Subsystems for Human Movement

- Mechanical Structure
- Actuators (or Motors)
- Control System
- Sensors
The following is a very superficial discussion (about one hour!)

From an Engineering point of view

Please see references for more detail and careful treatment of nomenclature
Mechanical Structure?

- Bones (which make up segments of structure)
- Joints (locations of segment connections)
- Purpose?
  - Support
  - Movement
Mechanical Structure of Lower Extremity ("the leg")

- 3 main segments
  - Foot, shank and thigh

- Joints
  - Ankle joint \(\text{(foot to shank)}\)
  - Knee joint \(\text{(shank to thigh)}\)
  - Thigh joint \(\text{(thigh to rest of body)}\)
  - Joints in foot and toes
Hip Joint

- Complicated bone/joint structure
- Shape of bones, how arranged together, and ligaments around them (for mechanical constraints and limiting range of movement) determine possible movements
Hip

- Movements along different surfaces, degrees of freedom
- Allows the limb to assume range of positions in space
Transverse axis XOX’, in frontal plane, controls movements of *flexion* and *extension*

Vertical axis OZ, coinciding with long axis of limb OR when hip is “straight”—controls *medial* and *lateral rotation*

Anteroposterior axis YOY’ in saggital plane, controls *adduction* and *abduction* (laterally away and medially towards plane of symmetry)
Knee Joint

- Modified hinge joint—lots of parts, ligaments

Movements of Knee Joint

- Mainly one degree of freedom – moving end of limb towards or away from its root—varying distance from trunk to ground
- Flexion/extension (includes some rolling and gliding motion)
  - Motion is asymmetrical, with different mechanical constraints
- Also Rotation (some—when flexed—more medial than lateral)
- Transverse axis XX’, in frontal plane, around which occur movements of flexion and extension in the sagittal plane.
- 2\textsuperscript{nd} DOF related to rotation around axis YY’ (not possible when knee fully extended).
Ankle Joint

- Ankle is Hinge joint, one degree of freedom, controls movements of leg relative to foot in sagittal plane
- Foot is more complicated—collectively foot joints and ankle, assisted by knee axial rotation, yield 3 degrees of freedom
- Allows foot to take any position in space and to adjust to irregularities of ground surface
Transverse Axis XX’ controls flexion and extension
Long Axis of leg Y controls adduction and abduction of the foot
Long axis of foot Z (medial and lateral movements)

Extension of ankle will change direction of z axis
Flexion and Extension

Flexion (dorsiflexion) is B in fig 2

Extension (plantar flexion) is C in fig 2
Foot movements

- Adduction (fig 2)
- Abduction (fig 3)
- Medial, supination (fig 4)
- Lateral, pronation (fig 5)
Mechanical Structure of Upper Extremity ( "the arm")

- More complicated than lower extremity
  - Upper arm, forearm, hand, fingers/thumb
- Joints
  - Shoulder Joint
  - Elbow joint
  - Wrist joint
  - Finger, thumb joints
Shoulder Joint

- Most mobile joint in body
- Ball and socket type joint
- No strong ligaments to envelop (muscles help)
- Movements—~3 Degrees of Freedom
Elbow Joint

- Intermediate joint—linking upper arm to forearm
- Allows forearm to assume any position in space (in combination with shoulder)
- Places hand at any distance from body
- Consists of 3 articulating surfaces of bone, in capsule
- Motions: ~3DOF—but they are linked to position
Wrist/Hand Joints

- Even more complicated!
- Wrist basically 2 degrees of freedom
- Combined with elbow motion, hand can oriented at any angle to grasp or hold an object
- Motions—most are coupled:
  - Hand flexion/extension, Hand radial abduction, hand ulnar adduction
  - Finger flexion, finger extension, finger abduction, finger adduction
  - Thumb abduction, thumb adduction, thumb opposition
Other things ...

