MASINDE MULIRO UNIVERSITY OF SCIENCE AND TECHNOLOGY
Technology for Development

ECE 331 – INTRODUCTION TO BIOMEDICAL ENGINEERING

STUDY GUIDE: MUSCULAR SYSTEM FOR BIOMEDICAL ENGINEERING

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1. INTRODUCTION TO THE MUSCULAR SYSTEM

The muscular system is a complex network of specialized tissues responsible for movement, stability, and heat generation. For biomedical engineers, understanding the muscular system is crucial for developing rehabilitation devices, prosthetics, biomaterials, surgical techniques, and diagnostic tools.

2. TYPES OF MUSCLE TISSUE

The human body contains three types of muscle tissue: skeletal (voluntary movement), cardiac (heart contraction), and smooth (involuntary actions in organs).

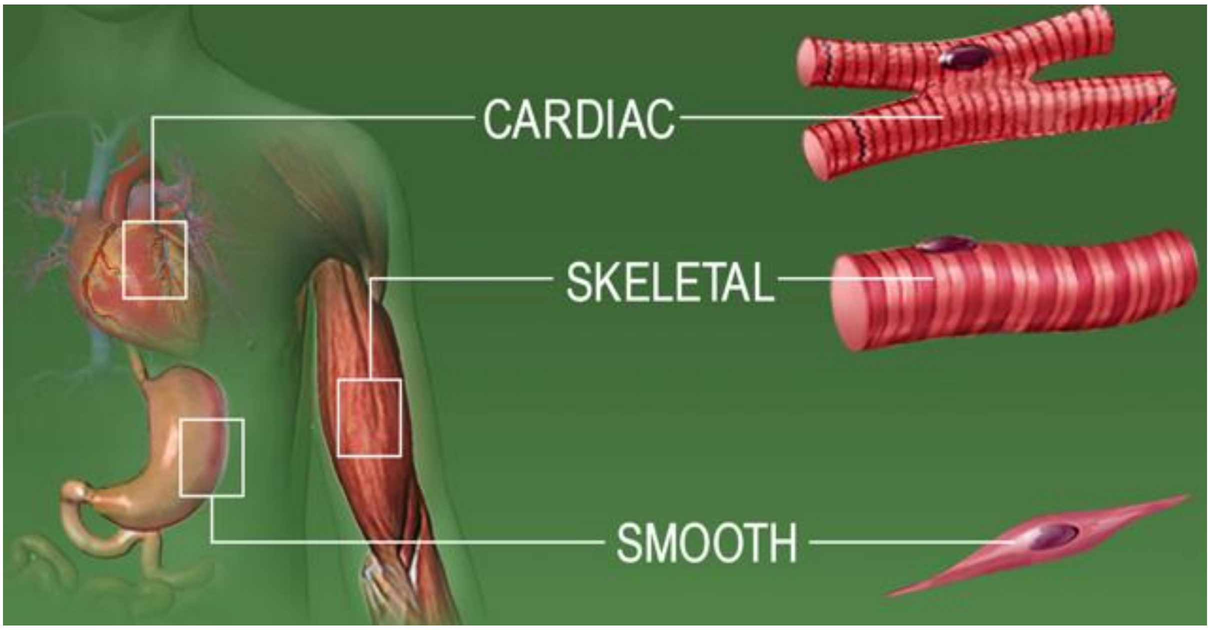

Figure 1. Types of muscles

2.1. Skeletal Muscle

2.1.1. Structure of skeletal muscle

Skeletal muscle is hierarchically organized into bundles of muscle fibres (cells) containing myofibrils, which are themselves composed of repeating sarcomere units that facilitate contraction through the sliding filament mechanism. Skeletal muscles are striated, multinucleated fibres under voluntary control.

