The motor system

To move things is all that mankind can do…
whether in whispering a syllable or in felling a forest
C. Sherrington 1920
• Principles

• Components: Muscles, Spinal cord and spinal tracts, Subcortical areas, Cortical fields.

• Learning and plasticity
Three main types of movements

- Reflex
- Rhythmic
- Voluntary
• **Reflex**: *involuntary* coordinated patterns of muscle contraction and relaxation elicited by peripheral stimuli (~40ms)

Noxious stimuli excites ipsilateral flexor, and excites contralateral extensor

Stretch reflex: contraction of same and synergist and relaxation of anatgonist
**Rhythmic**: Chewing, swallowing, and scratching, quadrupedal locomotion.

- The spinal cord and brain stem.
- Triggered by peripheral stimuli that activate the underlying circuits.
CPG: central pattern generators
Voluntary movements: principles

Goal directed

Reaching (~120 ms)
Feedback control (error correction)

1. Gain
2. Delay (phase lag)
Feed-forward (open loop)

1. Very hard computationally
Feedback control (error correction)

Feedforward (open loop)

Notice onset of muscles
Improve with practice

- Co-contraction of muscles

- **Internal models**: a neural representation of the relationship between the hand and the environment (how the arm would respond to the neural command).
Inverse and forward internal models

An internal model is used either:

- to predict the movement consequences of a motor commands (forward model).

- to determine the motor commands needed to achieve a desired movement trajectory (inverse model).
Motor programs and Invariants

Motor equivalence

(Donald Hebb, 1950)
Pre-planning in vectors

Is there online visual feedback?  
No - scaling of acceleration and speed

Invariant time (Isochrony)
**Kinematic** transformation: to transform a target position into a command to the skeletal system to move the hand i.e. to convert between coordinate systems;

**Dynamic** transformation: relate motor commands to the motion of the system; in the reaching task here considered, the forces applied changed the system without changing the kinematics.
Building blocks – segmentation - primitives

Isogony (equal angles)
Isochrony (duration independent of length)

2/3 power law: speed as a function of curvature
Stable behavioral gestures
Speed – accuracy tradeoff (Woodsworth, 1890)

Variability/noise of the components (neurons! much more than muscles)

Less time for feedback corrections?
No, even without sensory feedback
Overcoming noise: optimization principles

• Minimum jerk (smooth acceleration)

• Minimum signal-dependent noise

• Optimal control: minimize only what is relevant, and ignore other variables.
Hierarchical organization

- Cortex
- Basal-ganglia, cerebellum
- Brain stem
- Spinal tracts
- Spinal cord
- Muscles
Muscles

1. smooth muscles
2. cardiac muscles
3. skeletal muscles
Structure

Muscle fiber

myofibril

Sarcomere: functional unit
The "engine"

Cross bridges → Sacroplasmic reticulum

Longitudinal force

Thick filament
Thin filament
Myosin
Troponin
Tropomyosin
Actin
ADP
Ca²⁺
Exonzo binding site

A
B
C
D
E
Force depends on length

Deformation + overlap
Force depends also on velocity
The force of a single muscle fiber is a function of

- Stimulation rate
- Stimulation pattern
- The muscle length
- The velocity of contraction
- The fiber type
- The fiber organization
- The duration of exercise - fatigue
Motor unit: motor neuron and the muscle fibers it innervates (one to many)
3 types of motor unit:

Recruited by order of force (low to high)
Muscle proprioceptive organs

Spindle: length
Parallel

Golgi tendon: tension
Serial
The muscle spindles are sensitive to changes in length.
Active range can be dynamically modulated

A
Sustained stretch of muscle

B
Stimulate alpha motor neuron

C
Stimulate alpha motor neuron
Stimulate gamma motor neuron
Golgi tendon organs are sensitive to the tension
Spinal cord, Brain stem and spinal tracts
Spinal cord

1. Local interneurons
2. Propriospinal (across segments)
3. Projection (to upper centers)
4. Motor neurons

Motor nuclei: cell bodies of motor neurons that innervate a muscle.

Medial nuclei are long across segments
Lateral are shorter
Course of afferent fibers

Dorsal root ganglion

Ventral root

Dorsal horn

Ventral horn

Dorsolateral cell group

Intermediate zone

Motor nucleus (to axial muscle)

Motor nucleus (to limb muscle)

Distal limb

Flexor

Proximal limb

Extensor

Ventral
**Brain stem pathways**

**Medial** pathways (vestibulospinal, reticulospinal, tectospinal), terminates in ventromedial (axial) for postural control. **Lateral** pathways (rubrospinal) terminates in dorsolateral.
The corticospinal tract
Cortex and control of voluntary movement
Somato-topical organization
Stimulation in M1

Electrical and magnetic stimulation

Lowest intensity

Twitch in single muscle/joint

Large (Betz) cells in lamina V

Many locations -> same muscle
Location - > several muscles
Cortical inputs

A Inputs to primary motor cortex

B Inputs to premotor areas

CMA, Cingulate sulcus, SMA, PMd, PMv
Coding of force in M1

Evarts, 68

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**Experimental setup**
- Recording microelectrode in wrist area of right motor cortex
- Stimulating electrode in pyramidal tract
- Pulley
- Potentiometer (wrist angle)
- Weight (flexor load)
- Restraint

**Records of behavior and cell activity**

- **A** No load
  - Flexors
  - Extensors
  - PTN
  - PTN active before movement
  - PTN active with agonist muscle

- **B** Flexor load
  - Flexors
  - Extensors
  - PTN
  - PTN activity increases with increased load

- **C** Extensor load
  - Flexors
  - Extensors
  - PTN
  - No PTN activity: flexion movement results from relaxation of antagonist
Coding of external direction

$$fr_i(MD) \approx b_i + k_i \cos(\theta_i - \theta_{MD})$$

Georgopoulos 1982
Kinematics vs. dynamics

Extrinsic variables (end-point velocity/ position):
  Relative to torso
  Relative to eye
  Relative to shoulder

Intrinsic coordinates:
  Muscles shortening velocity
  Muscles tension

Joints’ velocity, torque, power.
The population vector

If:

⊙ Many cells “care” about direction of movement
⊙ Cells are tuned “cosine like” with a preferred direction
⊙ Preferred directions are uniformly distributed

Then:

The actual movement can be estimated in Cartesian coordinates by a linear combination of weighting the preferred directions with the actual firing rate

$$\overline{MD} \approx PV = \sum_{i=1}^{N} w_i \overline{C_i}$$
What can we do with it? Neural prostheses
Premotor areas
Premotor dorsal (PMd), premotor ventral (PMv), supplementary motor area (SMA), cingulate (CMA)

- Multi-joint representation
- Complex, meaningful
- Sensorimotor transformations
- Preparatory (set) activity
- Bimanual coordination (SMA)
- Sequence learning (SMA)
- Self-initiation (PMv, SMA) vs. cue-driven (PMd)
- Language, theory of mind
Representation of plan and execution

Illusion task trajectories. Top row is five cycles from M1 units. Bottom row is from the PMv. The hand trajectory is blue, cursor trajectory is green, and neural trajectory is red. Each displayed trajectory is the mean across five repetitions.

Andy Schwartz
The basal Ganglia