 12mm (1.45” x 1.45” x 0.45”)
Weight 15g (0.5 oz)
Input Impedance ≥1012Ω in parallel with 10pF
Input Range 0 – 2000µVRMS
Sensitivity <0.1µVRMS
CMRR >130dB
Channel Bandwidth 10Hz – 1kHz
Signal Output Range 0 – 1.0V RMS
Input / Output Gain 500
Supply Voltage 7.26V (± 0.02V)
Current Consumption 0.7mA (± 0.25mA)
Accuracy ±0.3µVRMS Plus ±4% of reading @25°C to 30°C

DELSYS Surface EMG Sensor Specifications[13]

EMG Sensors	DE-2.1	DE-3.1	DE-2.3
System	Bagnoli™	Bagnoli™	Myomonitor®
Type	Single Differential	Double Differential	Single Differential
Number of Contacts	2	3	2
Contact Dimension	10.0 x 1.0 mm	10.0 x 1.0 mm	10.0 x 1.0 mm
Contact Spacing	10.0 mm	10.0 mm	10.0 mm
Contact Material	99.9% Ag	99.9% Ag	99.9% Ag
Detection Area	10 mm2	200 mm2	100 mm2
Case Dimensions	41 x 20 x 5 mm	41 x 20 x 5 mm	41 x 20 x 5 mm
Case Material	Polycarbonate	Polycarbonate	Polycarbonate
Cable Length	1.67 m	1.67 m	1.67 m
Connector	Hypertronics D04	Hypertronics D04	Lemo 00
Temperature Range	0-40 °C	0-40 °C	0-40 °C
Electrical			
Preamplifier Gain	10 V/V ±1%	10 V/V ±1% (per diff. pair)	1000 V/V ±1%
Bandwidth	open	open	20-450 Hz ±10%
Noise	1.2uV (RMS, R.T.I.)	1.2uV (RMS, R.T.I.)	1.5uV (RMS, R.T.I.)
CMRR (60/10 Hz)	-92 dB (typical)	-92 dB (typical)	-92 dB (typical)
Power Consumption	20 mW (typical)	45 mW (typical)	40 mW (typical)
Input Impedance	>1015Ω //0.2pF	>1015Ω //0.2pF	>1015Ω //0.2pF

Notice how it is sometimes not easy to compare the accuracy, sensitivity, noise, amplifier gain or flatness among other important equipment specifications. There is no set standard in which a manufacturer must qualify these devices.

6 COMMENTARY

Developments in electromyography have come a long way since the time of Galvani and Emil du Bois-Reymond. Much of the physiological basis of EMG is well documented in medical literature, and EMG has established clinical applications in therapy/rehabilitation, monitoring and training in sports medicine, use as an evaluative tool in applied research and ergonomics studies. The technological challenges of today's EMG equipment appears to have been met by modern hardware and software to the extent that individuals can even be monitored wirelessly, or over a network such as the Internet.

All this does not go to suggest that common sense has been met. There may still be a wide range of seemingly high-end EMG equipment that do not perform as they claim, and for the most part get by simply because not very many people have the means to evaluate the accuracy of such equipment. Critical specifications are sometimes glossed and the quality of the equipment is negated by snazzy marketing designed to convince users that such and such a product is perfect for them, or this system has everything you need...

On another note, shown below is a MyoVision 8000 unit. This is an old PC-based system recently investigated to determine the accuracy of the system after a researcher became disturbed with the validity of his results. As it turns out, two major issues were found on this unit and so the results from months of research turned out to be a total waste of time.

The first issue was that the equipment gave nonlinear results at low signal levels. When a function generator and oscilloscope was connected to the probes of the device, a discreprancy between the reported reading of the equipment and that measured by a calibrated oscilloscope was found. With an input of 10μVrms at 200Hz, the equipment reported 22μVrms. This discrepancy

diminished for higher signal levels, but basically this tells us that this unit is providing bad data. The second issue had to do with the probe's cabling connection. Over long term use, these cables were damaged and gave intermitent signals. Unfortunately, due to an averaging of the signal, it was not easy to detect this and so once again bad information was collected.

Not being critical about the inaccuracy or incomplete specification of an EMG system can have the precipitating effect of a doing something tha is total waste of time for researchers and users alike. Aging equipment also posses a significant source of error in that the equipment can become inaccurate over time. Most electronic test equipment like oscilloscopes, function generators, and even voltmeters need to undergo periodic re-calibrations to ensure accuracy. Why should commercial EMG systems be any different?

All in all, I'm happy that I have had this opportunity to be exposed to the field of EMG and it's technological developments. Eventually and hopefully, I will be called upon to contribute to these developments in EMG and biosensing.

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