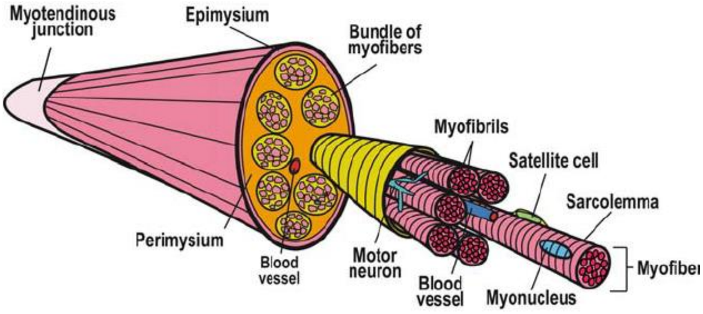

Figure 1. Structure of the skeletal muscle

2.1.2 Functions of skeletal muscle:

Skeletal muscle enables voluntary movement, maintains posture, and generates heat for thermoregulation.

2.1.3 Bioengineering Relevance of anatomy and physiology of skeletal muscles:

Skeletal muscle serves as the body's biological actuator, converting chemical energy into controlled mechanical force and movement, which is the fundamental principle behind biomechanics and the inspiration for robotic and prosthetic design. Specifically, the following biomedical engineering areas require knowledge of the anatomy and physiology of skeletal muscles:

a) Prosthetics and orthotics design

b) EMG-based control systems

c) Rehabilitation engineering

d) Biomechanical modelling

2.2. Cardiac Muscle

2.2.1 Structure of the cardiac muscle:

Cardiac muscle is a striated, branched tissue with single central nuclei and interconnected cells joined by intercalated discs that enable synchronized, involuntary contractions for pumping blood. **Cardiac muscles are striated, branched fibres with intercalated discs.**

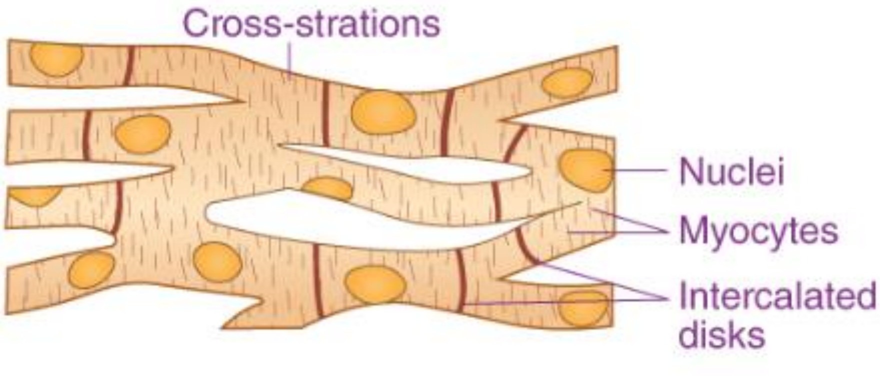

Figure 2. Structure of the cardiac muscle

2.2.2 Functions of cardiac muscle:

Cardiac muscle contracts rhythmically and involuntarily to **pump blood throughout the body, maintaining circulation.**

2.2.3 Engineering Relevance of the anatomy & physiology of cardiac muscles

Cardiac muscle functions as an autonomous, fatigue-resistant biological pump, providing the continuous hydraulic power necessary to circulate oxygen and nutrients throughout the body's closed circulatory system. Specifically, the following biomedical engineering areas require knowledge of the anatomy and physiology of cardiac muscles:

a) Cardiac assist devices

b) Pacemakers and defibrillators

c) Tissue engineering of heart muscle

d) Cardiovascular biomaterials

2.3. Smooth Muscle

2.3.1 Structure of smooth muscle

Smooth muscle in the human body is composed of involuntary, spindle-shaped (fusiform) cells with a single nucleus and no striations, organized into sheets within the walls of hollow organs. Key words: Non-striated, spindle-shaped cells.

