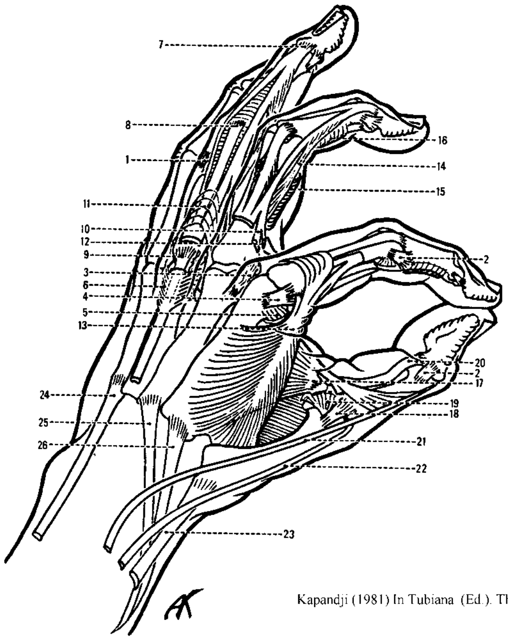


Kapandji (1981) In Tubiana (Ed.). The hand.

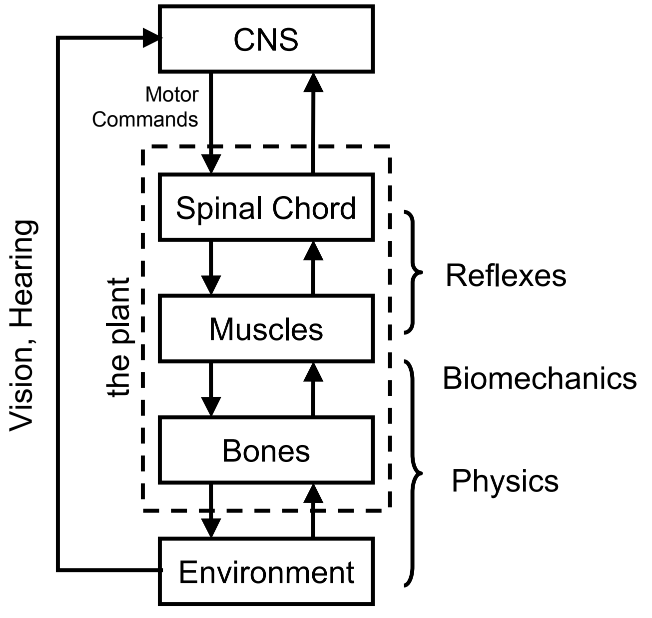
Human finger force control

gabriel.baud-bovy@iit.it

References

- Neuroscience
  - **Neuroscience** (4th Edition) by Dale Purves, 2007.
  - **Neuroscience: Exploring the Brain** (3rd Edition) by Mark Bear, Barry Connors, 2006
  - **Fundamental Neuroscience** (3rd Edition) by Larry L Squire et al., 2008
- Biomechanics
  - **Neuromechanics of Human Movement** (4th Edition) by Roger Enoka, 2008
- Motor control
  - **The Computational Neurobiology of Reaching and Pointing: A Foundation for Motor Learning**, by Reza Shadmehr & Steven P. Wise, 2005
- Haptics
  - **Sensorimotor Control of Grasping: Physiology and Pathophysiology** by Dennis A. Nowak, Joachim Hermsdörfer, 2009
  - **Human Hand Function** by Lynette A. Jones and Susan J. Lederman, 2006

Motor centers



- CNS and body have evolved together

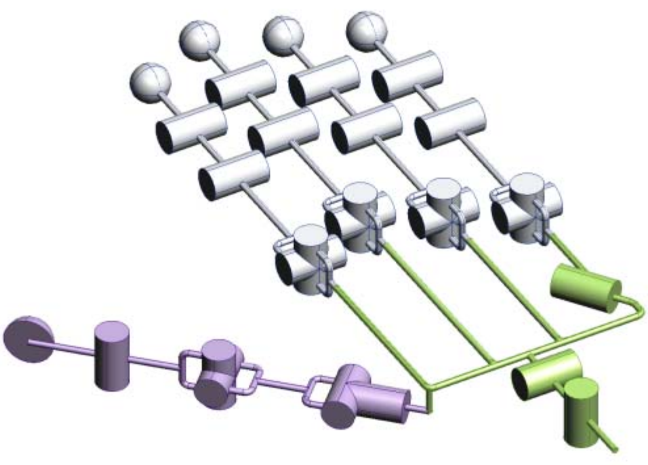
  Important to understand properties of the “plant” (body)

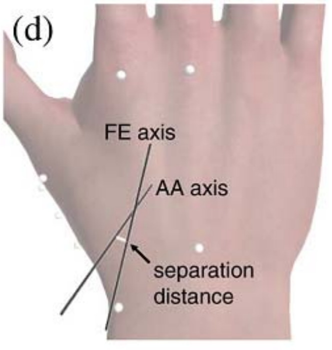
The plant

- Mechanical structure
  - Hand skeletton
- Actuators
  - Muscles
- Sensors
  - Skin mechanorecptor
  - Proprioceptors

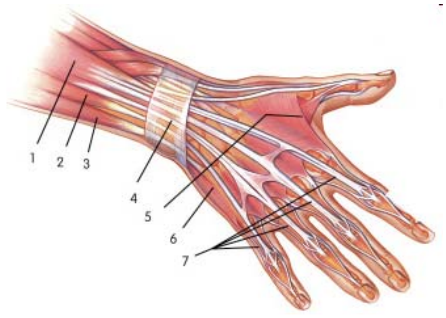
Hand skeletton

Hand kinematics

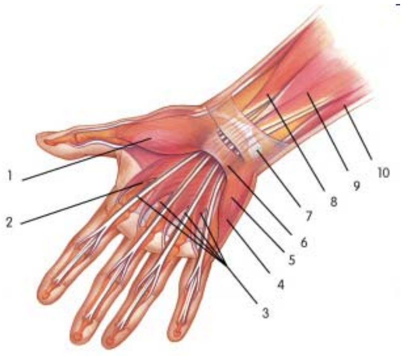




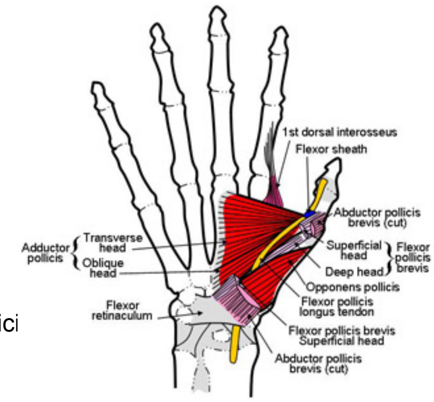
Hand muscles



1 Extensor digitorum
2 Extensor digiti minimi
3 Extensor carpi ulnaris
4 Extensor retinaculum
5 First dorsal interosseous muscle
6 Abductor digit minimi
7 Extensor digitorum tendons



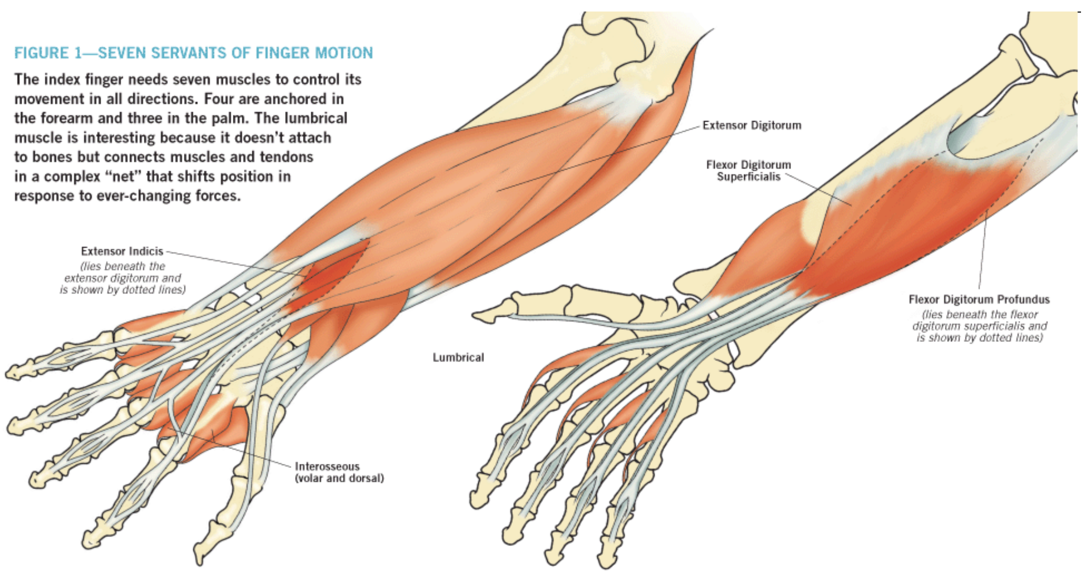
1 Abductor pollicis brevis
2 Adductor pollicis
3 Lumbricals
4 Flexor digit minimi
5 Abductor digit minimi
6 Flexor retinaculum
7 Antebrachial fascia
8 Flexor pollicis longus
9 Flexor digitorum superfici
10 Flexor carpi ulnaris



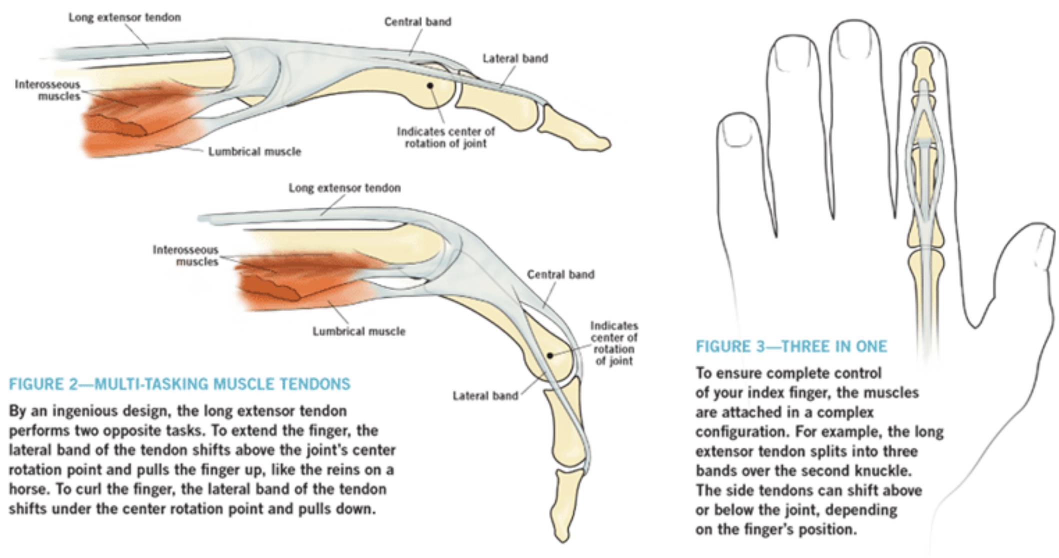
Hand biomechanics

FIGURE 1—SEVEN SERVANTS OF FINGER MOTION

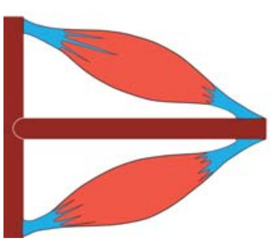
The index finger needs seven muscles to control its movement in all directions. Four are anchored in the forearm and three in the palm. The lumbrical muscle is interesting because it doesn't attach to bones but connects muscles and tendons in a complex "net" that shifts position in response to ever-changing forces.



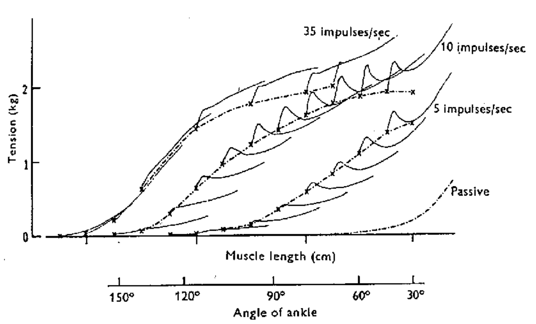
Hand biomechanics



Muscle properties



- Muscles can only pull and all joints must be actuated by two or more muscles to control the joint position
  - Co-contraction of antagonist muscles allow to control the stiffness
- Muscles are visco-elastic
  - Important for the stability of the musculoskelettal system
  - Force-length curve (elastic force)



Force-length relationship of an isolated cat soleus muscle in isometric condition (dotted line) and during a slow stretch (solid line)

Muscle mechanical model

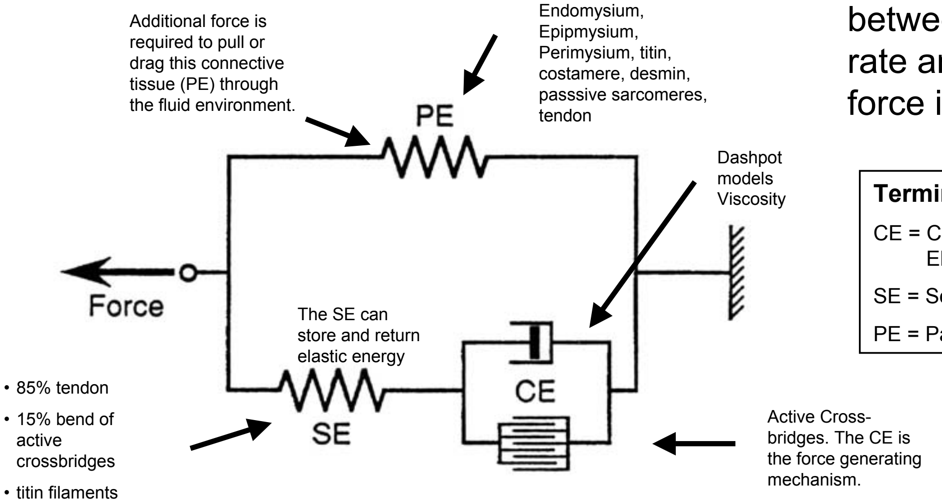


Figure 6.29 A three-element mechanical model of the sarcomere.

•The relationship between stimulation rate and muscle force is complex

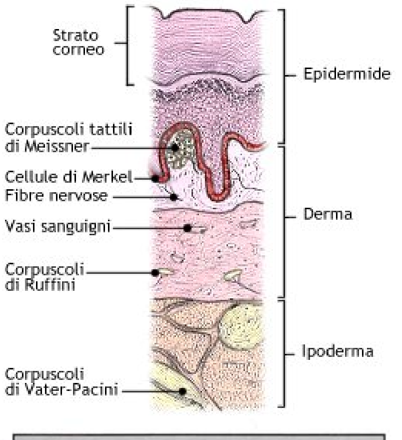
Terminology:

CE = Contractile Element

SE = Series Element

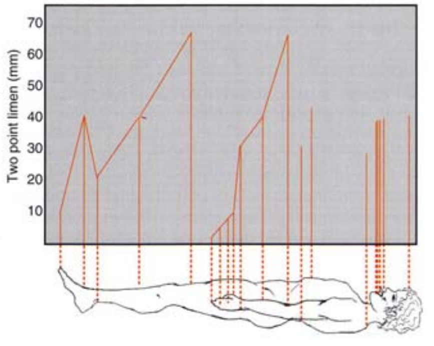
PE = Parallel Elementr

Skin afferents



- Four type of mechanoreceptors in the skin

	Adaptation	Receptive field [mm^2]
FA1 or RA (Meissner corpuscle)	Fast	11-12
FA2 or PC (Pacini's organ)	Fast	100
SA1 (Merkel's cell complex)	Slow	11-12
SA2 (Ruffini's ending)	Slow	60



- Inervation density varies on body surface

Two-point discrimination limen

Squire et al. (2003) Fundamental, 2nd ed. Neuroscience, p. 668

Mechanoreceptor densities

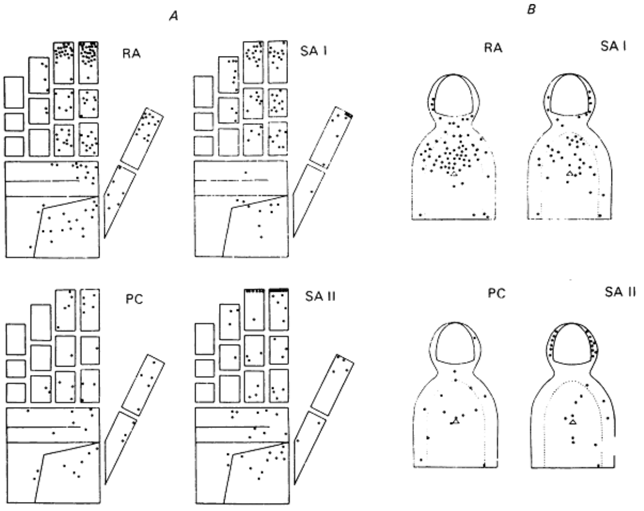
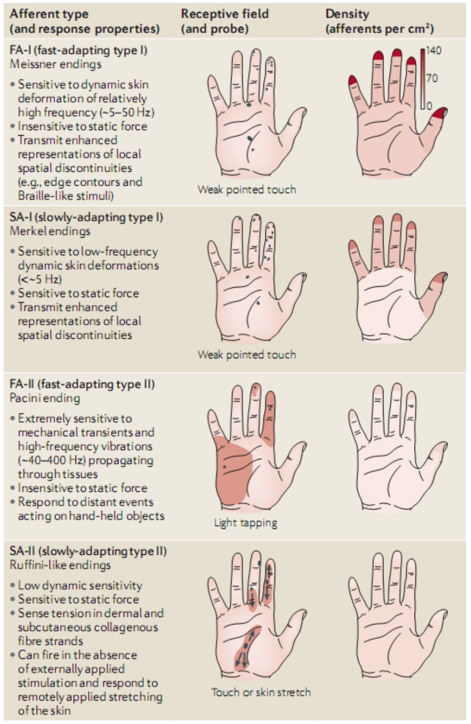


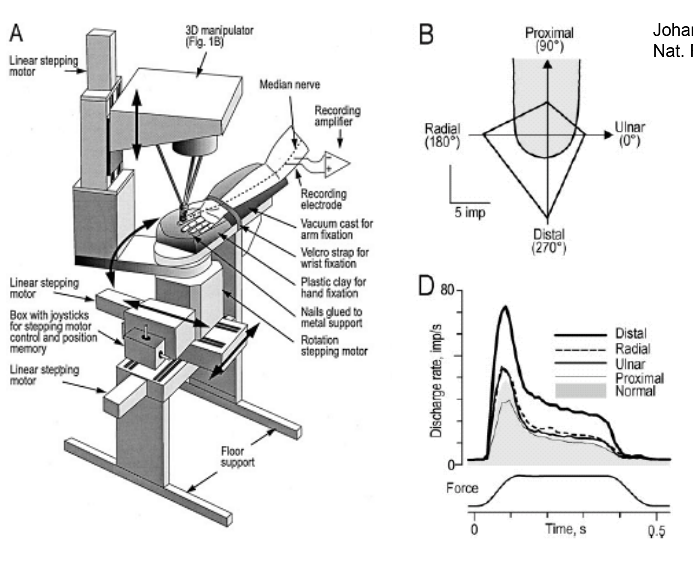
Fig. 3. Locations of the receptive field centres of 334 glabrous skin mechanoreceptive units separated according to unit type. *A*, total glabrous skin area. *B*, terminal phalanges and the nail projected on to a two-dimensional surface. Interrupted lines indicate the contours of the fingers as seen from the volar side while the triangles indicate the vortices of the skin ridges.

Johansson & Vallbo (1979) J. Physyiol.



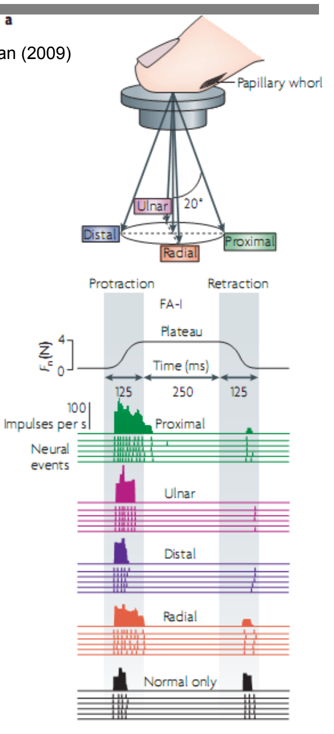
Johansson & Flanagan (2009) Nat. Rev. Neurosc.

Tangential forces



Birznieks et al. (2001) Journal of Neuroscience, 21(20):8222–8237

Johansson & Flanagan (2009) Nat. Rev. Neurosc.



- Normal force = 4 N (typical in object manipulation but higher than most studies focused on tactile afferents)

Object’s local shape

3 mm bar | Sine profile | Curvature

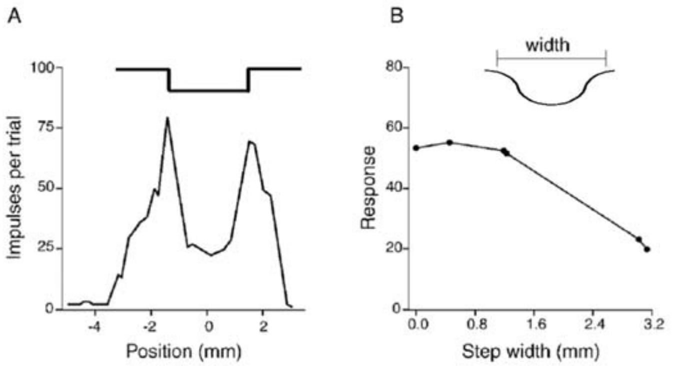
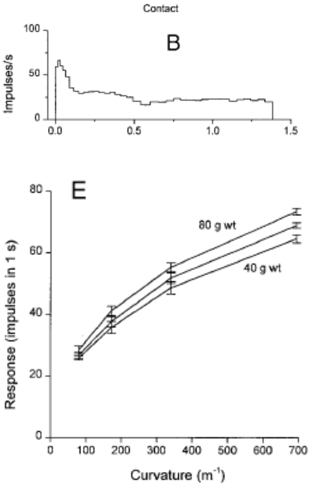


Figure 2 Responses of single SAI afferents in the monkey’s fingerpad. (*A*) Responses to a 3-mm bar stepped across the receptive field; the origin for position in the receptive field is arbitrary. Redrawn from Phillips & Johnson (1981a). (*B*) Responses to shaped steps. Each step is a half sine wave (from peak to trough) characterized by the step width (half the period). Redrawn from Srinivasan & LaMotte (1987).



Srinivisan & LaMotte (1987) J. Neurosc.

Goodwin, Macefield, Bisley (1997)
J Neurophysiol, 78(6):2881-2888

Temporal coding

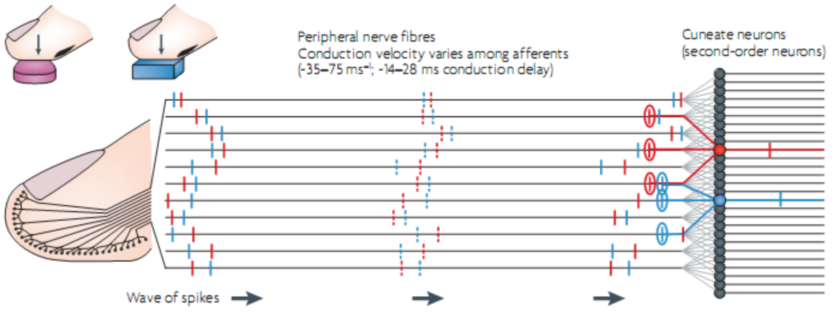
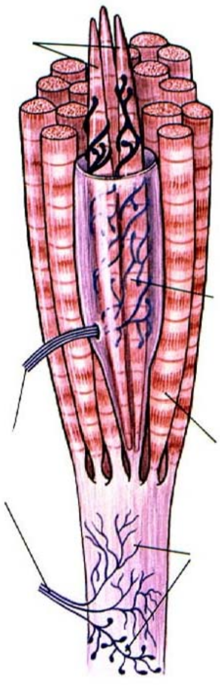


Figure 3 | **Hypothetical model for the fast processing of afferent information in somatosensory pathways.** Second- (and higher-) order neurons function as coincidence detectors and so are sensitive to specific spatiotemporal properties of impulse patterns in a population of tactile afferents. The first waves of impulses in an ensemble of afferents in response to the fingertip contacting objects with two types of surface shape (flat and curved) are schematically illustrated. The stimulus shape influences the first-spike latencies of the responsive afferents. The substantial divergence and convergence of primary afferents onto second-order neurons and the dispersion of conduction velocities among afferents provide parallel processing of the temporally structured information that aids feed-forward rapid classification of information by temporal-to-spatial conversion.

Johansson & Flanagan
(2009) Nat. Rev. Neurosc.

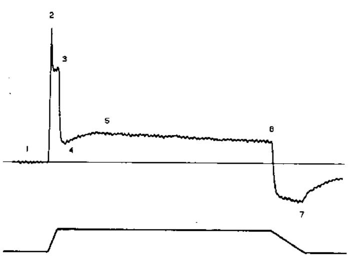
- Quick analysis of tactile inputs by second-order tactile neuron (spinal chord, cuneat nucleus in brainstem)
    - primary tactile afferents projects to 1700 cuneate neurons but each cuneat neuron recives inputs from only about 300 tactile afferent
    - Detection of coincidences together with large range of conduction velocities between tactile afferents would allow in principle of detection of large range of events.
    - Still a theoretical model (needs experimental validation)

Proprioceptors

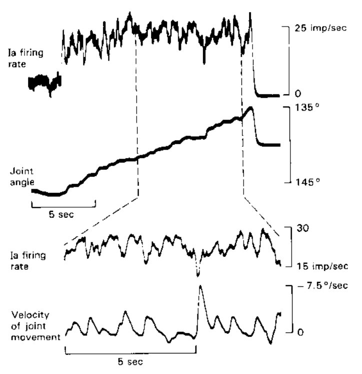


- Information about position and movement of the body as well as information about internal and external forces acting on body parts
  - **Golgi tendon organs** are found at the junction of muscle fibres and tendons (i.e., they are arranged in series with the contractile elements) and best mesure force
  - **Muscle spindles** (are small, elongated structures scattered among and arranged in parallel with the contractile extrafusal muscle fibres which best measure length (static fibers) or length changes (dynamic fibers)
  - **Joint afferents** (not shown)

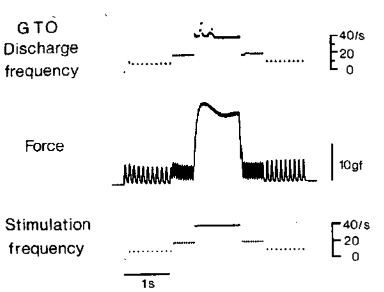
Length and force information



Receptor potential of a primary ending of an isolated cat spindle in response to ramp-and-hold stretch (Hunt, 1990).



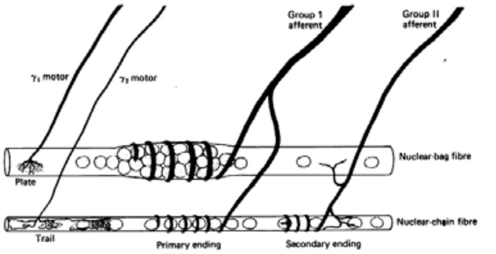
Velocity dependent activity of primary endings during active shortening (Vallbo, 1981)

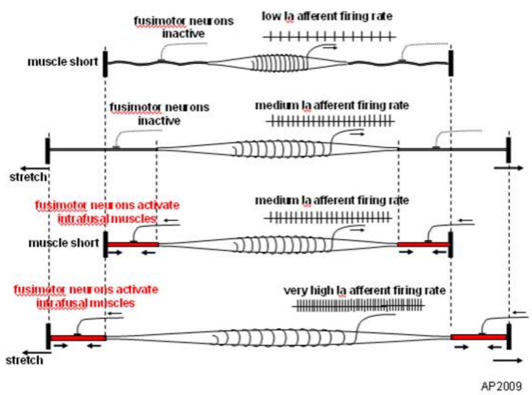


Response of tendon organ to a repetitive simulation of an in-series motor unit (Horcholle-Bossavit et al., 1989)

- Spindle primary afferents (Ia)
  - Muscle length information
  - Strong phasic activity
  - Instantaneous velocity information
- Golgi afferent (Ib)
  - Force information
  - Non-linear

Fusimotor drive





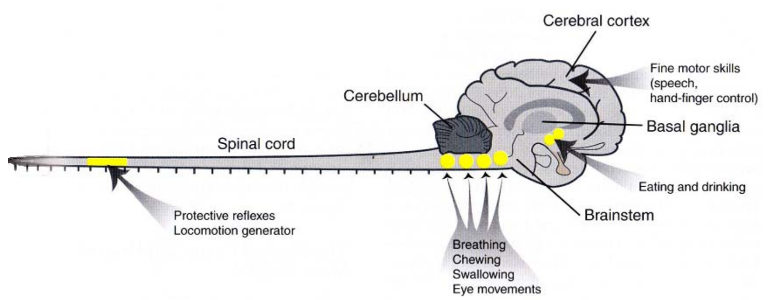
- Static fibers
- Dynamic fibers
- Gamma innervation

