Human Motor Systems

Lei Zhang

Institute for Neural Computation
Ruhr-Universität Bochum
lei.zhang@ini.rub.de

Autonomous Robotics: Action, Perception, and Cognition (ST 2023)
Prof. Dr. Gregor Schöner
Teaching unit: Human motor systems (06.07.2023)
Video: The humanoid robot Rollin' Justin, Institute of Robotics and Mechatronics, German Aerospace Center
Video: Individual cycle sport stacking world record 4.753s, Malaysia 2019 (Chan Keng Ian)
<table>
<thead>
<tr>
<th>Robot</th>
<th>Human</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powerful torque motor</td>
<td>Sluggish muscles</td>
</tr>
<tr>
<td>Conduction delay &lt; 1ms</td>
<td>Conduction delay &gt; 20ms</td>
</tr>
<tr>
<td>Accurate sensors</td>
<td>Noisy sensory receptors</td>
</tr>
</tbody>
</table>
Overview of human motor system

- Central nervous system (CNS)
  - Brain
  - Spinal cord

- Muscles
Outlines

• How muscles work?
  - muscles, motoneurons, reflexes, spinal cord

• How movements look like?
  - kinematic patterns

• How the brain works in movement generation?
  - neuroanatomy, function
“To move things is all that mankind can do, for such the sole executant is \textit{muscle}, whether whispering a syllable or felling a forest.”

Sir Charles Sherrington
Muscle structure and motor neuron

Each muscle fiber is innervated by a single axon

Bear et al. Figure 13-1

https://www.sciencenewsforstudents.org/article/explainer-what-is-a-neuron
Muscle structure and motor neuron

Each motor neuron innervates multiple muscle fibers

Each muscle is innervated by multiple motor neurons
Muscle fiber structure

T tubules conduct electrical activity from the surface membrane into the depths of the muscle fiber

Bear et al. Figures 12-13 and 13
The molecular basis of muscle contraction

The myofibril

Bear et al. Figure 13-14

- Z line
- Thin filaments
- Thick filaments
- Sarcomere

The myosin walk

Bear et al. Figure 13-16

- Actin filament
- Myosin filament
- Ca²⁺
- Troponin
- Tropomyosin

Bear et al. Figure 13-16

Ca²⁺
Muscle force generation

Single action potential => twitch
Summation of twitches => sustained contraction

Bear et al. Figure 13-8
The human spinal cord

Arm muscles

Leg muscles

Bear et al. Figure 12-11
The ventral horn of the spinal cord contains motor neurons that innervate skeletal muscle fibers.

Sensory signals enter the spinal cord through the dorsal roots. Cell bodies of sensory neurons lie in the dorsal root ganglia.
Muscle spindle structure
Muscle spindle structure

<table>
<thead>
<tr>
<th>Muscle fibers</th>
<th>Innervation</th>
<th>Force production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extrafusal</td>
<td>Alpha MN</td>
<td>Yes</td>
</tr>
<tr>
<td>Intrafusal</td>
<td>Gamma MN</td>
<td>No</td>
</tr>
</tbody>
</table>

Bear et al. Figure 13-20
 Gamma motor neuron function

- Gamma motor neuron adjusts the sensitivity of Ia sensory fibers
Gamma motor neuron function

A  Alpha-gamma co-activation reinforces alpha motor activity

B  Spindle activity increases during muscle shortening

Kandel et al. Figure 35-12
Three sources of inputs to Alpha motor neuron

Bear et al. Figure 13-9
Stretch reflex and reciprocal inhibition

Muscle stretched – Ia axon activity increases – alpha MN activity of the same muscle increases – the same muscle shortened (length increases) – alpha MN activity of the opposite muscle decreases – the opposite muscle relaxed
Flexor withdrawal reflex
Crossed-extensor reflex

Bear et al. Figure 13-27
The Ib axon of the Golgi tendon organ excites an inhibitory interneuron, which inhibits the alpha motor neurons of the same muscle.
Reciprocal inhibition and Renshaw cell

A  Ia inhibitory interneuron

Corticospinal pathway
Other descending pathways
Ia afferent fiber

B  Renshaw cell

Renshaw cell (interneuron) Descending pathways Ia inhibitory interneuron

Motor neurons

Muscle spindle Flexor muscle

Extensor muscle

Kandel et al. Figure 35-5
Modelling of spinal reflexes

Raphael, Tsianos, Loeb 2010

Tsianos, Goodner, Loeb 2014
The mass-spring model of muscles

• A physical mass-spring-damping system:
  - Elastic component k: proportional to position
  - Viscous component c: resistance depends on velocity

• Biological muscle-joint system has a similar “spring-like behavior”
  - But note: muscles can only pull, not push
  - A joint with agonist and antagonist muscles work bidirectional
  - Both passive mechanics and reflexes contribute

https://en.wikipedia.org/
Experimental measurement of muscle elastic property

- The resting length ($\lambda$) of the “spring” can be modified by brain descending command.

Reviewed in Feldman and Zhang, J Neurophysiol. 2020
The mass-spring model

λ is the muscle length when external force = muscle force = 0 (analogous to spring’s resting length)
Stabilization of EP is contributed by muscle passive mechanics and reflexes
Movement emerges due to the interaction between muscular system and external load.

The force-length characteristics do not change. Change of $\lambda$ results in change of EP.
Movement emerges due to the interaction between muscular system and external load

Change of external force (L) results in change of EP
Movement emerges due to the interaction between muscular system and external load.

The joint torque-angle characteristic (thick lines) is the algebraic sum of the corresponding muscle characteristics. Shifts of both $\lambda_f$ and $\lambda_e$ in the same direction result in a shift of the joint characteristic parallel to the angle axis.
Movement emerges due to the interaction between muscular system and external load

Shifts of $\lambda_f$ and $\lambda_e$ in opposite directions lead to a change in the slope of the joint characteristic

Latash. J Hum Kinet 2009
The mass-spring model – a modelling study

Muscle model (one $\lambda$ / central command per muscle):
Biomechanical models

CE: Contractile element
SE: Series elastic element
PE: Parallel elastic element

$I_{MTC}$: Muscle-tendon complex length

Kistemaker et al. 2007

OpenSim model

Chan&Moran 2006
**Current research topic:**
Using theoretical models of arm reaching (incl. reflex loops) to study the temporal profile of neural descending control signals

**The mathematical model:**

\[ A(t) = \left[ l(t - d) - \lambda(t) + \mu(t) \dot{l}(t - d) \right]^+ \]

\[ \dot{\theta} = \rho \left[ \exp(cA) - 1 \right] \]

\[ \tau^2 \ddot{\theta} + 2\tau \dot{\theta} + \theta = \ddot{\theta} \]

\[ F = M \left[ f_1 + f_2 \tan \left( f_3 + f_4 \dot{\theta} \right) \right] + k(l - r) \]

(Based on the model of Gribble et al. 1998)

**Experimental setup:**

Motion and electromyographic recordings
Summary: How muscles work?

- Muscles are the actuators for movement
- Muscle spindle senses muscle length
- Spinal reflex loops modulate motor output
- Muscles act as a non-linear mass-spring model
Textbooks: