Summary of
TTK26 Biomedical instrumentation and control

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Contents

1 History of medicine

Biomedical engineering is engineering applied in medicine. Early witch doctors also used some empirical methods. Hippocrates was maybe the first consciously scientific doctor. Romans fixed some public health, esp. for troops. Hospitals, esp. before the 19th century, were places with high death rates for patients and staff. Florence Nightingale realized that the deaths were usually due to hospital conditions—not illnesses—and hospitals changed accordingly around the world. Science and technology have later changed hospitals and medicine dramatically. The biomedical engineer is really just an engineer who does something related to medicine.

2 Ethics of biomedicine

Todo: Write.

3 Anatomy and physiology

Anatomy is the study of the structure of the body and its parts. Physiology is the study of the functions of the body.

3.1 Anatomical terminology

Tables 1–2 define important anatomical terminology.

Term	Meaning
anterior/ventral	front
posterior/dorsal	back
lateral	side
proximal	near trunk or attached end of limb
distal	far from trunk or attached end of limb
superior	closer to head
inferior	closer to feet
medial	close to midline
lateral	away from midline
cranial	in the direction of the head
caudal	in the direction of the feet

Table 1: Anatomical directions

The main anatomical regions are the *axial* (head, neck, thorax, abdomen, pelvis) and *appendicular* (upper and lower extremities) parts of the body.

The anatomical cavities are

- the dorsal cavity, which includes of the cranial and spinal cavity,

Term	Meaning
midsagittal	plane that divides body into symmetrical halves
sagittal	parallel to midsagittal, but divides into asymmetrical halves
frontal	perpendicular to midsagittal, divides into anterior and posterior parts
transverse	perpendicular to midsagittal, divides into superior and interior parts

Table 2: Anatomical planes

- the ventral cavity, which contains the thoracic and abdominopelvic cavities, separated by the diaphragm, and
- the smaller cavities (nasal, oral, orbital, tympanic, synovial).

3.2 Cells

Eukaryotic cells—cells in plants and animals—consist of a membrane, cytoplasm, DNA, and various organelles. They synthesize carbohydrates, lipids and proteins, all of which provide structure to the cells. The carbohydrates also transport/store energy. The lipids store (more) energy. There are many proteins. Enzymes catalyze reactions, others act as channels through membranes, signal activities, and defend against harmful bacteria. These are made from amino acids.

3.2.1 Plasma membrane

The plasma membrane surrounds the cell, and separates it from the environment. It is a two-layer shell of lipids with hydrophobic ends inward and -philic ends outward. Cholesterol is scattered in the membrane to stabilize it structurally. Protein channels in the membrane control the motion of substances in/out of the cell. Some substances can cross the membrane easily, while others must pass through protein channels. Osmosis is when substances are selectively passed through, and diffusion is when concentrations equalize across it. Osmosis requires energy in the form of ATP.

3.2.2 Cytoplasm and organelles

Cytoplasm is a fluid containing organellese, which are specialized "small organs". The nucleus contains DNA in the form of chromatin, inside of a membrane. Ribosomes are made in the nucleolus, inside the nucleus. Ribosomes leave the nucleus to synthesize proteins.

3.3 Tissues

- Epitular tissue: Covers most surfaces, such as of skin and organs.
- Muscle tissue: Muscles, can be skeletal (attached to skeleton), smooth (in wall of blood vessels), or cardiac (only in the heart).
- Connective tissue: Holds everything together, several variations depending on what to hold together.
- Neural tissue: Neurons and glial cells that maintain the neurons.

3.4 Organ systems

11 systems, nervous and muscular most important

- Circulatory: The heart, blood, and veins. Moves nutrients and waste around, and regulates body temperature. The heart is made out of two pumps, consisting of two chambers each (one receives, one expels blood). Right pump sends blood to the lungs, left sends blood to the body. Two types of arteries, pulmonary (to/from lungs) and systemic (to/from body). A heartbeat begins with a pulse from pacemaker cells. This causes ions to move into the cells. This leads to the mechanical beating of the heart. In an electrocardiogram you can see de/polarization of atriums and ventriculars.
- Integumentary: Skin, hair, nails.
- Endocrine: Glands that secrete hormones.
- Lymphatic: Houses white blood cells, used as part of the immune system.
- Digestive: Mouth, esophagus, liver, stomach, small intestine, large intestine, rectum, anus.
- Urinary.
- Reproductive.
- Respiratory: Moves air to surfaces where diffusion between air and blood may happen. The conduction zone heats/humidifies/cleans incoming air. The respiratory zone (lungs) exchanges

oxygen/co2 with the body. Properties of the lungs: Compliance (how easily they expand), elasticity (how easily they return to original size), surface tension (resistance to expansion). Volumes of the lungs: Tidal (air in/out of lungs during normal breathing), total capacity (maximum amount of air to breathe in), vital capacity (maximum breath out), residual (amount left when you have breathed out as much as possible).