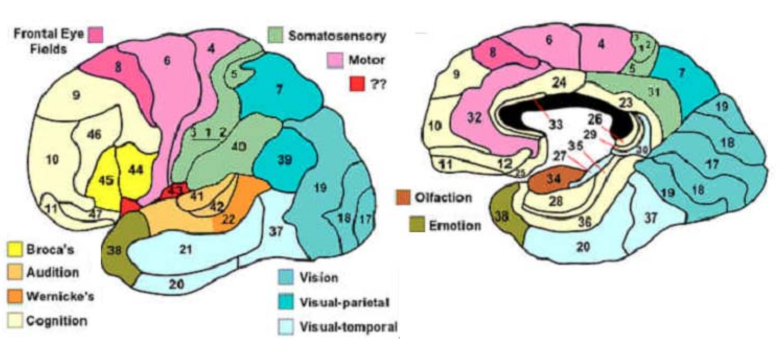
- Fusimotor drive

The controller

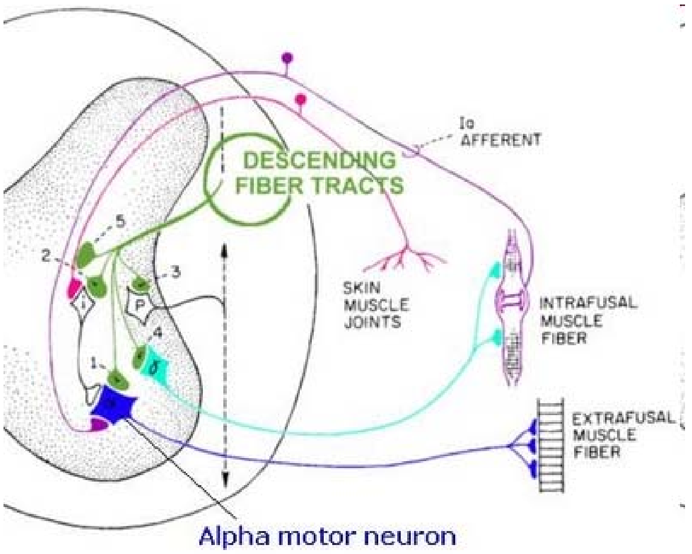
- Low level controller
  - The spinal chord
  - Spinal circuits & reflexes
- The bus
  - Ascending tracts
  - Descending tracts
- High-level controller
  - Primary motor area
  - Parietal and premotor areas

Central Nervous System Anatomy



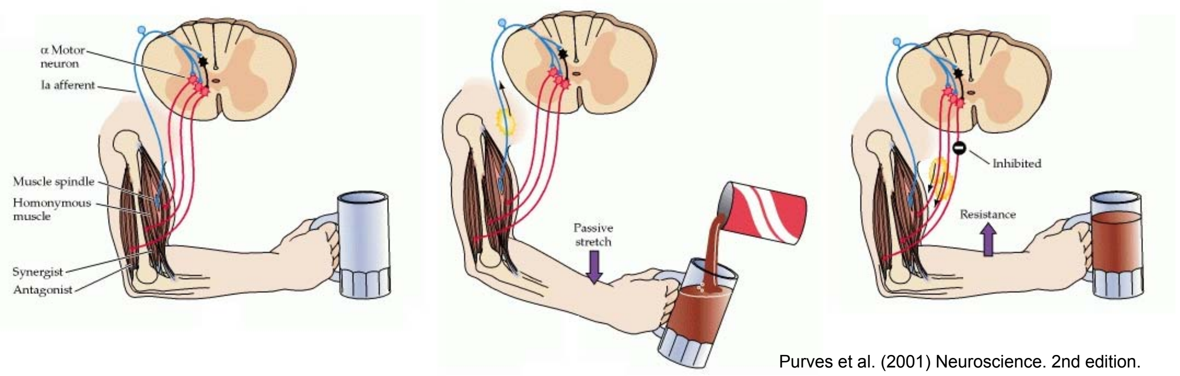


Spinal cord



- inter neurons (i) and propriospinal neurons (p) are involved in reflexes and other low-level motor synergies
- alpha motor neuron control muscles
- gamma motor neurons control the gain of spindles

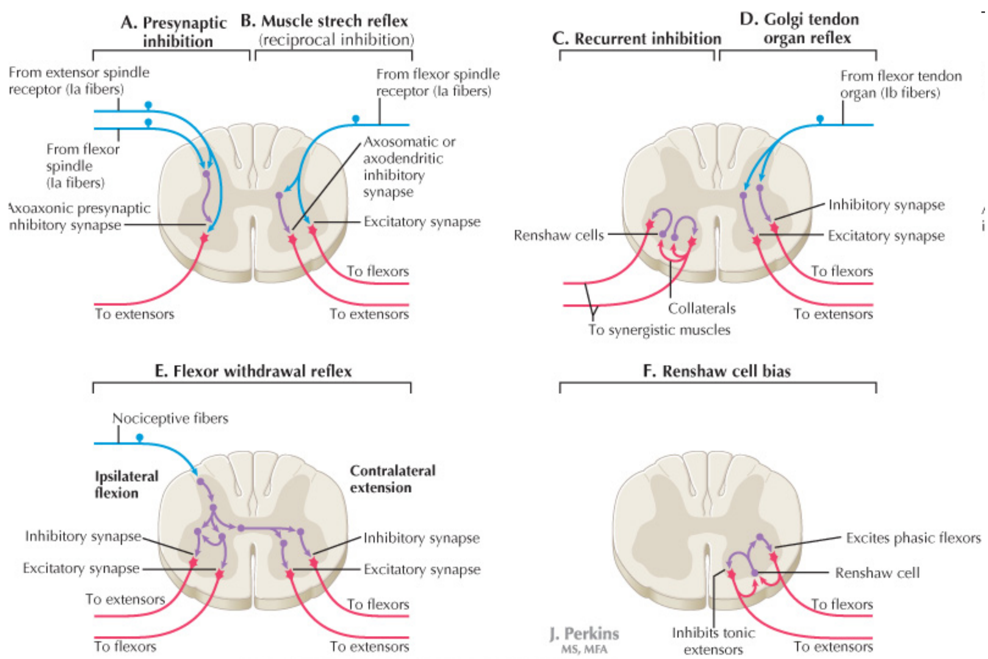
Stretch reflex



Purves et al. (2001) Neuroscience. 2nd edition.

- In terms of engineering principles, the stretch reflex arc is a negative feedback loop used to maintain muscle length at a desired value. The appropriate muscle length is specified by the activity of descending pathways that influence the motor neuron pool. Deviations from the desired length are detected by the muscle spindles, since increases or decreases in the stretch of the intrafusal fibers alter the level of activity in the sensory fibers that innervate the spindles. These changes lead in turn to adjustments in the activity of the α motor neurons, returning the muscle to the desired length by contracting the stretched muscle and relaxing the opposed muscle group, and by restoring the level of spindle activity to what it was before.

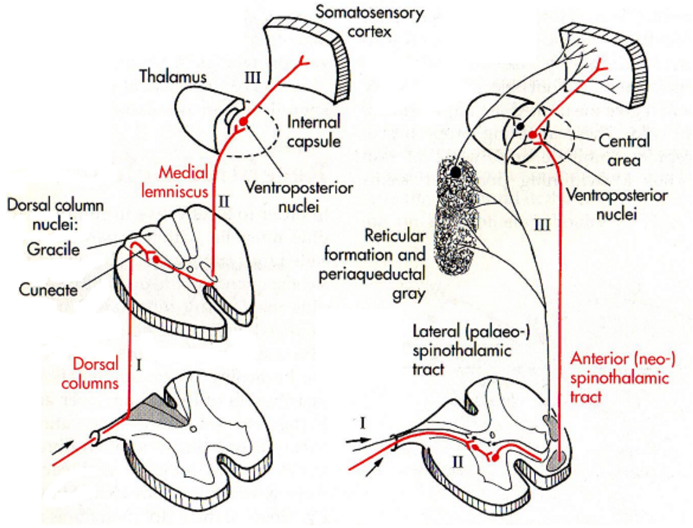
Reflexes & spinal cord circuits



Felten & Shetty: Netter's Atlas of Neuroscience, 2nd Edition.

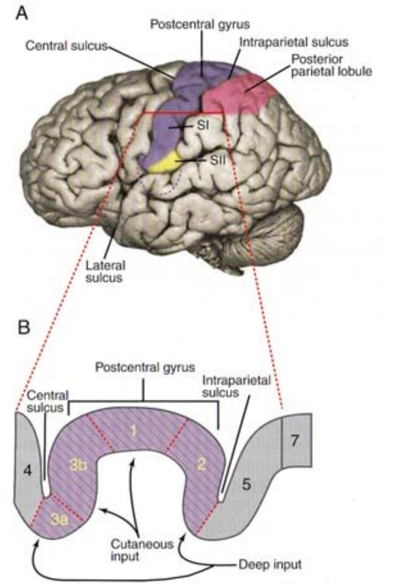
Ascending tracts

- Skin and muscles afferents project to somatosensory cortex via the thalamus (VPL)



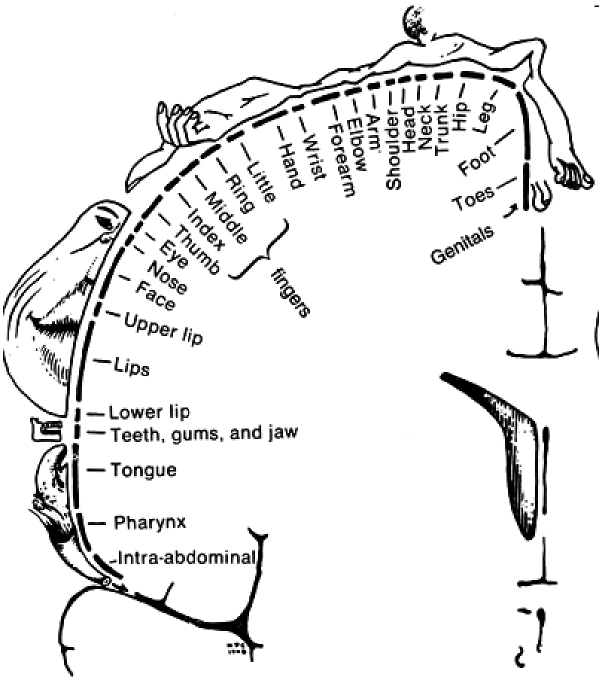
- Dorsal columns
  - Separated tracks for touch/proprioception and pain/temperature
- Anterior tract
  - Pain / temperature/ crude touch
  - Less developped in human

Carpenter (1997) Neurophsyiology, 3rd ed., p. 79.



Squire et al. (2003) Fundamental Neuroscience, p. 690

Sensory Homunculus

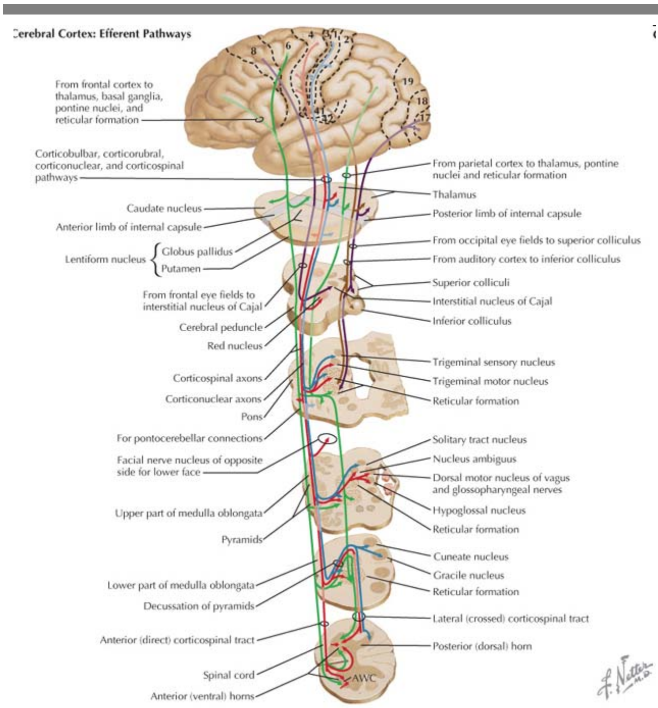


Penfield & Rasmussen (1950)

- Somatotopic organisation
- Cortical representation is proportional to inervatin density, not skin surface

British Museum, Natural History

Descending tracts



Felten & Shetty: Netter's Atlas of Neuroscience, 2nd Edition.

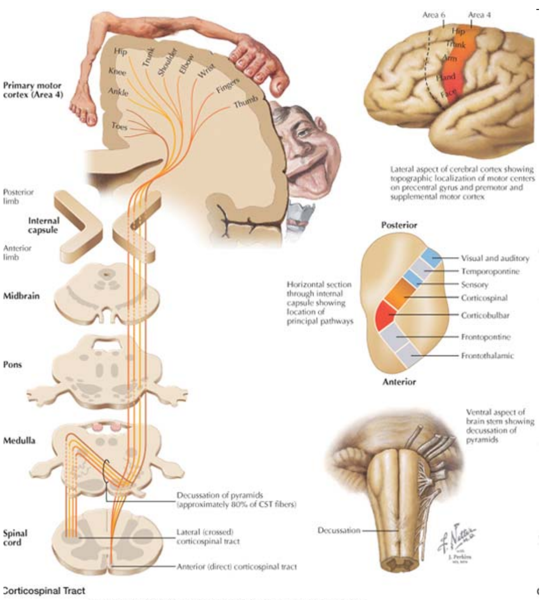
- Motoneurons and inerneurons in the spinal cords integrate the input of many different centers

  CS: cortico spinal tract

  RS: rubro-spinal tract

- Higher centers modulate refexes and, in more general, the state and functioning of spinal cord by acting on spinal interneurons
- Higher centers modulate / selects sensory information sent back to the brain (e.g. pain) by the ascending tracts.

Cortico-spinal tract



Felten & Shetty: Netter's Atlas of Neuroscience, 2nd Edition.

