Human Motor Systems

Lei Zhang

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

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Prof. Dr. Gregor Schöner
Teaching unit: Human motor systems (11.07.2024)
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 movements look like?
  - kinematic patterns

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

• How the brain works in movement generation?
  - neuroanatomy, function
Kinematic regularity

• The speed-accuracy trade-off

- Three initial positions
- Different movement times (140, 170, or 200ms)
- Variability in proportion to speed (force)

Kandel et al. Figure 33-4
Kinematic regularity

- Fitt’s law describes the speed-accuracy trade-off

\[
Movement\ duration = a + b \times \log_2\left(\frac{2A}{W}\right)
\]

- Narrow and wide targets (W)
- Different distances (A)
- Move as fast as possible

- Index of difficulty: \(\log_2\left(\frac{2A}{W}\right)\)

Kandel et al. Figure 33-8
Kinematic regularity

• Velocity* (V) vs. curvature** (C) obeys “power-law”

Viviani and McCollum 1983

* Tangential velocity  ** C=1/R
Kinematic regularity

- Velocity (V) vs. curvature (C) obeys “power-law”

- Smaller C (=1/R): larger V
- Points when movement direction is inverted: V goes to zero.
Kinematic regularity

- Hand path and velocity have stereotypical features
Kinematic regularity

- Velocity and acceleration as a function of distance

A  Actual hand path

B  Hand path measurements

Velocity

Acceleration

Kandel et al. Figure 33-12
Kinematic regularity

• Minimum jerk model

Smoothness can be quantified as a function of jerk, which is the time derivative of acceleration (Hogan 1984)

\[
\text{jerk } \dddot{x}(t) = \frac{d^3 x(t)}{dt^3}
\]

Minimum jerk cost

\[
\int_{t_i}^{t_f} \dddot{x}_i(t)^2 \, dt
\]

Solution: Minimum jerk trajectory

\[
x(t) = x_i + (x_f - x_i) \left(10(t/d)^3 - 15(t/d)^4 + 6(t/d)^5\right)
\]

i: initial; f: final; d: movement duration

Complete derivation see: https://courses.shadmehrlab.org/Shortcourse/minimumjerk.pdf
Kinematic regularity

- Reaching movements are straight (no obstacles)
Summary: How movements look like?

Human movements have certain kinematic patterns:

• Speed-accuracy trade-off – Fitt’s law
• Velocity vs. curvature - power law
• Bell-shaped hand velocity – minimum jerk model
• Force field adaptation (straight reaching movements)
“To move things is all that mankind can do, for such the sole executant is 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

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

(a) Each motor neuron innervates multiple muscle fibers

(b) Each muscle is innervated by multiple motor neurons

Bear et al. Figure 13-7
Muscle force generation

Single action potential $\Rightarrow$ twitch

Summation of twitches $\Rightarrow$ sustained contraction

Bear et al. Figure 13-8
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

**FIGURE 13.17**
A muscle spindle and its sensory innervation.

Bear et al.
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>
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
Three sources of inputs to Alpha motor neuron

Bear et al. Figure 13-9
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
The Ib axon of the Golgi tendon organ excites an inhibitory interneuron, which inhibits the alpha motor neurons of the same muscle.

Golgi tendon organ circuit

Bear et al. Figure 13-24
Reciprocal inhibition and Renshaw cell

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
The mass-spring model

$\lambda$ 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

Latash. J Hum Kinet 2009
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.

B: Coactivation command (c)

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

CE: Contractile element
SE: Series elastic element
PE: Parallel elastic element
$l_{MTC}$: Muscle-tendon complex length

Current research topic:

Using theoretical models of arm reaching (incl. reflex loops) to study the temporal structure of neural descending control signals

OpenSim model

Chan&Moran 2006
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
Overview of human motor system

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  - Brain
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- Muscles
Human brain circuits for movement generation

- Motor cortex
- Cerebellum
- Basal ganglia
Motor Cortex – descending control of spinal cord

Bears et al. Figure 14-6
Motor Cortex:
Primary cortex (M1)
Premotor area (PMA)
Supplementary motor area (SMA)
Premotor area (PMA)

Discharge of PMA neuron before a movement

Discharge of a mirror neuron in PMA

Bears et al. Figure 14-9

Bears et al. Figure 14-10
Cerebellum: coordination of movement
Cerebellum: anatomy

- Climbing fiber
- Purkinjje cell
- Mossy fiber
- Granule cell

Kandel et al. Figure 42-4

Bears et al. Figure 14-7
Cerebellum - control model

- **Inverse model** (Feedback error-learning)
- **Forward model** (Smith-predictor)
- **Multiple paired forward-inverse models**

Wolpert et al. 1998
Cerebellum: diseases

Deficits in coordination and timing

A Delayed movement
B Range of movement errors
C Patterned movement errors

Kandel et al. Figure 42-1

Kandel et al. Figure 42-11
Basal ganglia: modulation of movement

Bears et al. Figure 14-11

Bears et al. Figure 14-12
The substantia nigra (SNc) is the source of the striatal input of the neurotransmitter dopamine, which plays an important role in basal ganglia function.
Parkinson’s disease
- Resting tremor
- Rigidity/Freezing
- No tremor when moving
- Cause: loss of dopaminergic neurons
- Why such neurons die is unknown
Basal ganglia: Parkinson’s disease

Video: Cycling for Freezing Gait in Parkinson's Disease. www.youtube.com
Summary: How the brain works in movement generation?

- **Motor cortex** involves in the planning, control, and execution of voluntary movements

- **Cerebellum** coordinates voluntary movements

- **Basal ganglia** strongly interconnects with several brain regions for movement production
Conclusions

• Human movements have regular kinematic patterns.

• Muscle forces are driven by descending activations and modulated by spinal reflex loops.

• Several brain regions are directly involved in movement and interconnected. Deficits in those regions cause movement disorders.
Textbooks: