Biomaterials, Functional Electrical Stimulation and its Electrodes

Christian Huber
Daniel Indacochea
Presentation Outline

- Definition biomaterials, FES, and biocompatibility
- History of FES
- Relevant background anatomy
- Different electrode materials
- Different types of electrodes
- Advantages and Disadvantages
Outline (continued)

- Future advancements via electrodes
- Introduction to EEG, EMG (recording)
- Functional electrical stimulation
- Summary
- References
- Q & A period
What are biomaterials and FES?

- "A natural or synthetic material that is suitable for introduction into living tissue especially as part of a medical device"
  - http://www.sickkids.ca/

- "FES is the application of low-level, computer-controlled electric current to the muscles, including paralyzed muscles, to enhance or produce function"
  - calder.med.miami.edu/pointis/glossary.html

- "The ability of a material to perform with an appropriate host response in a specific application"
  - Williams dictionary of biomaterials
History of FES

- Wladimir Theodore Liberson’s electronic personal stimulator - patent
- In 1960, the heel-switch triggered the stimulator and thus caused dorsiflexion of the foot correcting drop foot abnormality
History (continued)

- FES of brain for treatment of spasticity, rigidity and epilepsy, Cooper, 1973
- FES for idiopathic scoliosis, Bobechko, 1972, Axelgaard
- FES for incontinence, Brindley, 1973
- FES in multiple sclerosis, Cook and Weinstein, 1973
- FES diaphragm pacing, Judson and Glenn, 1968
- FES and voluntary effort, Dimitrijević et al, 1968
- FES and hypnosis, Vodovnik et al, 1976
- FES and bio-feedback, Bowman et al, 1978
- FES cycling, Ragnarson, 1987, Petrofski, 1983

!!!Make q-cards here
Relevant background anatomy

- 3 types of muscle, we’re dealing with skeletal
- Accounts for 600 muscles, 40% body weight
- Somatic nervous system controls skeletal muscle
- Contractions controlled by peripheral spinal nerves
Relevant anatomy (continued)

- Contact area between nerve terminal (axon) is called motor end plate, where motor nerve connects to muscle
- Axon stores acetylcholine (neurotransmitter) in vesicles
Acetylcholine from somatic motor neurons initiates an action potential in the muscle fiber.

The action potential is conducted along the surface of the muscle Fiber and into the t-tubule. This signals for the release of Ca$^{++}$ from the sarcoplasmic reticulum (SR).

The t-tubules contain voltage sensing receptors (dihydropyridine Receptor or DHP) which are physically linked to (SR) channels which release Ca$^{++}$ into cytoplasm.
Tropomyosin uncovers binding site

Ca\(^{2+}\) binds to troponin

Myosin heads execute power stroke

Actin filament moves toward M line

Distance actin moves
More Relevant Anatomy

- Force of contraction increases with summation of muscle twitches.
- The force generated by a contraction can be increased by increasing the rate at which muscle action potentials stimulate the muscle fiber.
- If another action potential arrives before the 1st one has completely recovered it causes a greater depolarization (summation).
(a) Single twitches
(b) Summation

![Graph showing the summation of tension over time with peaks at specific time intervals.

Tension

Time (msec)

0 100 200 300 400 500

Triangles mark the time intervals where the tension peaks.


Functional Electrical Stimulation (FES), the details

- FES is a form of stimulus
- Why would someone receive FES?
- Sends action potential to desired nerve without stimulating others with proper electrode design
- Uses electron as signal in wire, and ions in nerves
FES (continued)

- Complete spinal cord injury
FES (continued)

- What are electrodes and how do they connect?
- Electrode-skin interface
- Electrode normally connects to epidermis, deeper layers consist of vascular and nervous components
Electrode Tissue behaviour

- Wire transfer carrier (electron) to electrodes from source, (voltage or current)
- As mentioned, signal is carried by ions in body
- Metal electrons are exchanged for ions in a solution
Skin impedance for 1cm² patch:

- 200kΩ @ 1Hz
- 200 Ω @ 1MHz
FES-Impedance vs. current density

Increasing current density
Electrode materials and requirements

- Stability
- Resistant to corrosion
- Composed of inert materials, both passively and when subjected to electrical stimulation because deterioration of the device may result in implant failure and the release of toxic products
- Minimal energy consumption
- Stable electrochemical characteristics
- Adjustable and stable impedance and frequency response
- Stability against artifacts and noises
- Typical Materials:
  Conductors: platinum, iridium, tungsten, and stainless steel
  Insulating Carriers: silicone elastomer, polytetrafluoroethylene, and polyimide
Advantages and disadvantages

- Proximity of electrode and nerve reduces the intensity of stimulation required for axonal excitation
- Reduction of hazardous electrochemical processes and power consumption of the stimulator system
- Minimal mechanical distortion of the electrodes during movement, reducing the chances for lead failure
- The electrical characteristics are not affected by changes in muscle length during movement
- Selective stimulation of fascicles within the nerve is possible, by multiple-contact electrodes and by manipulating the stimulation pulse parameters
- Recording of nerve electrical activity can be achieved with the same electrodes
Advantages and disadvantages

- Nerves can be damaged by the implanted electrode
- Implantation requires delicate surgical procedure, depending on the accessibility of the nerves
- Reverse order of recruitment of motor units during electrical stimulation leading to fast-fatigue production
- Selective stimulation requires careful testing after implantation given the variability in fascicular architecture of each peripheral nerve
Corrosion of Metals

- Corrosion is continued degradation of metals to oxide, hydroxide or other compounds through chemical reactions.
- The human body is an aggressive medium for inducing corrosion in metals: water, dissolved oxygen, proteins, chloride and hydroxide.
- Loss of Electrons is Oxidation
- Gain of Electrons is Reduction
Corrosion of Metals (continued)

Redox reaction:
\[ \text{Cu(s)} + 2 \text{Ag}^+(\text{aq}) \rightarrow \text{Cu}^{2+}(\text{aq}) + 2 \text{Ag(s)} \]

Ox.#: \[ \begin{array}{c} 0 \quad +1 \quad +2 \quad 0 \end{array} \]

We can envision breaking up the full redox reaction into two \( \frac{1}{2} \) reactions:

- Oxidation: \[ \text{Cu(s)} \rightarrow \text{Cu}^{2+}(\text{aq}) + 2\text{e}^- \]
- Reduction: \[ \text{Ag}^+(\text{aq}) + \text{e}^- \rightarrow \text{Ag(s)} \]

“half – reactions” half reactions are combined to a full reaction

Basic Reactions:
- Ionization: \[ \text{M} \rightarrow \text{M}^+ + \text{e}^- \]
- Oxidation: \[ \text{M} + \text{O}_2 \rightarrow \text{MO}_2 \]
- Hydroxylation: \[ 2\text{M} + \text{O}_2(\text{aq}) + 2\text{H}_2\text{O} \rightarrow 2\text{M(OH)}_2 \]
Corrosion of Metals (continued)

Mechanism of Corrosion:

- Materials have tendency to reach their lowest possible free energy (corroded state is preferred)
- Most alloys, oxides, hydroxides, sulfides have negative free energy of formation and they are thermodynamically favoured over the pure metal
- Metal atoms ionize, go into solution and combine with oxygen
- Metal flakes off
Types of Tissue Response to materials which are used in CNS

- Non-reactive
- Reactive
- Toxic
## Classification of material biocompatibility

<table>
<thead>
<tr>
<th>Conductors</th>
<th>Classification by Dymond et al.</th>
<th>Classification by Stensaas and Stensaas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Non-reactive</td>
<td></td>
</tr>
<tr>
<td>Cobalt</td>
<td>Toxic</td>
<td>Toxic</td>
</tr>
<tr>
<td>Copper</td>
<td>Toxic</td>
<td>Toxic</td>
</tr>
<tr>
<td>Gold</td>
<td>Non-toxic</td>
<td>Non-reactive</td>
</tr>
<tr>
<td>Platinum</td>
<td>Non-toxic</td>
<td>Non-reactive</td>
</tr>
<tr>
<td>Platinum–tungsten</td>
<td>Non-toxic</td>
<td></td>
</tr>
<tr>
<td>Silver</td>
<td>Toxic</td>
<td></td>
</tr>
<tr>
<td>Stainless steel</td>
<td>Non-toxic</td>
<td></td>
</tr>
</tbody>
</table>

| Insulators       |                                |                                        |
|------------------|--------------------------------|                                        |
| Polyethylene     | Non-reactive                   |                                        |
| Teflon TFE (high purity) | Non-reactive            |                                        |

| Semiconductors   |                                |                                        |
|------------------|--------------------------------|                                        |
| Silicon          | Non-reactive                   |                                        |
**Used Electrodes and their Applications**

<table>
<thead>
<tr>
<th>Type</th>
<th>Mode</th>
<th>Number</th>
<th>Contact site</th>
<th>Application</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Recording</td>
<td>&lt;25 Skull</td>
<td></td>
<td>Skull</td>
<td>Brain computer interface</td>
<td>Clinical practice</td>
</tr>
<tr>
<td>Surface Recording</td>
<td>2 Residual muscles</td>
<td></td>
<td>Residual muscles</td>
<td>Artificial limb control</td>
<td>Clinical practice</td>
</tr>
<tr>
<td>Surface Stimulation</td>
<td>4 Surface muscles</td>
<td></td>
<td>Surface muscles</td>
<td>Muscle stimulation</td>
<td>Clinical practice</td>
</tr>
<tr>
<td>Epineurial Stimulation</td>
<td>2 Peroneal nerve</td>
<td></td>
<td>Peroneal nerve</td>
<td>Drop foot</td>
<td>Clinical practice</td>
</tr>
<tr>
<td>Cuff Recording</td>
<td>1 Sural nerve</td>
<td></td>
<td>Sural nerve</td>
<td>Functional electrical stimulation control</td>
<td>Research/</td>
</tr>
<tr>
<td>Intracortical Stimulation</td>
<td>2 Subthalaric nuclei</td>
<td></td>
<td>Subthalaric nuclei</td>
<td>Parkinson’s disease</td>
<td>Clinical practice</td>
</tr>
<tr>
<td>Intracortical Recording</td>
<td>100 Cortex</td>
<td></td>
<td>Cortex</td>
<td>n.a.</td>
<td>Research</td>
</tr>
</tbody>
</table>
Cuff-Electrode

Materials:
- Insulation material: Polyimide
- Electrode material: Platinum or Indium

Advantages:
- Circular wire electrodes embedded in the inner wall of insulating hollow cylinder
- Placed in tissue with the nerve trunk along the axis
- Low stimulus current required
- Good isolation from surrounding excitable tissue
- With multiple cuff, a multigroove electrode, or a multiple contact electrode, one can obtain selective stimulation of individual fascicles.

Disadvantages:
- Surgical procedure required for installation
- Bulk
Penetrating Microelectrodes

- Silicon-based shaft microprobes: produced at Center for Integrated Sensors and Circuits of the University of Michigan
- Substrate is either needle- or wedge-shaped to allow penetration in the nervous tissue
- Recording or stimulation: → on surface and → at defined depths where electrodes are placed
- Multichannel silicon microelectrodes:
  → cochlear nerve of animals for auditory stimulation
  → sacral spinal cord for bladder contraction
- Highly flexible polyimide-based devices developed for interfacing per. nerves
  → not fully tested for intrafascicular nerve recording and stimulation
- Research: multielectrode arrays with 100 or more needle-shaped electrodes in silicon or silicon-glass technology for neural applications
- Silicon-glass technology for producing 3D arrays of 128 electrodes
Future advancements
Brain-machine interface for controlling movement of prosthetic limb

a.) BrainGate sensor
b.) silicon microelectrodes array:
   100 electrode sensor
   96 available for neural recording
   1 mm long; thinner than hair
c.) MRI of brain: electrode into right precentral gyrus
d.) first participant in the BrainGate trail:
   Move Cursor, send emails, play computer game
EEG & EMG Electrodes and BCI (Brain Computer Interface)

EEG:
- Sources of the EEG are the action potentials of the nerve cells in the brain.
  Most of the signal stems from the cortex
- Electrodes attached to scalp

Applications of EEG:
- epilepsy monitoring
- sleep analysis
- BCI
- evoked potentials
- biofeedback
EEG

- Cortex as source for EEG → int. 10/20 System

- Alpha: relaxed, eyes closed (8-13 Hz)
- Beta: waking activity (above 13 Hz)
- Theta: drowsy, dreamlike (4-7 Hz)
- Delta: deep sleep (below 4 Hz)

EEG & EMG Electrodes and BCI (continued)

Material:

- 99.9% real Silver (Ag) or Stannous (Sn)
- Silver-Electrodes get provided either with a silverchlorid (AgCl) or with a Gold (Au) coating
- Real Silver
- Polymer or nylon with silver deposits or carbon filled silicon rubber in the form of a thin film
EEG & EMG Electrodes and BCI (continued)

BCI:

Vorstellung einer Fußbewegung an zwei verschiedenen Meßtagen. Erregung der Fußregion am Vertex (oben)
References

Papers:
- Electrical stimulation of excitable tissue: design of efficacious and safe protocols
- A critical review of interfaces with the peripheral nervous system for the control of neuroprostheses and hybrid bionic systems
- Micromachined Multichannel Cuff Electrodes for Interfacing Small Nerves
- Neuronal ensemble control of prosthetic devices by a human with tetraplegia (Nature 442)
- Graz-BCI: State of the Art and Clinical Applications
- Control of hand orthosis by EEG vs. EMG in a patient with lesion at level C5/C6
- EEG-based neuroprosthesis control: A step towards clinical practice

Books:
- Bioelectricity: A Quantitative Approach (Second Edition, Plonsey and Barr)
- Biomedizinische Technik 1 (Hutten; Springer, New York, 1992)

Homepages:
- http://www.ifess.org/ (international FES society)
- http://people.brandeis.edu/~sekuler/eegERP.html (Image of EEG man)
- http://www.tugraz.at
- http://www.jhu.edu
- http://www.ottobock.ca
- http://www.sickkids.ca
- http://www.pubmed.com
- http://www.uspto.gov
- http://www.medcat.nl/supplies/DE/EEGelec.htm
Q & A period

- Are there any questions or comments?
- (nothing complicated please and thank you)