- CST fibers originate from motor and sensory motor areas.
- Approximately 80% of the CST axons cross in the decussation of the pyramids and terminate directly and indirectly with alpha and gamma LMNs that control movements of the distal extremities, especially the hands and fingers
- Fibers originating from sensory motor area modulate sensory feedbacl

Motor cortex

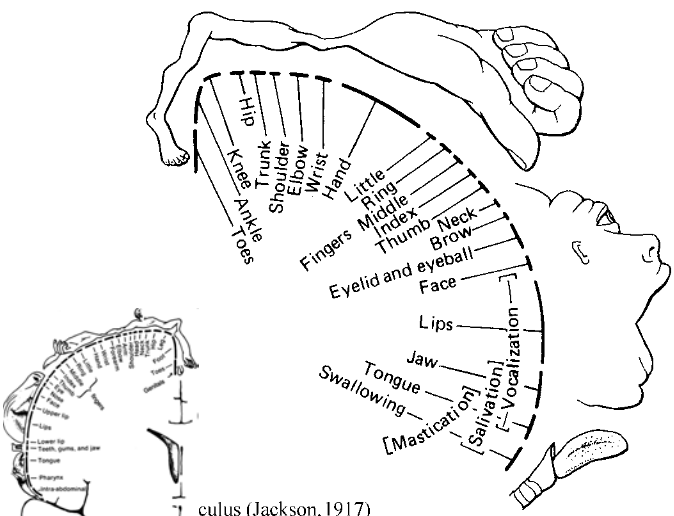
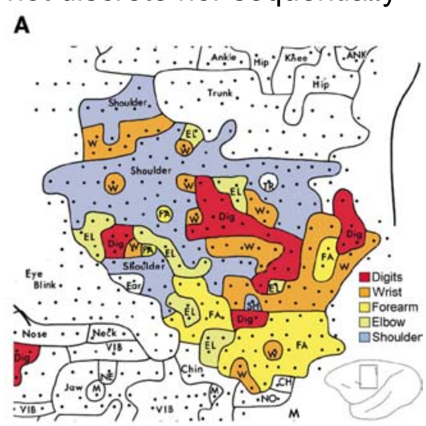


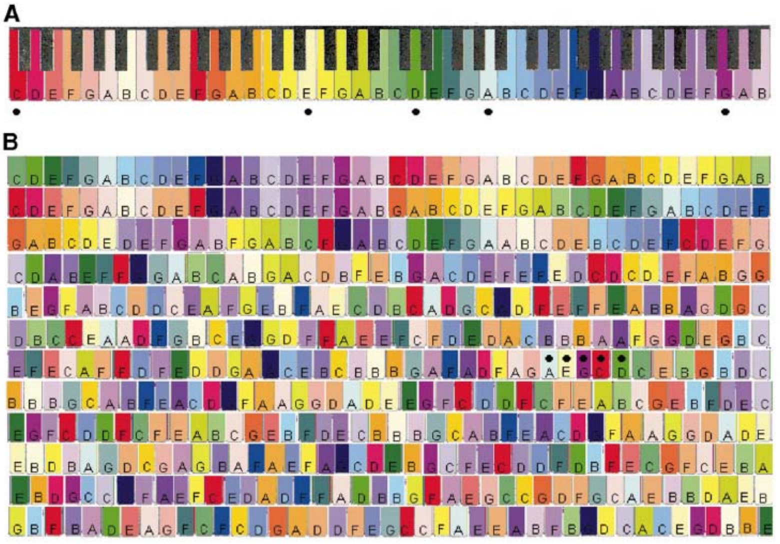
Figure adapted from Penfield & Rasmussen (1957)

- Primary motor cortex (M1) contains a motor representation of the body (motor homonculus)
- Within-limb somatotopy in M1 is not discrete nor sequentially



A. ICMS of M1 of anesthetized owl monkey

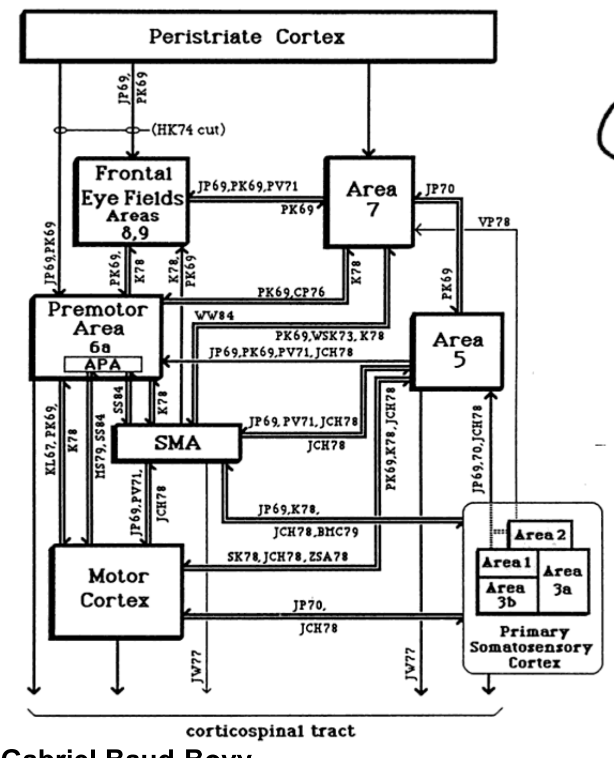
Motor Cortex (M1)

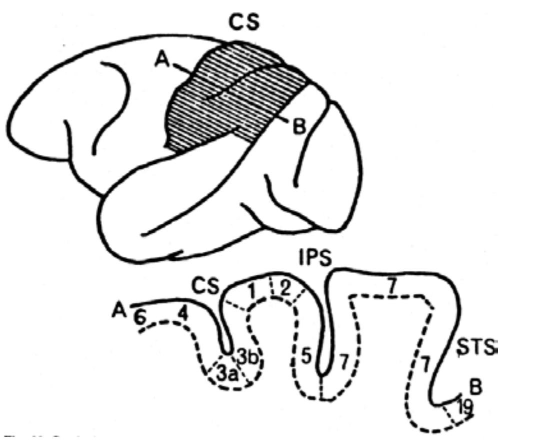


The Keyboard Analogy. In Schieber (2001) J.Neurophysiol.

Underlying substrate for high-level synergies by representing together combinations of elementary movements?

Sensory-Motor Cortical Areas

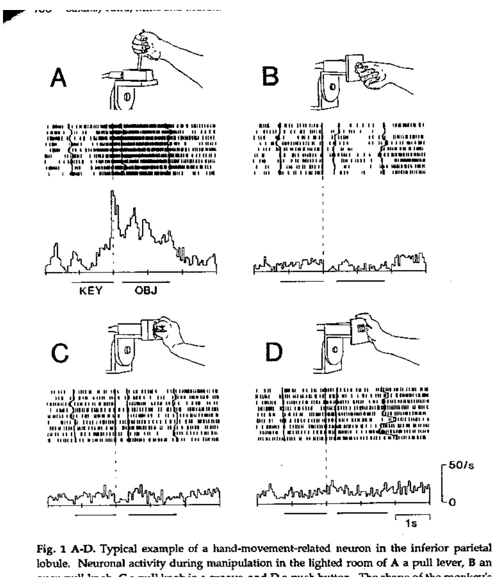


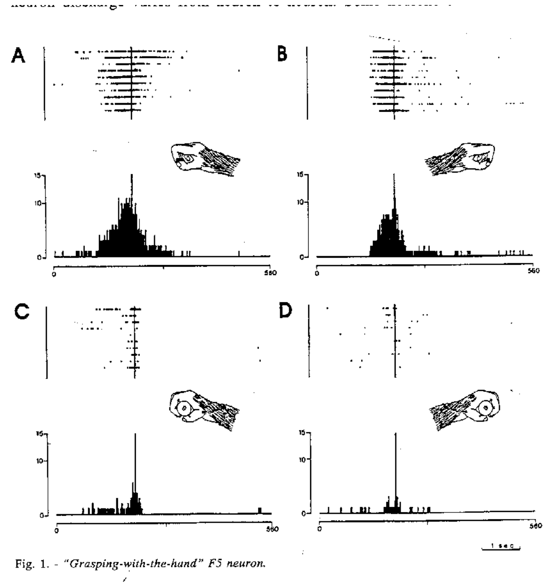


Gordon (1978) Active Touchl

Iberall & Arbib (1989) Schemas for the Control of Hand Movements: An Essay on Cortical Localization. In Vision & Action: The Control of Grasping, Ablex Publishing.

Premotor (F5) and Parietal (AIP) Areas



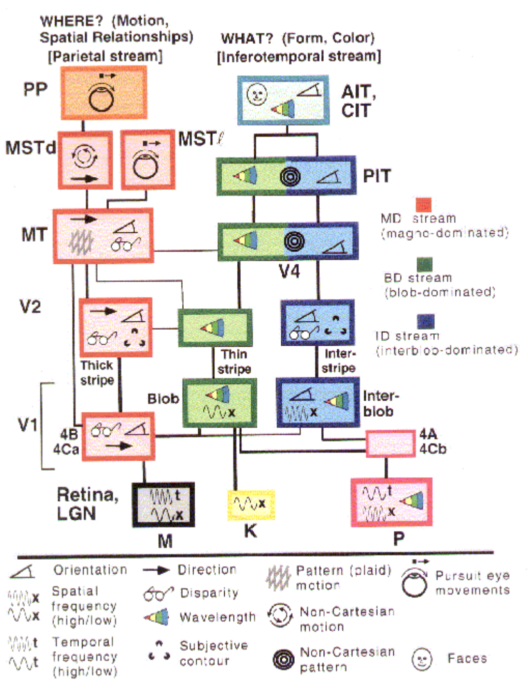


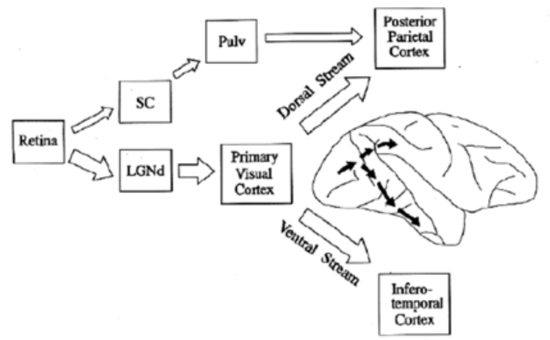
Sakata et al. (1992) Exp. Brain. Res. Series, 22.

Rizzolatti et al. (1999) Arch. It. Biol., 137.

High level control: Object recognition and grasp selection.

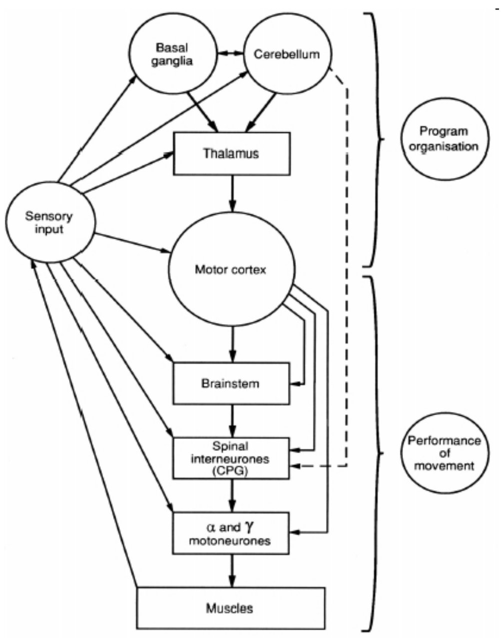
Visual inputs





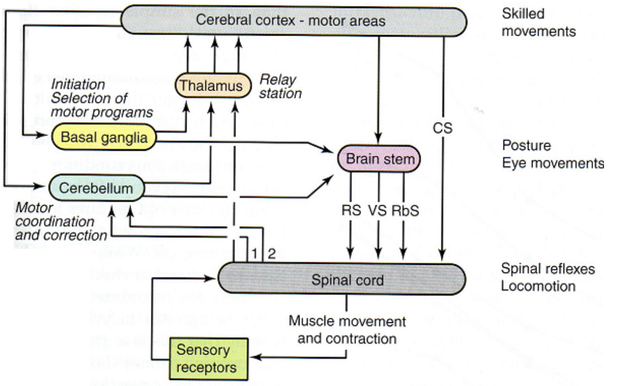
- Dorsal (Where/How) pathway
  - Spatial cues (orientation, motion)
  - Involved in unconsious sensorimotor coordination
- Ventral (What) pathway
  - Color vision
  - Involved in conscious object recognition/identification

Motor Control



MOTOR SYSTEM FUNCTION: CENTRES AND CONNECTIONS

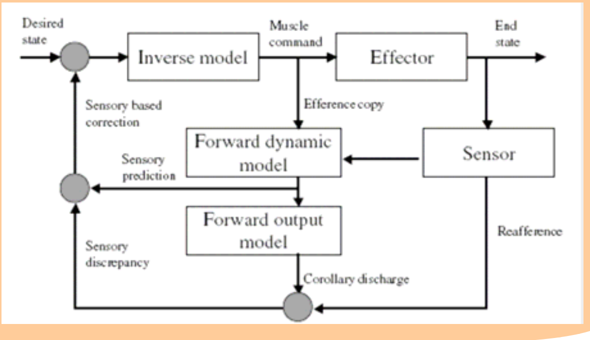
- At the neurophysiological level, many different cortical, subcortical and spinal structures are involved in human grasping
- The structures involved in the motor system are hierarchically and parallelly organized.



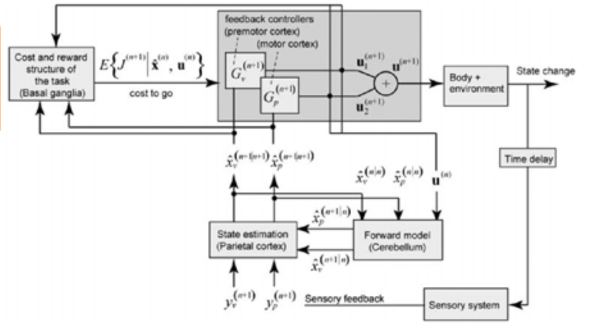
Squire et al. (2003) Fundamental Neuroscience, p. 763

Gabriel Baud-Bovy **Italian Institute of Technology 2010**

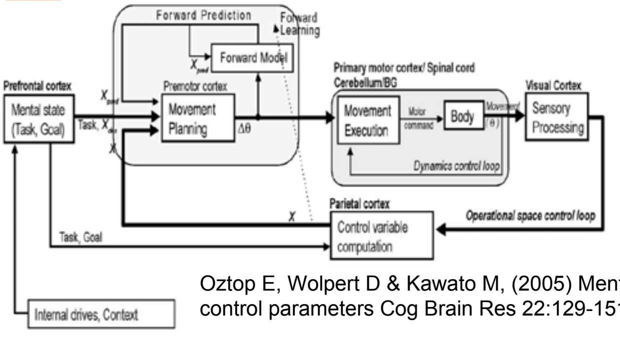
Motor control models



Winstein Wing & Whitall (2003) Motor control and learning principles for rehabilitation of upper limb movements after brain injury.



Shadmehr & Krakauer (2008) Exp Brain Res 185: 359-81



Oztop E, Wolpert D & Kawato M, (2005) Mental state inference using visual control parameters Cog Brain Res 22:129-151

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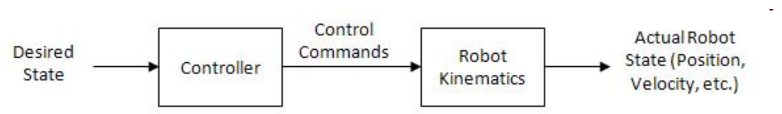
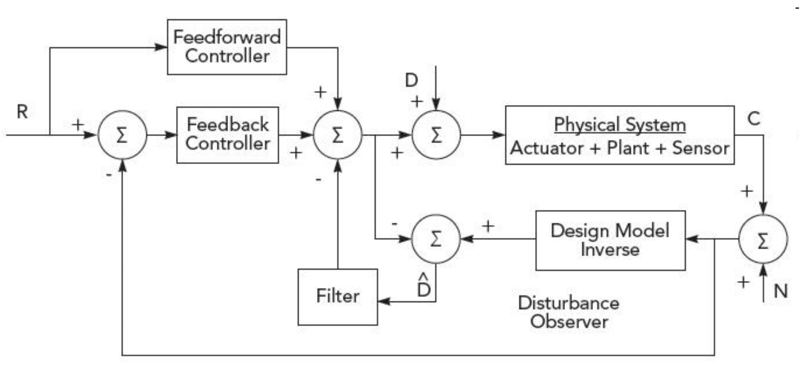
Robotic control schemes





Finger force analysis

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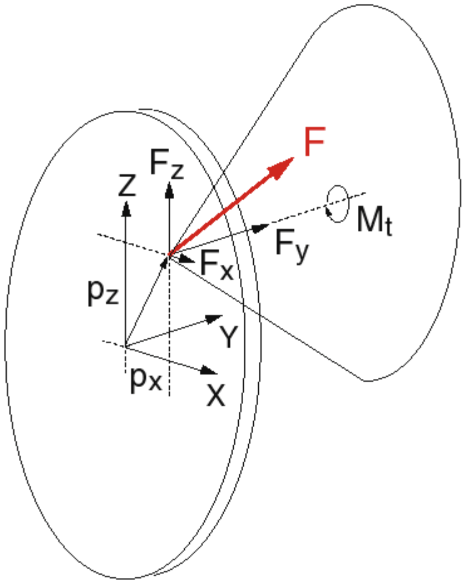
"Soft Finger" & friction constraints



- **Four parameters** are necessary to describe a contact force

$$(F_x,\ F_y,\ F_z, M_t)$$

where $F = (F_x, F_y, F_z)$ is a vector that give the direction and magnitude of contact force and M_t is the normal torque.

- **Squeezing constraints**: The finger force must apply a force against the object:

$$F_y > 0$$

where F_y is the *normal force*.

- **Friction constraints:** The force must be inside the *friction cone*:

$$(F_x^{\ 2} + F_z^{\ 2})^{1/2} < \mu\ F_y$$

where $F^t = (F_x^{\ 2} + F_z^{\ 2})^{1/2}$ is the *tangential force* (parallel to the contact surface)

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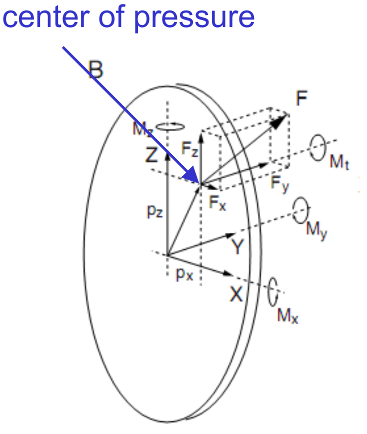
Measuring finger forces



- A six degree of freedom force sensor is necessary to measure all parameters

$$F = (F_x, F_y, F_z, M_x, M_y, M_z)$$

The force/moment components are measured in a system of coordinate having its origin at the center of the sensor

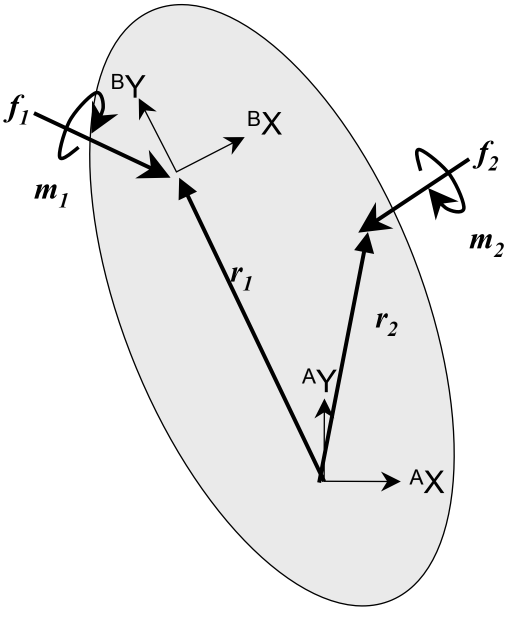
- The position of the center of pressure is:

$$p_x = M_z / F_y$$
$$p_z = -M_x / F_y$$

- The forces measured (F_x, F_y, F_z) applied at the center of pressure correspond to the forces applied at the center of pressure
- By definition, moments around the x and y axes are zero at the center of pressure.
- Moment around the normal (F_y)

$$M_t = p_z F_x - p_x F_z + M_y$$

Equilibrium equations



- Equilibrium equations

$$^A f_{net} = \sum_i {}^A f_i$$
$$^A \tau_{net} = \sum_i {}^A \tau_i + {}^A r_i \times {}^A f_i$$

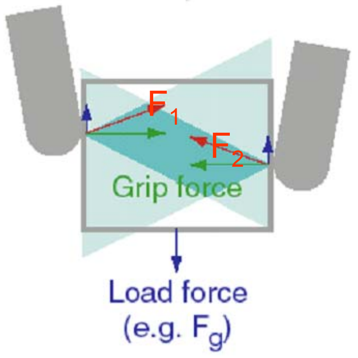
6 equations => 6 constraints

- Number of redundant degrees of freedom in any grasp is

$$4\,n - k$$

where *n* is the number of finger and *k* the number of constraints on the value of the net force and torque (k≤6).

Pinch grasp



- Analysis of forces in the vertical plane

$$F^{net} = \begin{bmatrix} F_x^{net} \\ F_z^{net} \end{bmatrix} = \begin{bmatrix} F_{1x} \\ F_{1x} \end{bmatrix} + \begin{bmatrix} F_{2x} \\ F_{2x} \end{bmatrix} = F_1 + F_2$$

$$T = r_1 \times F_1 + r_2 \times F_2$$

=> four parameters (F_{1x}, F_{1z}, F_{2x}, F_{2z}).

- Tasks constraints in the lift and hold task

$$F_x^{net} = 0, F_z^{net} = -F_g, T = 0$$

imply $F_{1x} = -F_{2x}$,

$$F_{1z} = F_{2z} = -\frac{F_g}{2}$$

(three constraints)

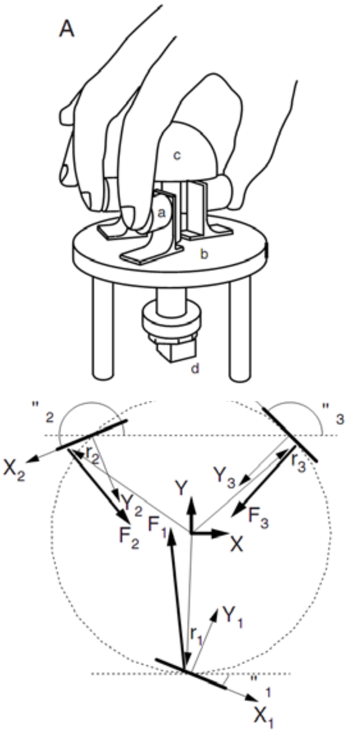
- One degree of freedom (the grip force) is not constrained by equilibrium equations

$$F_{grip} = |F_{1x}| = |F_{x2}|$$

- Friction conditions constrain partially the grip force

$$F_z < \mu F_{grip}$$

The tripod grasp



- Analysis of forces in the horizontal plane

$$F = \begin{bmatrix} F_x^{net} \\ F_y^{net} \end{bmatrix} = \begin{bmatrix} F_{1x} \\ F_{1y} \end{bmatrix} + \begin{bmatrix} F_{2x} \\ F_{2y} \end{bmatrix} + \begin{bmatrix} F_{3x} \\ F_{3y} \end{bmatrix} = F_1 + F_2 + F_3$$

$$T = r_1 \times F_1 + r_2 \times F_2 + r_3 \times F_3$$

=> six parameters ($F_{1x}, F_{1y}, F_{2x}, F_{2y}, F_{3x}, F_{3y}$)

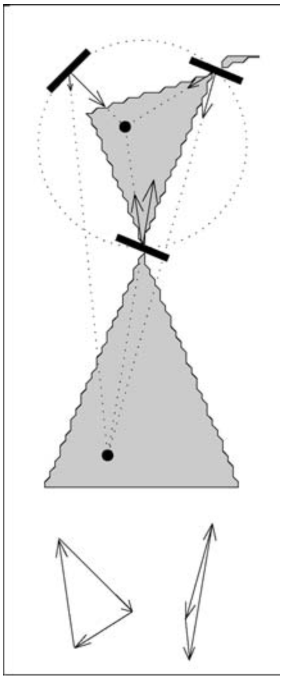
- In a simple lift and hold task, net force F and moment R in the horizontal are equal to zero (if the object is held horizontally)

  => three constraints ($F_x^{net}=0,\ F_y^{net}= 0, T=0$)

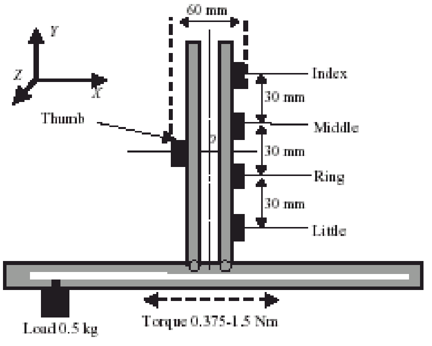
- Three degrees of freedom are unconstrained in the horizontal plane by equilibrium conditions

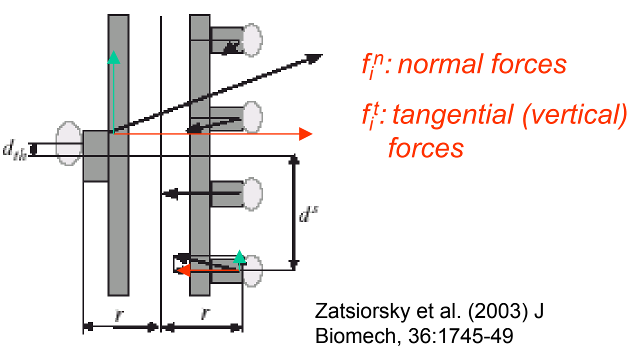
Internal force in the tripod grasp

- The internal forces in the tripod grasp have a simple geometric interpretation because it can be demonstrated they intersect at a point called **the force focus** (Yoshikawa & Nagai, 1991)
- Therefore, the following three parameters are sufficient to identify internal forces:
  - the position of the force focus (2 parameters)
  - magnitude of the force triangle or grip force
- The position of the force focuse is limited by frictional constraints (grey area).



Five-finger prismatic grasp





Zatsiorsky et al. (2003) J Biomech, 36:1745-49

- Force analysis in the frontal plane:

$$F_x = f^n_{thumb} - (f^n_{index} + f^n_{middle} + f^n_{ring} + f^n_{little})$$
$$F_z = F^t_{th} + (f^t_{index} + f^t_{middle} + f^t_{ring} + f^t_{little})$$
$$T = \underbrace{\sum_i d_i F_i^n}_{\text{moment of normal forces } M^n} + \underbrace{\sum_i r_i F_i^t}_{\text{moment of tangential forces } M^t}$$

where F_x,F_z is the the net force and T the net torque

Predictive control & Internal model

Grip force Load force coupling

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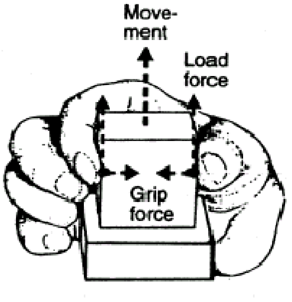
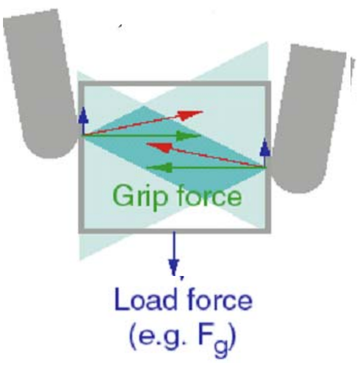
Load and grip forces





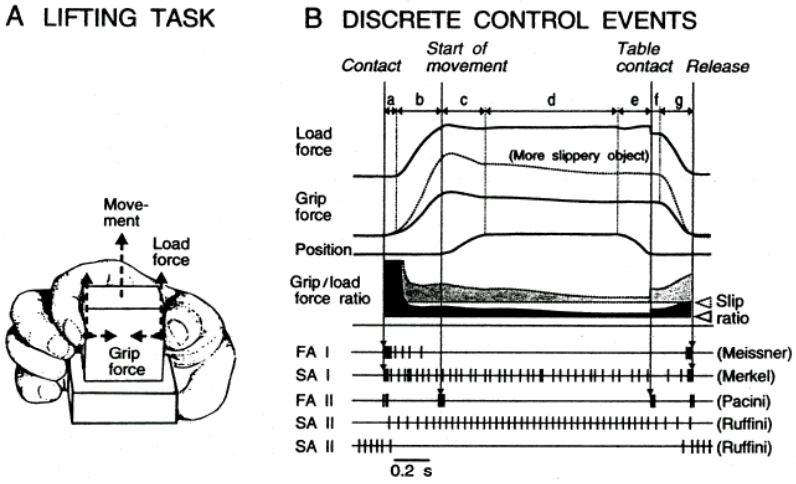
- CNS must adjust grip force as a function of the load to insure grasp stability

$$F_i^t < \mu F_i^n$$

- When the load is parallel to the contact surfaces, *grip force is mechanically independent from the load*

- Grip force is a window on the functioning of the CNS

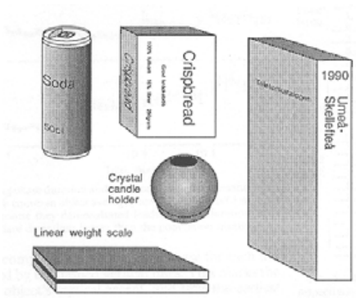
Predictive control



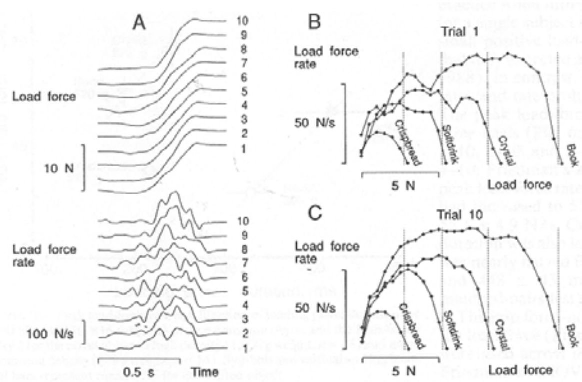
Johansson Cole (1994) Can. J Physiol. Pharmacol., 72:511-524

- Brain typically adjusts grip force in a predictively manner

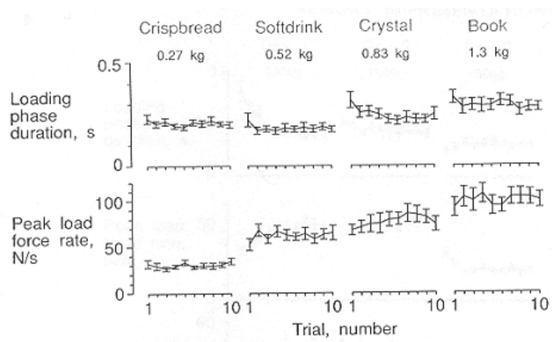
Familiar object



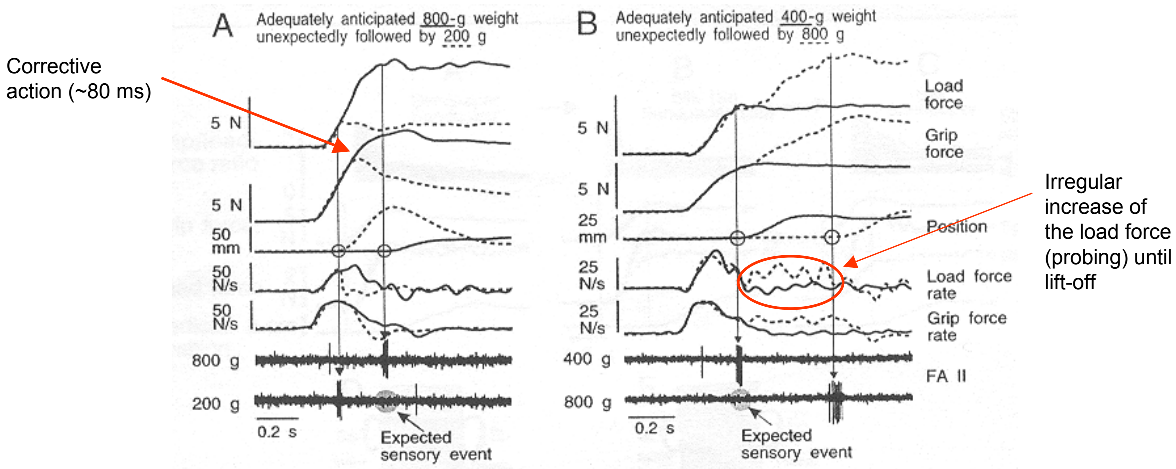
Gordon et al. (1993) J. Neurophysiology



- Load force is scaled to the weight of familiar objects from the onset



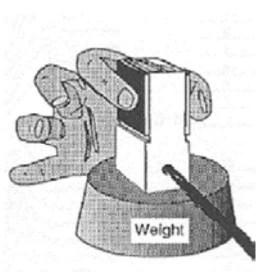
Unexpected weights

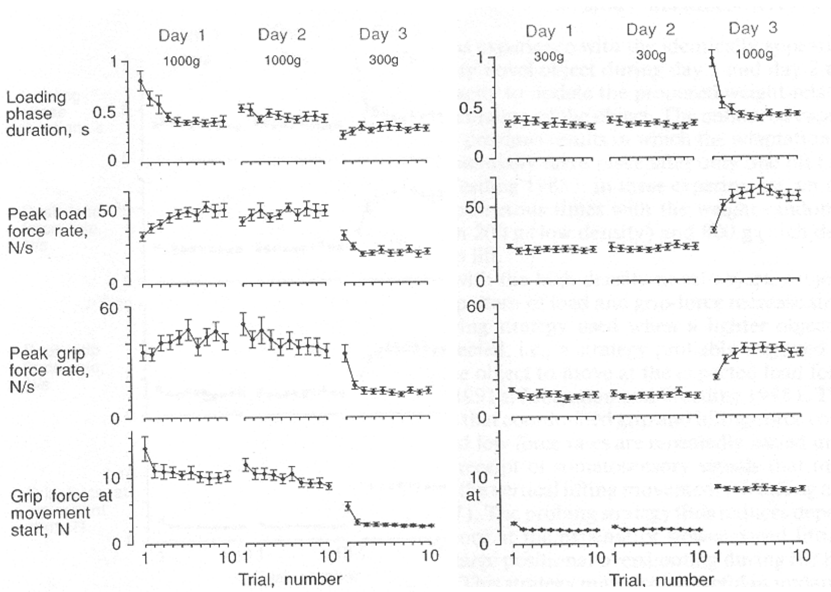


Johansson & Cole (1992) Cur. Op. Neuriobiology

- Sensory events (or lack thereof) trigger corrective or compensatory action

Novel weights

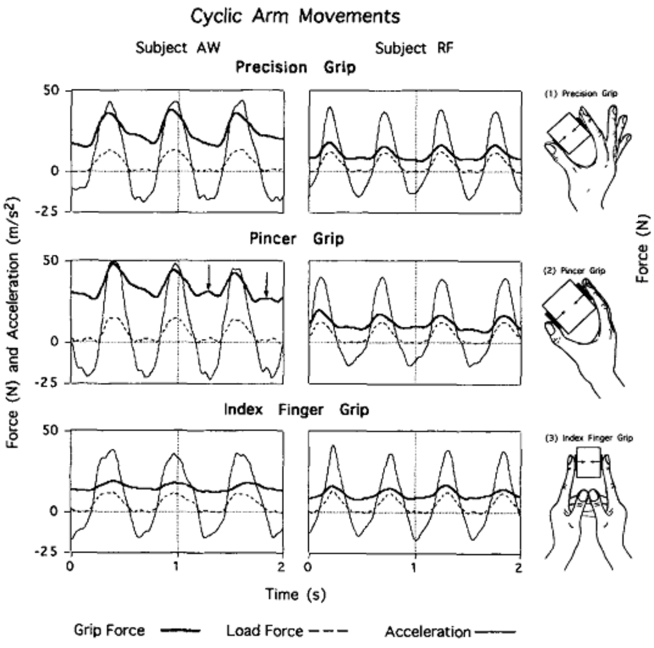


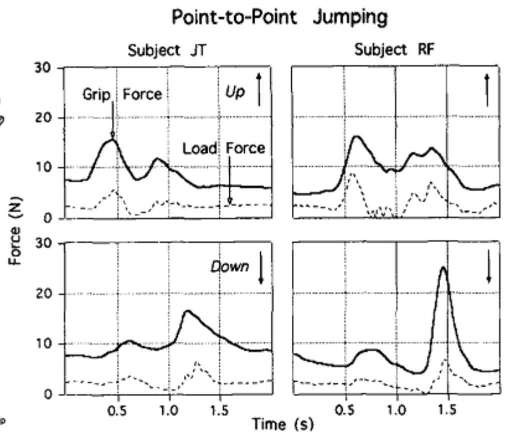


Gordon et al. (1993)
J. Neurophysiology

- Memory representations of novel weights develop quickly

Self produced loads

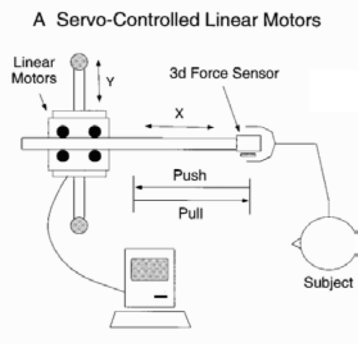


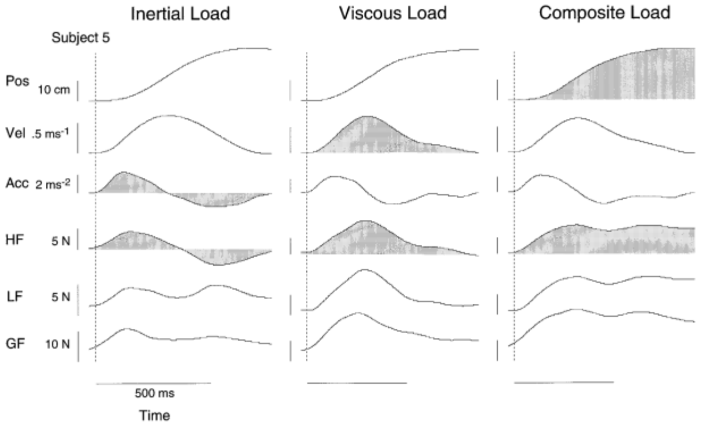


Flanagn & Tresilan (1994) JEP:HPP.

- GF/LF coupling during object transport reflects a general anticipatory control strategy that is not specific to any particular grip or mode of transport.

Unusual loads

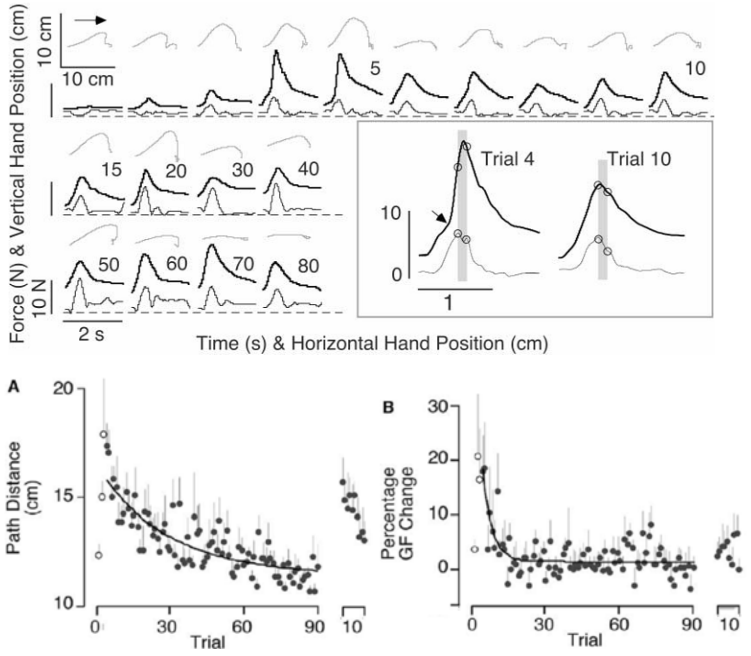




Flanagan & Wing (1997) J. Neuroscience

- CNS can learn to adjust grip force with different type of loads

Learning and control



For each trial, the hand path is shown and the grip force (thick trace) and load force (thin trace) records are shown below. The dashed line represents zero force. The first three trials are warm-up trials in which the load was incrementally increased. The inset shows grip force and load force records from trials 4 and 10. For both trials, the left margin of the gray bar is aligned with peak load force, and the width of the bar is 100 ms. The open circles indicate the grip and load force at the start and end of this 100-ms epoch.

- Grip force adjusts to load faster than hand trajectory
- Prediction precedes control in motor learning

Flanagan et al. (2003) Current Biology

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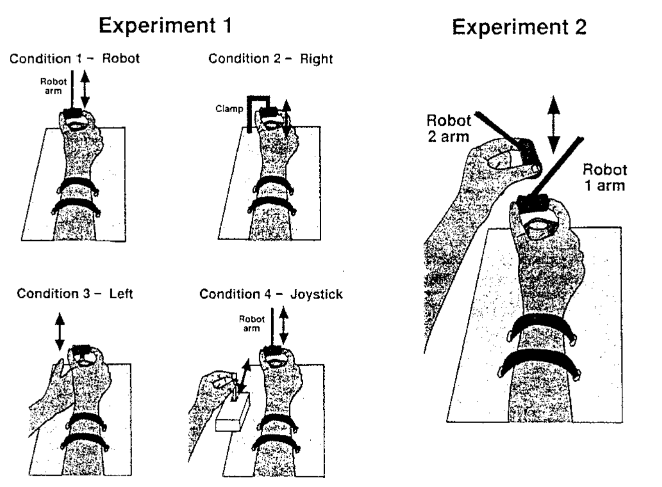
Predictive control limits



Blakemore et al. (1998) J. Neuroscience, 18(18):7511-7518

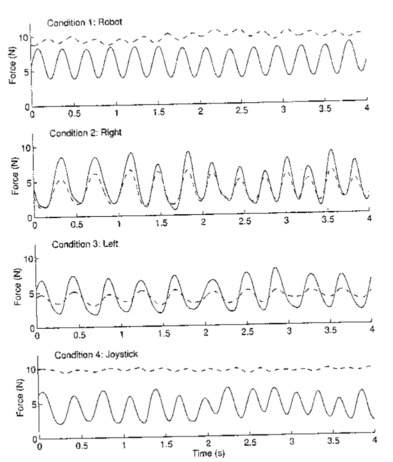


Figure 2. Typical example of grip force *(dashed line)* and load force *(solid line)* traces for the four conditions of Experiment 1 taken from a single subject tracking a frequency of 3.5 Hz. The data are taken from the same 4 sec time period in each trial and have been low pass-filtered.

Blakemore et al. (1998) J. Neuroscience, 18(18):7511-7518

- Physical properties of the object must be realistic for grip-load force coupling to occur in normal conditions.
- Grip-load force coupling is context dependent.

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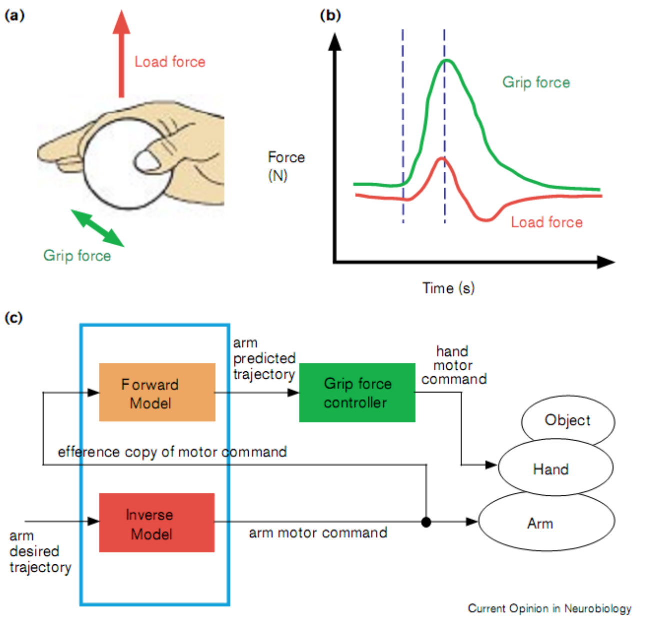
Summary



Kawato (1999) Current Opinion in Neurobiology

- Efficient force scaling to the properties of the object
- Precise temporal coupling between grip force and load force
- GF/LF is first observed at 8-10 months of age with mature pattern occurring at 8 years of age

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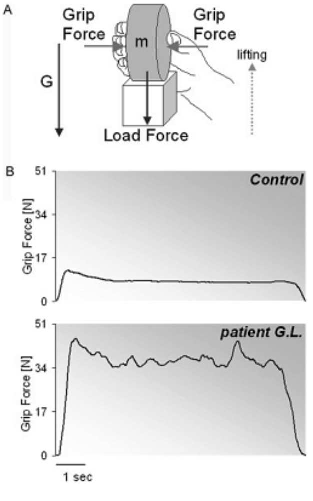
Functional pathology of grasping

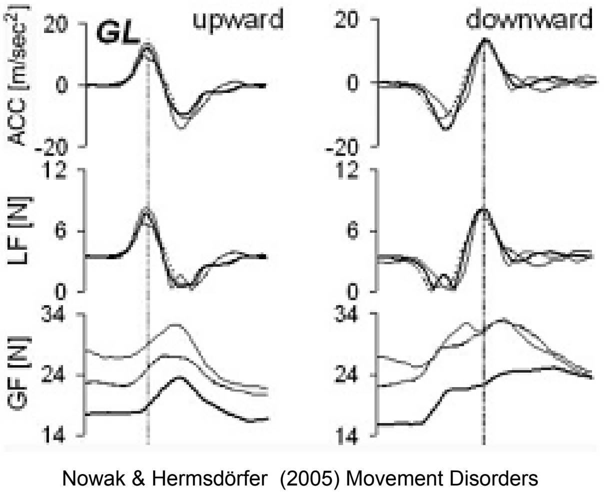
Nowak & Hermsdörfer (2006) Objective evaluation of manual performance deficits in neurological movement disorders. Brain Res. Rev., 51:108-124.

Deafferentation



Grip forces produced by a chronically deafferented patient and a healthy control subject when lifting a 0.61 kg weight

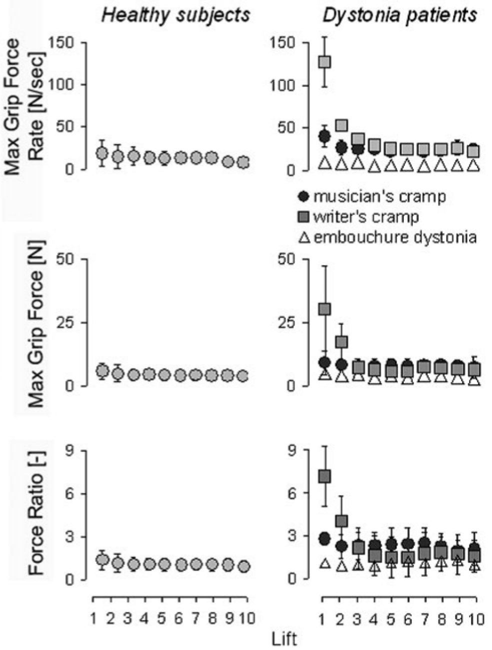
- Large increase of grip force



Nowak & Hermsdörfer (2005) Movement Disorders

- Absence of GF/LF coupling suggest that at least intermittent somatosensory feedback is necessary to exploit effective predictive control mechanisms during object manipulation (e.g. Update internal models).

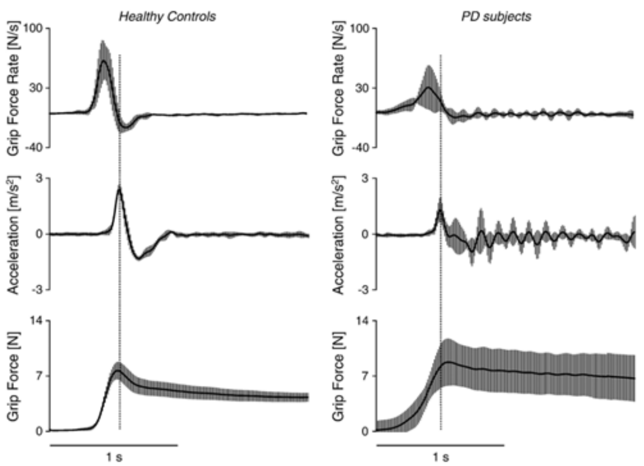
Hand dystonias

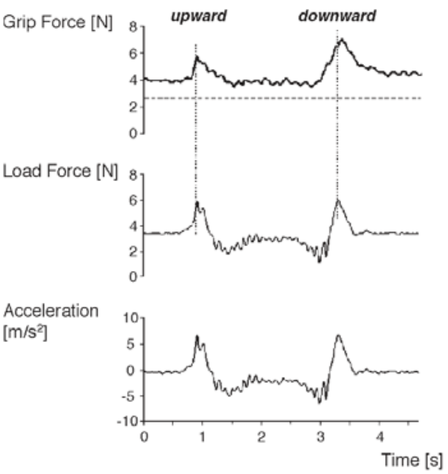


Nowak & Hermsdörfer (2006) Brain Res. Rev.

- Theory that dystonia results from impaird sensory–motor integration has attracted increasing interest (Abbruzzese & Beradelli, 2003).
- Grip force is too large during the first trials of lifting a novel object of unknown weight
- However, patients are able to quickly adjust grip force
- It has therefore been proposed that elevated grip force levels may be pre-learned and a consequence of an effortful writing style (Schenk and Mai, 2001; Schenk et al., 2004).
- Schenk and colleagues have demonstrated that a behavioral training tailored to reduce the force output can be effective.

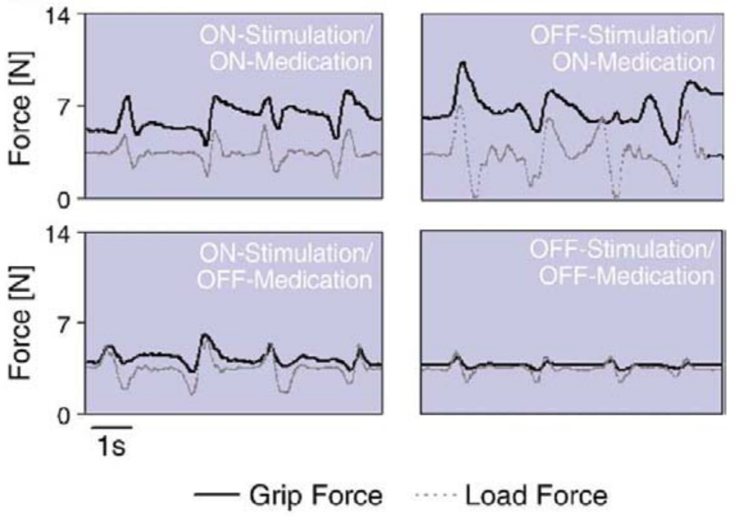
Parkison's Disease





- Bradykinesia: Lower grip force rate
- Postural tremor (5-7Hz)
- Increased variability of grip force (action tremor 10Hz)

PD treatment effect

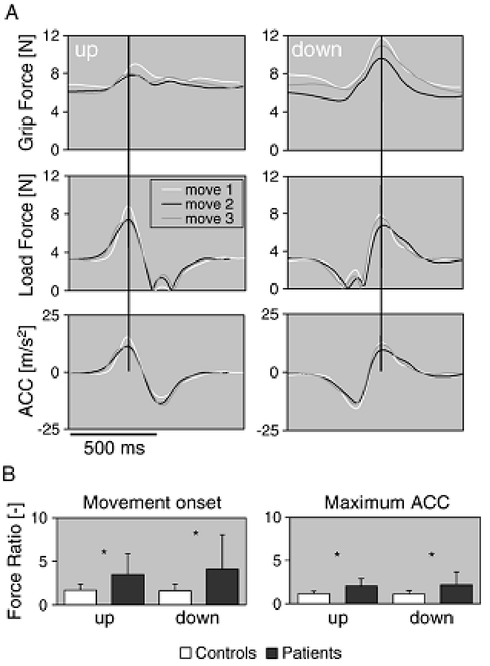


Georgiou et al., 1997

- levodopa-induced dyskinesia: Larger arm movement (load) and grip force
- subthalamic nucleus stimulation reduced levodopa-induced dyskinesias
- Bradidynesia (reduced arm movement) in absence of stimulation and medication

Grip force analysis may be a useful tool to objectively evaluate the effectiveness of therapeutic efforts in subjects with Parkinson's disease

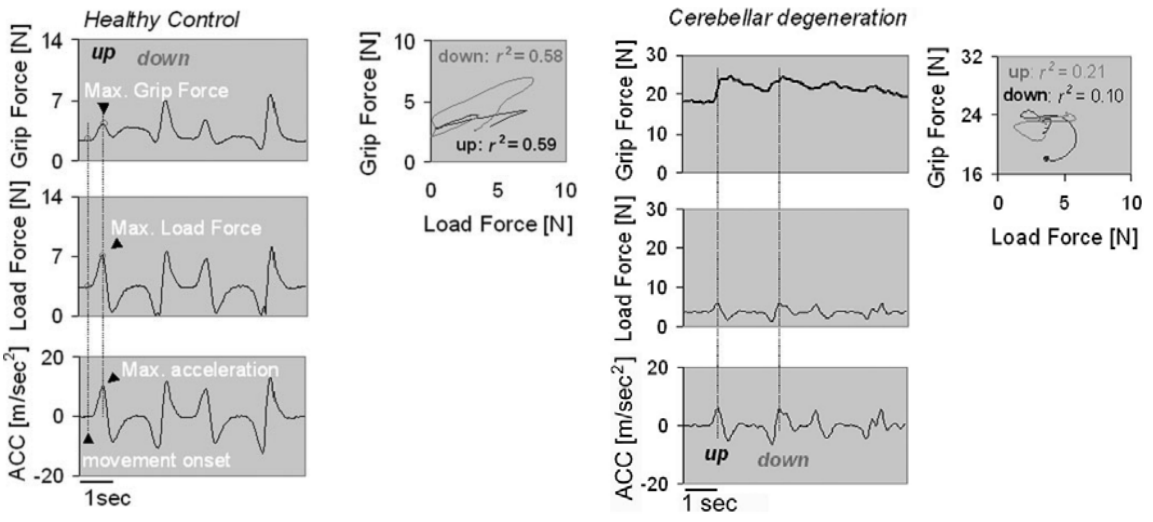
Gilles de la Tourette syndrome



Nowak & Hermsdörfer (2006) Brain Res. Rev.

- Larger grip force and Grip/Load force ratios than controls
- Preserved temporal coupling

Cerebellar degeneration



Nowak & Hermsdörfer (2006) Brain Res. Rev.

- Deficits of predictive grip force control in cerebellar disorders in in cerebellar degeneration and when the territory of the superior cerebellar artery is affected.

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Bernstein’s problem

Selection of contact froce in multi-finger grasp

Bernstein’s degree of freedom problem

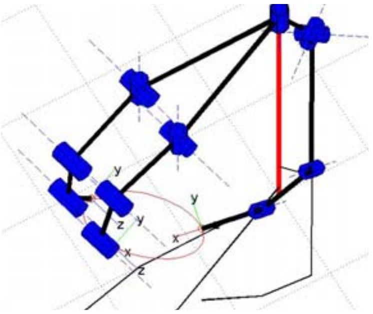
- Bernstein’s degree of freedom problem: “The coordination of a movement is the process of mastering *redundant* degrees of freedom of the moving organ, in other words its conversion to a controllable system” (Bernstein, 1967, p.127).

- Nicholai A. Bernstein (1896-1966)
- “The coordination and regulation of movements”, Pergamon, 1967.
- Reedition with a modern commentary of Bernstein's work “On Dexterity and its development” (ed. Latash), Erlbaum, 1996.

Degrees of freedom

$$x + y + z = 0$$
$$x - 2y - 3z = 0$$

- Number of free parameters in a system of equation



- Kinematic degrees of freedom: Number of free parameters in a robotic structure

- The body is a mechanical structure with many degrees of freedom.
  - The number of degrees of freedom corresponds to the number of parameters that can be varied independently.
  - A mechanical structure is said to have *redundant degrees of freedom* if it has more degrees of freedom than required by the task

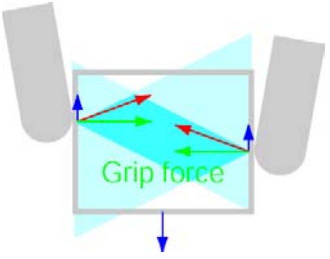
- In multi-finger grasp, there are typically many more degrees of freedom than task constraints

Redundant degrees of freedom

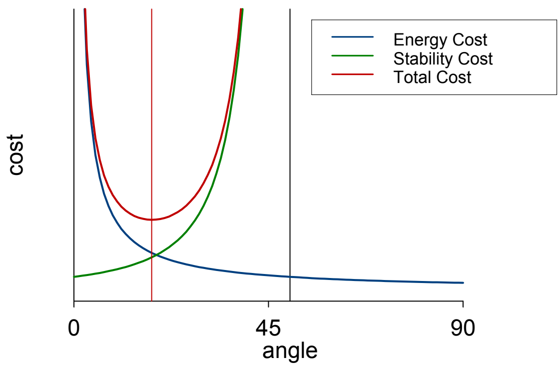
Grasp	Pinch		Tripod	
Friction	No	Yes	No	Yes
# fingers (n)	2	2	3	3
# dofs (4n)	8	8	12	12
# constraints (k)	6	4	6	4
# redundant dofs (4n-k)	2	4	6	8

• Optimal control (minimization of some cost function) is a common approach both in robotics and humans studies to solve ill-defined problem (e.g., Minimum Jerk, Minimum torque change)

Optimal control in the pinch grasp



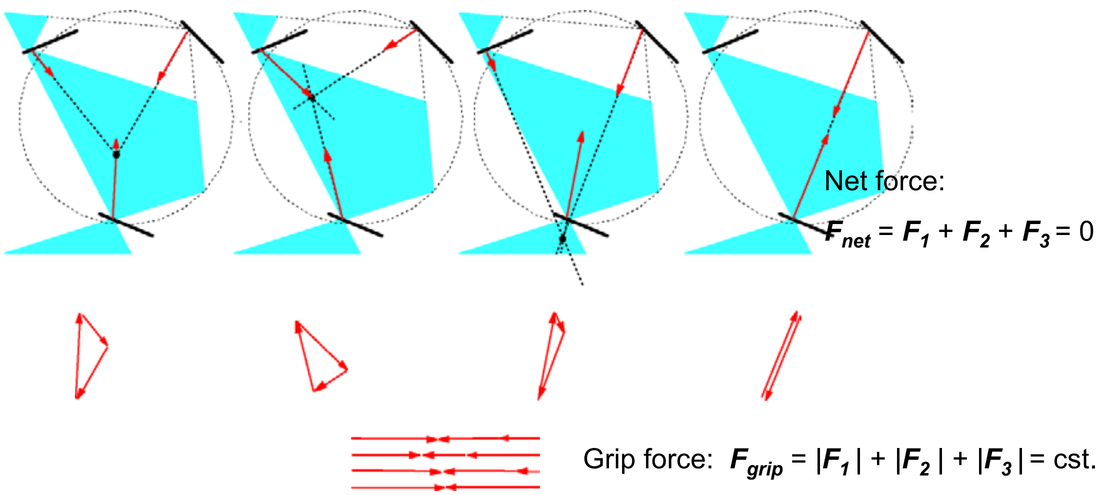
- The motor system selects the solution that is most efficient:
  1. minimizing energy expenditure
  2. maximizing grasp stability.