- Skeletal: Protects, supports body, helps with motion, produces blood cells and stores minerals. A living system, cont being replaced. three types of joinery: fibrous (solid, immovable), brusk (allows some motion during compression or twist), sinovial (fluid-filled cavities, regular joints)

- nervous: integrates and controls all bodily functions. central nervous system (encapsulated in bone, brain and spine), peripheral (everything else). can be divided also as somatic (non-autonomous control) and autonomous (everything that is done without consiocsness). latter divided into sympathic (fight or flight) and parasympathic (relaxing to normal condition when no danger). nervous system consists of neurons (cell body, axon, dendrites). dendrites receive signals, send them to axons. many neural circuits exist, such at convergent/divergent circuits. brain is the largest part of the nerv system: built off cerebrum (the two halves). frontal lobe (conscious action), isselapper (hud/muskelstimuli), tinningslapper, bakhodelappene. diencephalon: connect stem to halves. consists of thalamus, hypothalamus, apithalamus brainstem and small brain. stem connects brain to spine. small brain second largest part of brain, coordinates balance/position/timing and precision of movements

- muscular system: agonist (biceps), antagonist (triceps), synergist (assisting agonists). three types of tissue: cardiac (heart only). skeletal (connected to bone, skin, tendons). smooth muscle (surrounds tissue in most organs) slow and quick tissue, muscles consist of a mix of both. properties of muscle tissue: contractability, excitability, extensibility, elasticity (return to original shape).

3.5 Homeostasis

homeostasis: all systems of the body work to maintain a constant environment. homeostasis is the process where physical and chemical stuff is maintained in the face of external effects extracellular fluid is important for this: surrounds cells, etc.

4 Studying the nervous system

Dendrites: Receptors. Axons: Transmitter of the nerve cell. Some short (micrometers), some long (meters). Myelin sheath protects axon and helps signal transmission (insulative). Axons release neurotransmitters, which are picked up by other cell's dendrites. Cell body/soma receives signals and sends to axon as an action potential.

Presynaptic cell sends a signal, post- receives. The synaptic gap is between them. The action potential cause the neurotransmitters to move to the other cell. Synaptic transmission: Synapses are where two neurons exchange neurotransmetters.

Glial cells maintain the nervous system. Microglia protect the central nerv system. Macroglia do other supportive stuff.

4.1 Cellular components of the nervous system

4.2 Neurons

Sensory neurons have no dendrites, but have cell bodies responsive to term/touch/etc.

4.3 Neural circuits

Neurons org. in groups. nerv circuits. Flow of information: Afferent nerv cells: Information inward. Efferent: Information outward. Internerv: Korte lokale.

5 Electrical signals of nerve cells

Resting: Constant potential when neuron is inactive. Inside negative rel. to outside of cell. Na+ is "pumped" in and K+ out all the time, but not identical flows. This reaches equilibrium with the diffusion of the cells, and therefore reaches a constant, nonzero potential across the cell membrane. Receptorpotential:

Axons: Poor conductors.

Neurotransmitters cause dendrites to accept Na+ from intracellular fluid (?), which raises the cell potential from the negative resting potential. With only a few Na+, the potential stabilizes back at the resting pot., but with enough Na+ in a short interval, the potential rises above a threshold. Then proteins in the axon hillock (where axons are connected to the soma) change when the threshold is reached, which make them permeable to Na+, so it flows into the cell, and further increases the potential. A second threshold opens proteins that let through only K+, which flows in and reduces potential. The potential reduces to also stop Na+ proteins. This electrical pulse (action potential) propagates through the axon in a chain reaction. The nerve cell has a "refractory period", and cannot generate a new pulse until it has more or less returned to equilibrium.

Vesicles are blobs of membrane filled with something useful.

5.1 Long-distance transmission of electrical signals

5.2 How ion movements produce electrical signals

5.3 Forces that create membrane potentials

5.4 Electrochemical equilibrium in an environment with more than one permeant ion

5.5 The ionic basis of the resting membrane potential

5.6 The ionic bases of action potentials

6 Origin of the myoelectric signal

muscle is made out of a bundle (facicle) of muscle fibres (which are cells with many nuclei), made out of a bundle of myofibriles, made out of a bundle of sarcomeres (smallest contractile unit)

sarcomeres: z-disc, i-band, a-band, h-zone, actin/myosin-filaments that overlap to varying degree depending on contraction troponin/tropomyosine hinders contraction / promotes relaxation

motor units: single nerve, connected to a number of muscle fibers. tension generated function of frequency of motor nerve signal and number of motor units recruited

nerves connect to muscle fibers at fibre end plates, via axons. a firing of the neuron depolarizes the fibre. this eventually leads to a release of calcium ions in the fibre, which pulls tropomyosine away to allow myosine to attach to actine, and mechanically ratched the muscle, causing contraction. troponine blocks the myosine from attaching to the actine when there is no calcium to pull it away

muscle fibre action potentials are just like in the nerve cells, but much stronger due to their size

1. latent period: Na causes Ca to be released and troponin/tropomyosin begins to lift from the actine 2. contraction period: cycles of myosine binding to actine and releasing 3. Ca is pumped out of the fibre and increasingly more myosin is ... blocked?

something about proprioceptors ("spend some time on the spindle") alpha motor neurons control regular muscle fibers (extrafusal) gamma motor neurons centrol the intrafusal muscle fibers. a nerve cell grows around the intrafusal fibre, an afferent nerve cell. intra- and extrafusal fibres are actuated in parallel, and the intrafusal detect if there is a mismatch/error between the response and the desired value. this is fed back to the alpha neurons and then to the extrafusal fibres. (WILL BE ON EXAM, understand the mechanism!)

length-tension relation graph

7 Myoelectric control

About how the MES is acquired, processed, and used for control of upper limb prostheses. Control systems are usually either off/on or proportional controllers for speed control.

7.1 Variation of the MES with contraction level

Surface electrodes cannot very well discern activation of individual motor units, but the variance of the noise-like signal they read is related to the contraction level of the muscle.

7.2 Acquiring the MES

The signal picked up must be amplified: Capacitive coupling between the human and 50/60 Hz power lines gives a common mode voltage component to electrodes on the skin. The common mode voltage is rejected with a differential amplifier (Figure 1), while the voltage difference is amplified. Sometimes a notch filter is used to attempt further removal of the common mode signal.

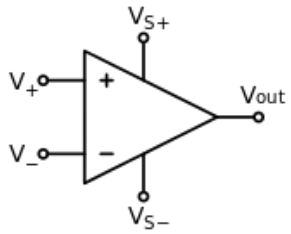

Figure 1: A differential amplifier

7.3 Motion artifact

If the electrodes move relative the skin, the skin under them is stretched, or they are lifted, the output signal is corrupted. The extra noise can be confused with the true MES. For real-life use, the only way to avoid this is to make sure the electrodes stay put in the prosthesis, i.e. the prosthesis must fit very well.

7.4 Processing the MES

The MES is roughly zero-mean noise, but variance is related to contraction. A square law device is seemingly optimal in the sense of minimizing error. To lower power consumption, a full wave rectifier is usually used to the same effect. The rectified signal is low pass filtered to give a smooth curve. The result is a processed myoelectric signal (PMES).

7.5 Two-site control of prosthetic function

Two-site control uses two separate muscle groups to control the prosthesis. Usually antagonistic muscles, because it feels more intuitive and therefore shortens learning time.

A small signal can be picked up when the muscles are resting. This signal must be removed/ignored. That can be done by a simple threshold. With a two-site system, you must address the issue of co-contraction. Usually the first muscle to activate is prioritized, and signals from the other muscle are ignored until the first is relaxed.

7.6 Controlling the speed of the terminal device

With proportional control, the speed of actuation is proportional to level of the PMES. Especially useful for large joints (e.g. elbow) that need fast coarse motion as well as slow fine motion. An alternative method is to move the joint proportional to the difference of the PMES at each of the two sites. Furthermore, the co-contraction signal has been used as a “switch” to change operation mode.

Because lowering speed by means of lowering the motor voltage also lowers the torque, prostheses usually lower the speed with PWM, running at nominal voltage.