- Description of the degrees of freedom, and limits of motion, for each joint of the upper extremity (ie: shoulder, elbow, wrist, hand, fingers, thumb)

- Note: limits of joint motion may depend on positioning of other joints
Actuators (Muscles)

“Muscles are the only motors that you can eat”

- Muscles supply the power to move the skeleton (about 330 in humans—and ~300 joints)
- Tendons attach muscles to bones
- No “standard” muscle—different shapes for different purposes (and different in different individuals)
- Different design optimization (speed, range of movement, constraints to movement)
Properties of Muscle

Spring-like properties
1. Distensibility—external force can stretch them [within limits]
2. Elasticity—stretched muscle will recoil from stretching

Other properties
1. Contractility—ability to produce force between ends –like a “power spring”
2. Irritability—ability to respond to stimulation
Muscle structure

- Two components of muscle
  - Muscle fibers (active contractile elements)
  - Inert compliant materials—this connective tissue provides spring properties [in series and parallel with contractile elements]—and it blends into tendons
  - Different architectures for different types of muscles
  - Muscle has good blood supply (for energy, waste removal)
Nerve Supply of Muscles

- Large motor nerve fibers
  - “alpha motorneuron” (cell body in spinal cord), branches successively to supply lots of muscle fibers
  - “motor unit”—the alpha motorneuron and all of the muscle fibers that it serves (5-thousands)
Nerve Supply of Muscles

- Smaller gamma motoneurons
  - Innervate muscle spindles—used to provide means of central regulation of muscle contraction ("gamma loop")

- Sensory nerve fibers
  - Type I neurons (signals from muscle receptors—spindles and tendon organs)
  - Type III fibers (smaller)—sense muscle pain
Muscle Contraction

- Natural or artificial means
- Electrochemical process
- At molecular level—increasing understanding of mechanism [sliding filaments, sarcomeres, actin-myosin interaction]
- Aggregation of many many A-M pairs, binding and breaking---leads to contractions (shortening of muscle fiber)
- Muscle relaxation, however, is purely passive
Muscle Properties

- Force produced depends on:
  - Stimulus characteristics
  - Length of muscle at stimulus and during contraction

Fig. 1.18: Force vs. length curve for isolated muscle: 1) passive elastic tension; 2) total force; and 3) force calculated by subtracting of passive force from total force.
Muscle Properties

- Force produced depends on:
  - Velocity of muscle contraction
  - Muscle fatigue—this is an actuator that "gets tired" and needs to "recharge"—by various mechanisms and time scales

*Fig. 1.19: Velocity of contraction vs. normalized muscle force. Negative velocity relates to eccentric contraction, while the positive to active contraction.*
Muscle Properties

- Single twitches
- Combined single twitches to get smooth and graded force
- Some muscles are “fast twitch” and some are “slow twitch”
Electrical Stimulus Issues

- Force produced depends on “how many” muscle fibers are “recruited” by electrical signal and “how often”
Recruitment

- "How many"
- Depends on pulse width, pulse amplitude
- Threshold effect (no measurable force below threshold level)
- Approximately linear, but with saturation
- Fatigue increases with duration of stimulation
Pulse Frequency Modulation

- “How often”
- The more often, the more force generated
- A limit however—if pulses too often, force not generated
- If too sparse—just get successive separated twitches
- Fatigue increases with frequency increase
Natural vs Artificial Stimulation

- In natural stimulation and spinal stimulation, different motor units in same muscle are driven by different signals.
- In FES (artificial stimulation), this is much harder to do.
- Rate of fatigue greater and force production less using FES.
Interesting nonlinear phenomenon

- Doublet (two fast twitches) often used at the beginning of a motion, to get very rapid response
How muscles act

- Groups of muscles can act together
- Groups of muscles can also act in opposition (co-contraction)—providing stiffness as well as force regulation
- Muscles can act on different numbers of joints (uniarticular, biarticular, multiarticular)
References

- Popovic and Skinkjaer, *Control of Movement for the Physically Disabled* chapter 1
- I.A. Kapandji, *The Physiology of the Joints* (Vol. 1-3)
- T. A. McMahon, *Muscles, Reflexes and Locomotion*