HEALTH TECHNOLOGY AND HUMAN SYSTEM: MAN AS A LIVING MACHINE

Health technology as defined by the World Health Organization is the application of organized knowledge and skills in the form of devices, medicines, vaccines, procedures and systems developed to solve health problems and improve quality of life. When treating the body as a machine, these technologies serve to fix, replace or enhance mechanical functioning.

Biomedical engineering is an interdisciplinary field based in both Engineering and Life sciences. It is important for biomedical engineers to have knowledge about it and be able to communicate in both areas. Biomedical engineers must understand the basic components of the body and how they function well enough to exchange ideas with physicians and life scientists. Two of the most basic terms in life sciences are Anatomy (internal and external structures of the body and their physical relationships) and Physiology (study of the functions of those structures) have knowledge on how the body functions. Physiology is just applied control systems, fluid mechanics, electrical engineering, and mechanics—but with living components.

The human body is regarded in biomedical engineering as a sophisticated, autonomous, biological machine. Just as mechanical systems require fuel, structural integrity and control mechanisms. The human body consists of interconnected organ systems (skeletal, digestive, circulatory, respiratory) that work together to produce, sustain and protect life. It is a living entity that processes fuel (food/oxygen) to produce work, heat and structural growth. Many systems e.g. digestion, heart beats functions without conscious thought via autonomous nervous system. It is a complex, adaptive featuring sensors, feedback loops and self-repair capabilities. The respiratory system is the part of the body that handles breathing. The digestive system is concerned with food breakage. The circulatory system pumps blood to all parts of the body.

Why Engineers Study Physiology

Engineers design for the body, but the body is not a car or bridge. It is a self-regulating, adaptive, living system. A device that works perfectly in the lab can fail in a patient if you don't understand how the body will respond. The solution is to model the body as interconnected subsystems with inputs, outputs, feedback, and control loops.

Why View Man as a Living Machine?

Design by Analogy: If the heart is a pump, we can design an artificial pump to replace it.
Quantification: Engineering deals with measurable quantities – pressure, flow, voltage, force. Viewing the body this way allows us to measure and control biological processes.

System Thinking: The body is not isolated organs. It's a network where failure in one part affects others, just like a mechanical or electrical system.

Intervention: If we understand the "design" of the body, we can intervene when it fails – with drugs, devices, or surgery.

Limitation: Unlike machines, the body can self-repair, adapt, and regulate itself. This is called homeostasis and makes it more complex than any man-made machine.

The Human Body as an Engineering System - The Body as a System of Systems

The body is organized in levels, from simple to complex:

Atom → Molecule → Cell → Tissue → Organ → Organ System → Organism.

Combination of tissues that perform complex tasks are called organs and organs that function together form organ systems. The human body has 11 major organ systems: integumentary, endocrine, lymphatic, digestive, urinary, reproductive, circulatory, respiratory, nervous, skeletal and muscular. The integumentary system (skin, hair, nails and various glands) provides protection for the body. The endocrine system (ductless glands such as the thyroid and adrenals) secretes hormones that regulates that regulate many chemical actions within the cells.

For biomedical engineering, we focus on organ systems because devices usually interact at this level.

We can break the body into subsystems, each with an engineering equivalent

System	Engineering Analogy	Main function	Key measurable variables
Cardiovascular	Fluid pump and pipe network with valves	Transport oxygen, nutrients , waste	Blood pressure, flow rate(L/min), heart rate
Respiratory	Air handling unit and gas exchanger	Gas exchange: Oxygen in, carbon dioxide out	Tidal volume, respiratory rate (breaths/min), SpO2(%)
Nervous	Electrical signal network with sensors	Control, sensing, communication	Action potential, nerve conduction velocity(m/s)
Musculoskeletal	Mechanical structures and actuators	Support, movement, structure	Force, torque, angle
Renal	Filtration plant and fluid control	Filter blood, maintain fluid balance	Urine output(ml/day)
Thermoregulatory	Feedback control system	Maintain body temp	Core temp(C), Sweat rate (L/h)

Every physiological process has measurable inputs, states, and outputs and can be described using engineering concepts: flow, pressure, resistance, capacitance, control, feedback, energy conversion. That's why sensors and devices can interface with the body.

Homeostasis: The Body's Control System

Homeostasis is the body's ability to maintain a stable internal environment despite external changes. The body maintains stability through feedback control, just like engineered systems. Most physiological control uses negative feedback to reduce deviation from set point.

Feedback Mechanisms

Negative Feedback- The main mechanism: The body is a set of negative feedback control systems with set points. This is the most common. It reduces the output to bring the system back to set point. For example; Body temperature regulation. The set point is 37^{o}C, sensors are skin and core temperature receptors, controller is hypothalamus, and effectors are sweat glands, blood vessels and muscles. If temp >37°C, sweat glands activate and blood vessels dilate to cool down. . If temp <37°C, shivering + vasoconstriction heat the body.

In biomedical engineering application, Insulin pumps and ventilators are artificial negative feedback systems. Engineering parallel: e.g. a thermostat controlling an air conditioner.

Positive Feedback: This amplifies the output. It is rare and usually for processes that must complete quickly. It is not used for regulation. For example; Blood clotting and childbirth contractions. This is highly risky and can cause instability if not controlled. This is why uncontrolled clotting is dangerous.

Engineering parallel: e.g. Audio feedback when a microphone is too close to a speaker.

Why This Matters for Health Technology

Medical devices mimic or assist these control systems:

i. Insulin pump: Measures blood glucose and adjusts insulin delivery which serves as artificial negative feedback.
ii. Ventilator: Controls airflow to maintain blood CO_2 at set point.
iii. Pacemaker: Senses heart rate and sends electrical pulses if it drops too low – artificial pacemaker for the nervous system.

1. **The Cardiovascular System – A Fluid Mechanics Problem**

The heart is a pump. Blood vessels are pipes. Blood is a non-Newtonian fluid.

Key engineering parameters:

Cardiac Output: CO = Heart Rate × Stroke Volume. Normal: 5 L/min at rest.

Blood Pressure: BP = CO × Total Peripheral Resistance. Normal: 120/80 mmHg.

Blood Flow: Governed by Poiseuille's Law: $\text{Flow} \propto \Delta P \times r^4 / \mu L$

Application of this system in biomedical engineering includes: Pressure sensors (Arterial lines, non-invasive BP cuffs), Pumps (Heart-lung machine, ventricular assist devices), Valves

(Mechanical and bio-prosthetic heart valves), Flow measurement (Doppler ultrasound, electromagnetic flow meters),

Design constraint: Blood cells are fragile. Shear stress >400 Pa damages red cells. So pumps must be designed carefully.

2. **The Respiratory System – A Gas Exchange System**

The respiratory system moves air to and from the gas exchange surfaces in the body where diffusion can occur between air and the circulating blood. This system functions to bring Oxygen to blood and remove Carbon dioxide. It is a counter-current gas exchanger with ventilation-perfusion matching.

Key parameters:

Tidal Volume: Air moved per breath. Normal: 500 ml.

Respiratory Rate: 12–20 breaths/min at rest.

Alveolar Ventilation: Effective gas exchange volume.

Oxygen Saturation (SpO_2): Percentage of hemoglobin carrying oxygen. Normal value is between 95–100%.

BME applications are; Ventilators (Control volume, pressure, and rate to maintain blood gases), Pulse-oximeter (Measure SpO_2 using light absorption – Beer-Lambert Law), Spirometers (Measure lung volumes and flows).

3. **The Nervous System – An Electrical System**

Is responsible for the integration and control of all the body functions. It has fast communication and control using electrical signals.

Key concepts: The nervous system contains Neurons-Cell that transmits signals via action potentials.