Spacing between electrodes affect the signal. Wide spacing gives more smearing and loss of high-frequecy information. Narrow spacing gives a better signal representation.

7.7 Multi-function control strategies

Multi-function control strategies control the elbow and hand with the same myoelectric system. An example is a system as described above combined with switches and harnesses (for body-powered control).

7.8 Single myoelectric channel model

The MES $M(t)$ can be written as a sum of individual muscle signals $m_i(t)$:

$$\begin{aligned} M(t) &= \sum_{i=1}^{m} m_i(t) \\ &= \sum_{i=1}^{m} U(t, \lambda_i, p_i) P(t, r_i) \end{aligned} \tag{1}$$

where

- $U(t, \lambda_i, p_i)$ is the pooled innervation point process with firing rate λ_i and pattern p_i,
- $P(t, r_i)$ is the average motor unit action potential seen at an electrode with distance r_i.

The firing rate, or recruitment, λ_i is controlled voluntarily. σ_i^2 is the variance of m_i. σ_m^2 is the variance of $M(t)$. By the relationship

$$\sigma_m^2 = \sum_{i=1}^{m} k_i \lambda_i \tag{2}$$

we see that we have also voluntary control of the variance. For time-varying λ_i, the relation is

$$\sigma_m^2(t) \approx \sum_{i=1}^{m} k_i \lambda_i(t). \tag{3}$$

So we can voluntarily control a signal $\sigma_m^2(t)$ which can be acquired by electrodes and used for prosthesis control. $\sigma_m^2(t)$ is the variance of the detected MES, and it is roughly a weighted sum of recruitment parameters $\lambda_i(t)$, which are controlled by muscle contraction.

8 Muscle modeling

The main purpose of a mathematical model is

- *comprehension*, the ability to aid in understanding the system, and
- *prediction*, the ability to predict dynamics outside of experimental boundaries.

Further, a good model should have

- *credibility*, that it predicts well, and
- *tractability*, that it is simple.

In a way, these oppose each other: A very precise model is often also very complex. It is necessary to balance these qualities.

8.1 Types of muscle models

Divided first by the level they represent:

1. Microscopic (crossbridge/sarcomere) models
   (a) Conventional cross-bridge models (introduced by Huxley)
   (b) Unconventional cross-bridge models (based on different postulates than Huxley's)
2. Macroscopic (whole muscle) models
   (a) Viscoelastic models (consider muscle as viscoelastic material)
   (b) Hill-type models (based on Hill, 1938)
   (c) Black box models (use system identification methods)
3. Fiber models

8.2 Conventional microscopic models

Introduced by Huxley, 1957 and improved upon since. Assumes all sarcomeres identical, and macroscopic properties can be calculated through integrals on $n(x, t)$, where n is ...

Huxley's model was extended by hill with more states of the ...

8.3 Unconventional microscopic models

Founded on different assumptions.

Bornhorst & Minardi Modeling each cross-bridge as linear energy converters.

Iwazumi No direct binding between myosine and actin, ATP causes hydrolysis.

Tirosh Hydrodynamic model

Hatze Assume elastisity in Z-disks and M-lines rather than in the cross-bridges.

8.4 Macroscopic models

Viscoelastic Assume muscle is viscoelastic material. Can be represented by a spring-damper in series with an undamped spring.

Hill-type Improvement upon viscoelastic. Most used model for dynamic analysis and control. Consists of a series elastic element, a contractile element, and a parallel elastic element. Made to model contraction under max stimuli over short contraction distances. Has been further developed in many directions.

$$\dot{L} = C(P)\dot{(P)} - F(P, P_0) \tag{4}$$

8.5 Black box models

Based on statistics: Do a bunch of experiments, and fit a model to the data. Many model types can be used

- LTI SISO
- etc...

Simplest form is an LTI SISO system

$$y(t) = \int G(t-\tau)\dot{x}(\tau)\,\mathrm{d}\tau \tag{5}$$

Time delay τ represents phase delay at high frequencies and is sometimes simplified away.

Can also write a 2I1O-model: Muscle force a function of length and activation.

8.6 Fiber models

Fibres are assumed non-uniform, as opposed to other models.

8.7 Distribution-moment models

Represents the bond restriction function $n(x,t)$ from Huxley model as a Gaussian probability distribution dependent on stiffness, force, and elastic energy.