- For the pinch grasp, energy expenditure and grasp stability are two contradictory principles.

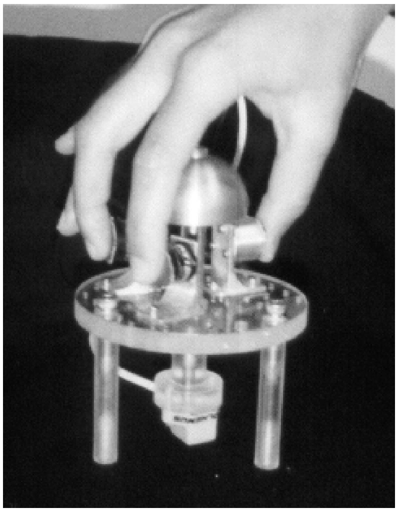
Optimal control in multi-finger grasps

- In multi finger grasps, additional degrees of freedom allow to vary grasp stability independently from grip force.



- Grasp stability can be maximized independently from energy expenditure

Contact forces in the tripop grasp



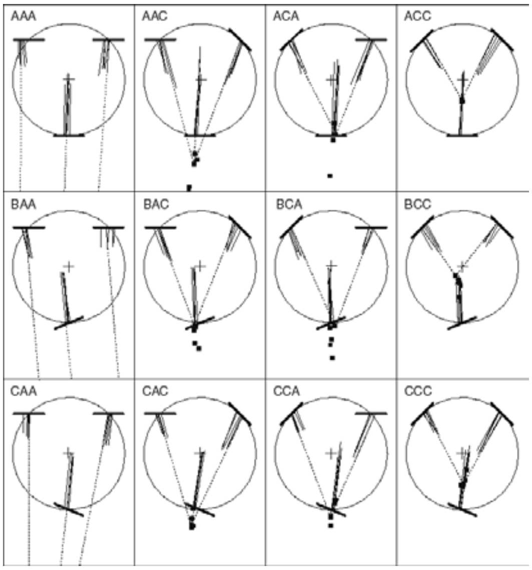
Baud-Bovy & Soechting (2001) J. Neurophysiol. 86:604.

- This study analyzed contact forces under various conditions:
  - object geometry
  - finger positions
  - object center of mass

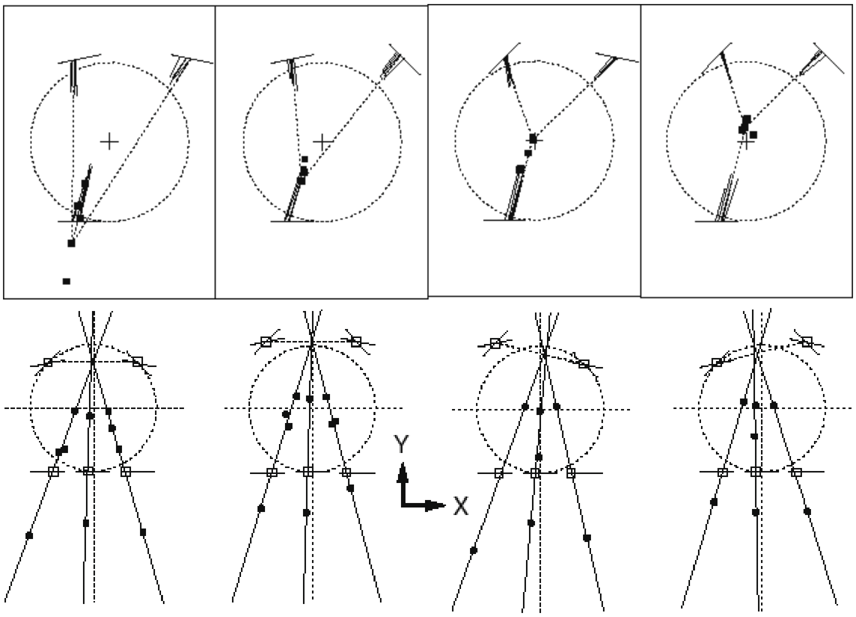
Object geometry

- Changing the orientation of one of the two surfaces opposed to the thumb affect directions of the contact forces of both fingers.The direction of the thumb force does not change.

- Thumb force direction is directed toward a point at mid-distance between the two opposing fingers.



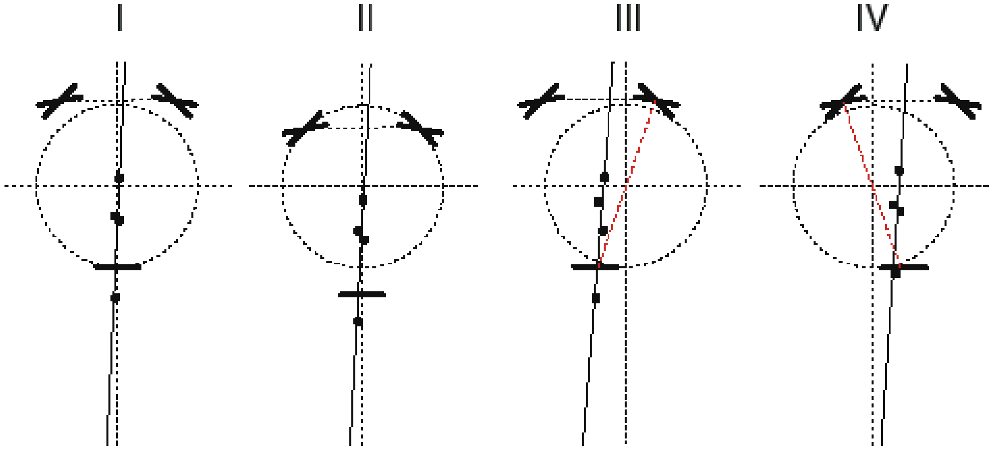
Finger Placement



Baud-Bovy & Soechting (2001) J. Neurophysiol. 86:604.

Thumb force is directed toward a point at mid-distance between the two fingers whatsoever the finger positions.

Center of mass position

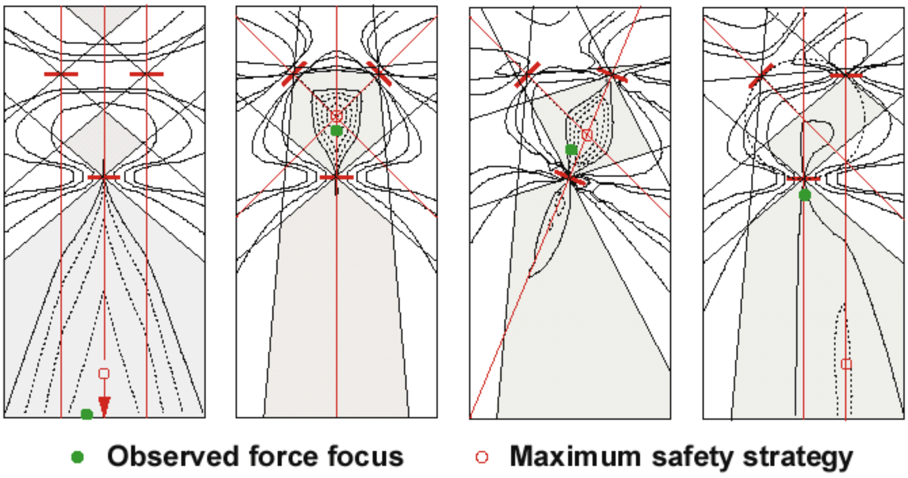


Baud-Bovy & Soechting (2001) J. Neurophysiol. 86:604.

- Center of mass position does not affect direction of the thumb force.

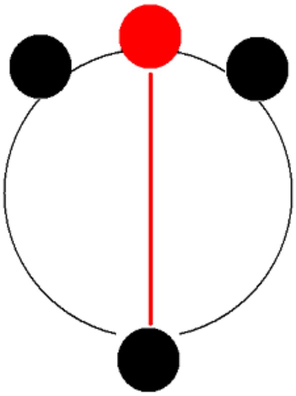
Grasp stability

- Is grasp sability maximized?



- The synergy is sub-optimal from a stability point of view

Virtual finger hypothesis



- The index and middle finger force are controlled in such manner that the direction of the thumb force does not vary.
- In other words, these two fingers can be replaced by a single virtual finger aligned with the direction of the thumb force (approximatively at mid-distance betwee the the two contact points).
- The tripod gras has therefore two virtual fingers and one opposition space

Hierarchical control scheme

Task constraints

↓

Virtual fingers

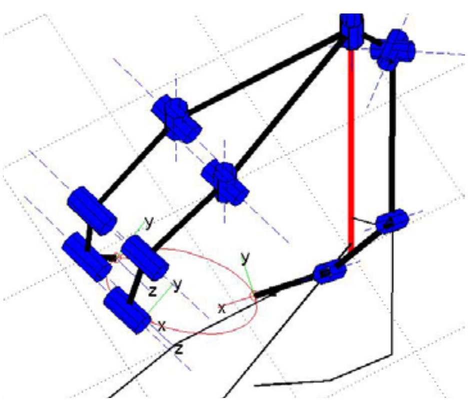
↓

Real fingers

- Task parameters
  - Equilibrium constraints
- Virtual Finger
  - VF position introduce additional constraints on contact forces
  - VF position independent from thumb position and center of mass position.
- Individual fingers
  - Grasp stability is maximized under higher-level constraints

Minimizing Energy Expenditure

- Given a certain level of grip force, what is the direction of the finger forces that minimize torques?
- Is nature well done?



$$\|K\tau\| = \|K\,J'\,F\| \rightarrow \min$$

$$\tau = [\tau_1 \ldots \tau_{12}]'$$

$$K = diag(w_1,\ldots,w_{12})$$

$$J = J(\theta_1,\ldots,\theta_{12}) \quad \text{Jacobian}$$

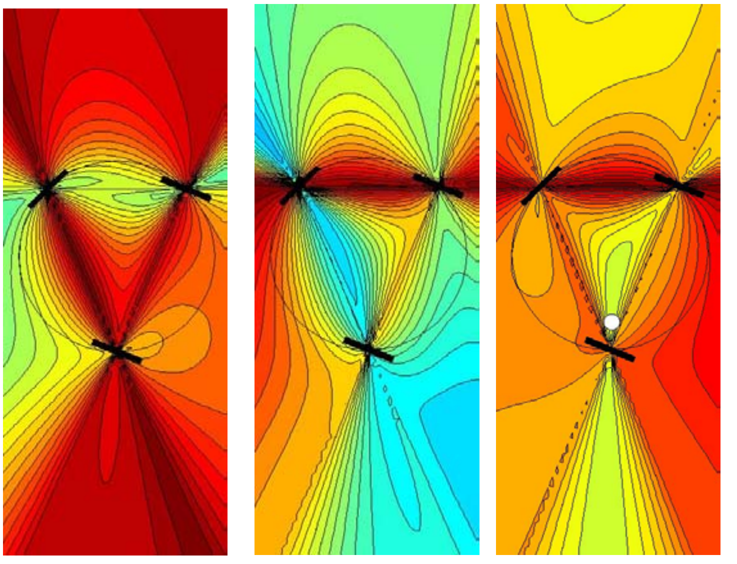
$$F = [F_1\ F_2\ F_3]' \quad \text{such that} \quad |F_1|+|F_2|+|F_3| = cst.$$

Baud-Bovy et al. (2005) In *Multi-point Interaction with Real and Virtual Objects*, STAR 18, Springer, pp. 21–40, 2005.

Minimizing Energy Expenditure

- Cost function that do not take into account the orientation of contact surfaces.

  Minimum does not satisfy squeezing or frictional constraints



$K = I$

$$K_b = \begin{bmatrix} .3 & .6 & .7 & 3 \\ 7 & .5 & 1 & 5 \\ 7 & .5 & 1 & 5 \end{bmatrix}$$

$$K_h = \begin{bmatrix} .1 & .1 & .1 & .1 \\ 2 & 1 & 1 & 1 \\ 2 & 1 & 1 & 1 \end{bmatrix}$$

- Cost function depends on weight matrix K
- Realistic hand model with tendons and muscles would be needed

Minimizing Energy Expenditure

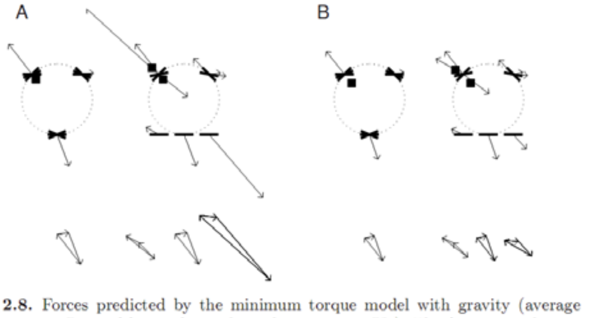


Fig. 2.8. Forces predicted by the minimum torque model with gravity (average hand posture $\mathbf{J}_{av}$ and biomechanical weighting matrix $\mathbf{K}_b$). The force triangles are plotted below. The thumb position is shifted laterally in some panels (the short black lines represent the contact surfaces). A: Grip force unconstrained. B: Constrained grip force ($F_{grip} = 5$N).

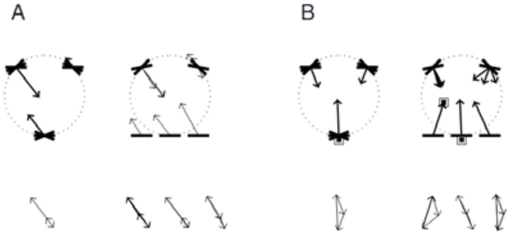
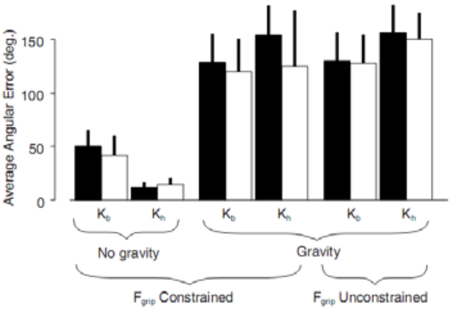


Fig. 2.9. Effect of matrix $\mathbf{K}$ on the predicted forces in absence of gravity (average hand posture, and constrained grip force). Same format as Fig. 2.8. A: Biomechanical weight matrix $\mathbf{K}_b$. B: Heuristic weight matrix $\mathbf{K}_h$.



- Simulation results suggest that observed contact forces are near optimal from an energetic expenditure point of view if external force are not included.
- This make sense because the optimum, from an evolutionary point of view, should not depend on arbitrary factors such as the external force.