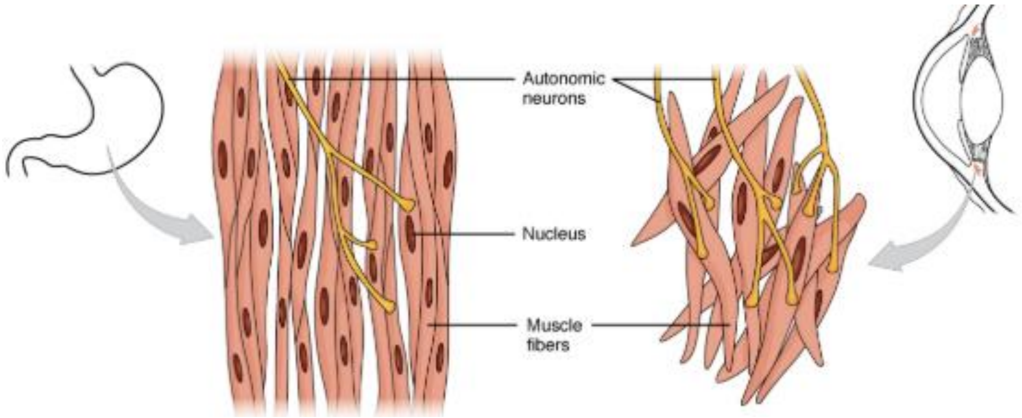

Figure 3. Smooth Muscle

2.3.2 Functions of smooth muscle

Smooth muscle performs involuntary, sustained contractions that propel substances through internal passageways (like digestion) and regulate the diameter of structures (like blood vessels and airways).

2.3.3 Engineering Relevance of Knowledge of Smooth Muscles

Smooth muscle acts as the body's innate system of micro-valves and pumps, autonomously regulating the flow of fluids and materials within vital organ systems like circulation, digestion, and respiration. Specifically, the following biomedical engineering areas require knowledge of the anatomy and physiology of smooth muscles:

a) Drug delivery systems

b) Stents and vascular grafts

c) Gastrointestinal devices

d) Urological implants

3. MUSCLE STRUCTURE AND ORGANIZATION

3.1 Hierarchical Organization:

1. **Muscle** → 2. **Fascicle** → 3. **Muscle Fiber** (cell) → 4. **Myofibril** → 5. **Sarcomere**

3.2 Key Components:

- **Sarcomere**: Basic contractile unit (Z-disc to Z-disc)
- **Myofilaments**:
  - Thick filaments: Myosin
  - Thin filaments: Actin, troponin, tropomyosin
- **Sarcoplasmic Reticulum**: Calcium storage
- **T-tubules**: Transmission of action potentials

3.3 Mechanism of Muscle Contraction

3.3.1 Sliding Filament Theory

1. **Excitation**: Action potential reaches neuromuscular junction
2. **Excitation-Contraction Coupling**:
   - AP travels along T-tubules
   - Calcium release from sarcoplasmic reticulum
3. **Cross-Bridge Cycling**:
   - Calcium binds troponin → tropomyosin moves
   - Myosin heads bind actin
   - Power stroke occurs
   - ATP binds to myosin → detachment
4. **Relaxation**: Calcium reuptake into SR

3.4. Engineering Applications

- Mathematical modelling of contraction dynamics
- Design of muscle-like actuators
- Development of synthetic muscles

4. MUSCLE BIOMECHANICS

4.1 Force Production Factors:

1. **Length-Tension Relationship**: Optimal sarcomere length for maximal force
2. **Force-Velocity Relationship**: Inverse relationship between velocity and force
3. **Force-Frequency Relationship**: Increased stimulation frequency increases force

4.2 Types of Contractions:

- **Isometric**: Constant length, changing tension
- **Isotonic**: Constant tension, changing length

    - Concentric: Muscle shortening
    - Eccentric: Muscle lengthening

4.3 Engineering Considerations

- Material properties of muscle tissue
- Stress-strain relationships
- Fatigue resistance
- Energy efficiency

4.4 Neuromuscular Physiology

Motor Units:

- **Definition**: A motor neuron and all muscle fibers it innervates
- **Size Principle**: Smaller motor units recruited first