The Action Potential is a rapid, temporary spike in electrical voltage that travels down a neuron's axon to transmit information across the nervous system.100 mV electrical pulse, 1–120 m/s conduction velocity. Synapse: Junction where chemical signals convert to electrical signals.

Key parameters:

Membrane Potential: -70 mV resting.

Threshold: -55 mV to trigger action potential.

Frequency Coding: Stronger stimulus = higher firing rate.

Applications of the nervous system in biomedical engineering are:

Electroencephalogram (EEG): Is a non-invasive medical test that tracks and records the electrical activity of the brain. Small metal discs (electrodes) are placed on the scalp to detect brain cell communication. It is used by healthcare providers to monitor epilepsy and seizure disorders and also to investigate sleep disorders.

Electrocardiograph (ECG): is a simple non-invasive medical test that records the electrical signals the heart produces each time it beats. Small sensors (electrodes) are attached to the chest, arms and legs. These patches are connected to a machine that translates the hearts electrical activity to a visual tracing on a screen or paper.

Cochlear Implants: is an electronic device that improves hearing. It is unlike hearing aids that makes sounds louder, it bypasses the damaged inner ear hair cells and directly stimulates the auditory nerve to transmit sound signals to the brain. In simpler terms, it converts sound to electrical signals for the auditory nerve.

Deep Brain Stimulation: Is a neurosurgical procedure that implants a pacemaker-like device to send electrical impulses to targeted areas of the brain. It is an electrical stimulation to treat Parkinson's.

Design constraint: Signals are microvolts (the electrical activity being transmitted is incredibly weak and delicate) Devices need high input impedance and shielding to avoid noise.

4. **The Musculoskeletal System – A Mechanics Problem**

The function of this system is for Support, movement, protection.

In an engineering view, Bones are beams, joints are hinges/ball-sockets, muscles are actuators, tendons are cables.

Key parameters:

- *Force*: Muscle can generate 30–40 N/cm².

- *Torque*: Force × lever arm. Determines joint movement.

- *Range of Motion*: Limited by joint geometry.

BME applications:

Prosthetics & Orthotics: Replace or assist limb function.

Joint Implants: Hip, knee replacements using titanium and UHMWPE.

Gait Analysis: Use force plates and motion capture to study movement.

Exoskeletons: Assistive devices for rehabilitation.

Design constraint: Implants must match bone stiffness to avoid "stress shielding" and bone loss.

5. **Renal and Thermoregulatory Systems – Fluid and Energy Balance**

The Renal System filters 180 L of blood/day and produces 1.5 L urine. It controls water, electrolytes, pH.

BME application: Dialysis machines replace kidney filtration.

The Thermoregulatory System maintains core temp at 37°C ±1°C. It uses sweating, vasoconstriction/dilation, shivering.

BME application: Incubators for neonates, cooling blankets for hyperthermia.

How Health Technology Interfaces with the Human Machine

Health technology interacts with the body at 3 levels:

- **i.** **Monitoring Level** Devices measure signals without changing the body. Examples: ECG electrodes, pulse oximeter, thermometer, BP cuff. Engineering principle: Sensors + signal conditioning + display.
- **ii.** **Assisting Level** Devices take over or support a failing function. Examples: Ventilator assists breathing, dialysis machine filters blood, and hearing aid amplifies sound. Engineering principle: Control systems, fluid mechanics, signal processing.
- **iii.** **Replacing Level** Devices permanently replace a body part. Examples: Artificial hip joint, heart valve, cochlear implant, prosthetic limb. Engineering principle: Biomaterials, biomechanics, biocompatibility.

Translating Physiology to Engineering Design

Every time you design a device, ask:

1. What variable am I measuring or controlling? Pressure, flow, voltage, temperature?

2. What is the normal range? Device must work in 95–99% of patients.

3. What is the dynamic range? Body variables change 10–100x during exercise.

4. What is the time constant? Heart rate changes3 in seconds, glucose in minutes, temperature in hours.

5. What are the safety limits? Electrical current >500µA can cause micro shock.

For Example: In designing a pulse oximeter, Variable: Light absorption at 660nm and 940nm, range for SpO_2 is 70–100% with time constant: 5–10 seconds for averaging. Safety: LED power <10 mW to avoid burns.

Key Equations

1. **Ohm's Law for Blood Flow**: In hemodynamics, ohms law states that blood flow (F or Q) is directly proportional to pressure difference and inversely proportional to vascular resistance.

i.e. $\Delta P = Q \times R$

Pressure difference = Flow × Resistance. Used in BP and dialysis design.

Flow (F or Q) - the volume of blood passing a specific point per unit time. (L/min)

Pressure difference- the driving force or pressure gradient that pushes blood forward. i.e. difference between the initial pressure(arterial) and final pressure(venous).

Resistance- friction opposing the blood flow.

Ohms law is the fluid equivalent of the electrical formula I=V/R, where, flow→electrical current

Pressure→voltage

Resistance→electrical resistance

Engineers leverage this framework to: (A) Design medical devices (by calculating the required pump pressures for ventricular assist devices or heart lung machines). (B) Model arterial networks (simulates how blood diverts through parallel and series vessel pathways in organs)

2. **Poiseuille's Law**: this describes how the rate of fluid flow depends on the fluids viscosity, the tube dimensions and the pressure difference. It is widely applied to blood flow in the human body.

$Q = \pi \Delta P r^4 / 8\mu L$. Where: Q – volume flow rate

r - Radius of the pipe or tube

μ- Viscosity of the fluid

L- Length of the tube

ΔP- pressure difference between the two ends

Poiseuille's law is used by BME to model blood flow in arteries and veins. It is important when design implants like vascular stents or synthetic grafts to minimize resistance and maintain tissue perfusion. Small changes in vessel radius cause huge changes in flow. Explains hypertension.

3. **Nernst Equation**: E = (RT/zF) ln (out/[C]in)

Explains resting membrane potential of neurons.

4. **Beer-Lambert Law**: is used to determine the concentration of substances in a solution. The Beer-Lambert Law is the foundational physical principle in biomedical engineering that relates the attenuation of light to the properties of the material or tissue it travels through.

$A = \varepsilon c l$

Applications in BME. Basis for pulse oximetry- Standard clinical pulse oximeters use the law to measure oxygen saturation in arterial blood (SpO2). Oxygenated hemoglobin and deoxygenated hemoglobin absorb different wavelengths of red and infrared light. Measuring the ration of the light absorbed, the device calculates the ration of oxygenated to total hemoglobin.

Applications in Health Technology Design

Understanding “man as a living machine” directly guides device design:

1. Prosthetic Limb Design: Uses principles of levers, torque, and control systems from the musculoskeletal system.

2. Cardiovascular Devices: Stents and artificial valves are designed using fluid mechanics of blood flow.

3. Wearable Sensors: Designed based on electrical properties of skin and tissue to measure heart rate, glucose, etc.

4. Rehabilitation Robotics: Mimics neural control and muscle activation patterns to retrain movement after stroke.

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Common Design Mistakes When Ignoring Physiology

1. Ignoring variability: Designing for a 70kg male only. Women, children, elderly differ.

2. Ignoring feedback: A drug pump that doesn’t account for the body’s natural insulin response causes hypoglycemia.

3. Ignoring biocompatibility: Material triggers inflammation, device fails.

4. Ignoring dynamics: Device responds too slowly for heart rate changes.

Summary

1. The body is a set of interconnected control, fluid, electrical, and mechanical systems.

2. Homeostasis is maintained by negative feedback loops. Most medical devices mimic or support these loops.

3. Every physiological process can be described with engineering parameters: pressure, flow, voltage, force.

4. Good BME design requires understanding normal physiology, normal ranges, and safety limits.

One-line takeaway: If you don’t understand how the healthy system works, you can’t fix the broken one.