Proprioception:

- **Muscle Spindles**: Detect muscle length and rate of change
- **Golgi Tendon Organs**: Detect muscle tension

5. BIOMEDICAL ENGINEERING APPLICATIONS

5.1. Prosthetics and Orthotics

- Myoelectric control systems
- Powered exoskeletons
- Adaptive control algorithms

5.2. Diagnostic Tools

- Electromyography (EMG)
- Muscle biopsy analysis
- Motion capture systems

5.3. Surgical Interventions

- Muscle flap reconstructions
- Tendon transfers
- Surgical robotics

5.4. Tissue Engineering

- Scaffold design for muscle regeneration
- Bioreactors for muscle tissue growth

- Stem cell therapies

5.5. Rehabilitation Engineering

- Functional electrical stimulation
- Robotic therapy devices
- Virtual reality rehabilitation

5.6. Biomaterials

- Synthetic muscles (electroactive polymers)
- Smart materials for responsive implants
- Biocompatible coatings

5.7. Other Applications

- Musculoskeletal simulation
- Prosthesis control
- Surgical planning
- Sports biomechanics

6. KEY CONCEPTS IN MUSCULAR SYSTEM FOR BIOMEDICAL ENGINEERS

6.1 Electromechanical coupling

Electromechanical coupling in the muscular system describes the fundamental process by which an electrical stimulus, an action potential, is transduced into a mechanical force output, or contraction.

6.2 Energy conversion

In the muscular system, energy conversion is a multi-stage biochemical-to-mechanical process where the chemical energy stored in adenosine triphosphate (ATP) molecules is ultimately transformed into the kinetic energy of contraction; this process is initiated by ATP hydrolysis, which provides the energy for myosin heads to perform a power stroke, pulling actin filaments and shortening the sarcomere, with immediate ATP reserves replenished through the rapid phosphorylation of ADP by creatine phosphate and longer-term synthesis of ATP via anaerobic glycolysis and aerobic oxidative phosphorylation in the mitochondria to sustain muscle function. Emphasis is on the efficiency of chemical to mechanical energy conversion

6.3 Adaptability

Skeletal muscle is a highly adaptive biomaterial whose structure and function are dictated by its mechanical loading history. In response to progressive training, muscle undergoes hypertrophy by increasing protein synthesis and recruiting satellite cells to add sarcomeres in parallel, thereby increasing its force-generating cross-sectional area and improving neuromuscular efficiency. Conversely, mechanical disuse triggers rapid atrophy through pathways like the ubiquitin-proteasome system, degrading proteins and reducing mass and strength. Adaptability deals with muscle response to training, disuse, and rehabilitation.

6.4 Fatigue

Muscle fatigue is the exercise-induced reduction in the force-generating capacity of muscle, a phenomenon driven by a complex interplay of metabolic and neural factors where, from a biomedical engineering perspective, the system's efficiency degrades due to a failure at multiple points.

6.5 Biocompatibility

Biocompatibility is the fundamental property of a material that allows it to perform its desired medical function—be it as an implant, sensor, or drug delivery vehicle—without eliciting any undesirable local or systemic effects in the host. It is not merely a passive state of being inert; rather, it describes a harmonious, controlled interaction where the material does not provoke a detrimental immune response, such as significant inflammation, thrombosis, or toxicity, while the host environment does not cause the material to degrade or fail in its function prematurely. For a biomedical engineer, designing for biocompatibility involves meticulously selecting materials and surface treatments to guide this biological response, ensuring the device is safe, effective, and integrates successfully with biological tissues for its intended application.

7. STUDY QUESTIONS

1. Compare and contrast the THREE types of muscle tissue from a materials science perspective.
2. Design a simple experiment to measure the force-velocity relationship in skeletal muscle.
3. How would you approach designing a biomimetic actuator based on muscle physiology?
4. What factors would you consider when developing an implantable device that interacts with muscle tissue?
5. Explain how understanding muscle biomechanics would inform the design of a rehabilitation robot.