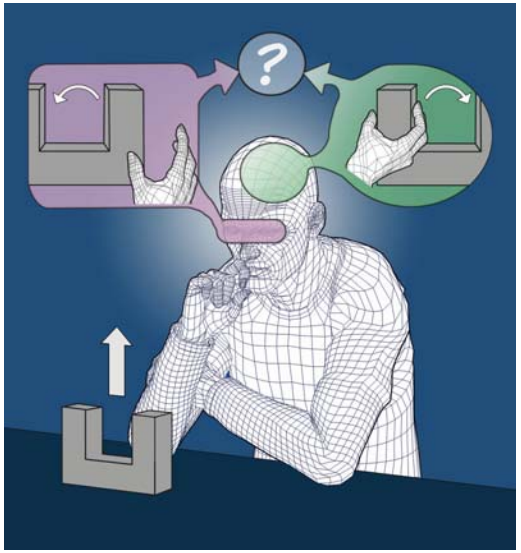
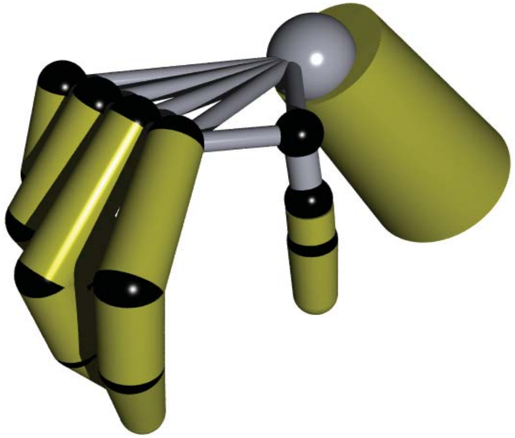
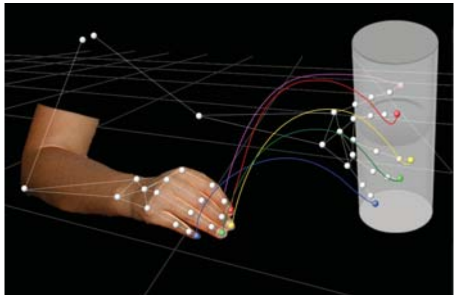
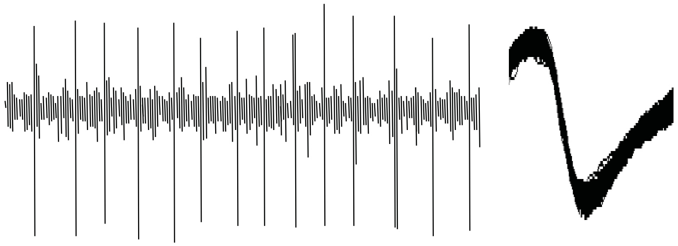
Human Grasping: Neural mechanisms underlying learning and control of grasping and manipulation









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Workshop on Human vs. Robot Grasping and Manipulation – How can We Close the Gap?
Robotic Science and Systems 2014, University of California, Berkeley

Outline

Introduction

Neural Control of Movement Lab: Research approaches

The human hand: A complex system

Synergies

- From neuroscience to robotic and prosthetic applications
- From robotics to neuroscience applications

High-level representations of dexterous manipulation

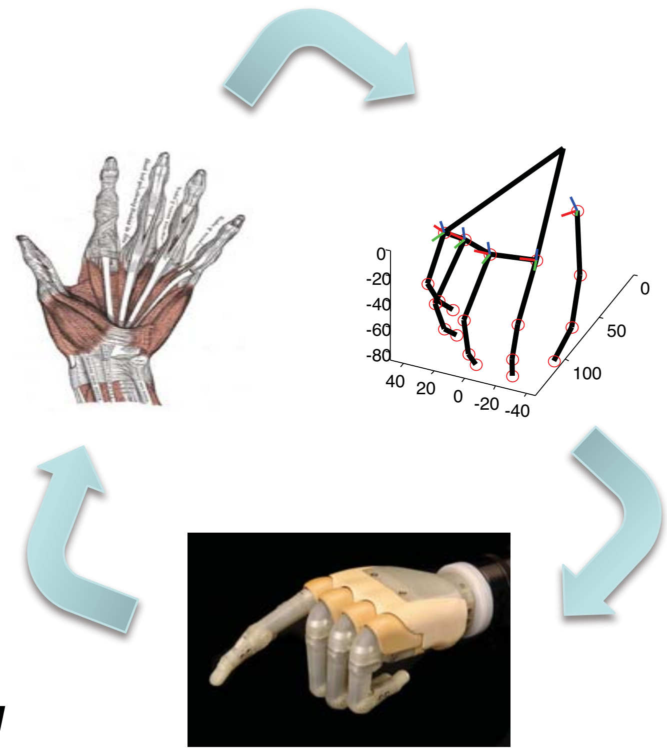
Digit force-to-position coordination

Conclusions and open questions

The hand plays a crucial role in activities of daily living

A better understanding of how the central nervous system controls the hand has impact on clinical applications, e.g.:

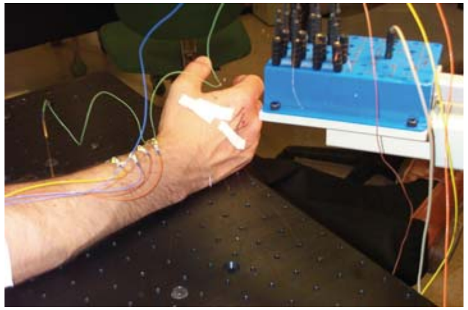
- *development of hand prosthetics*
- *design novel approaches for*
  - *rehabilitation of hand sensorimotor function*
  - *assessment of effectiveness of clinical intervention*
- *promotion of neuroplasticity: motor execution and learning*

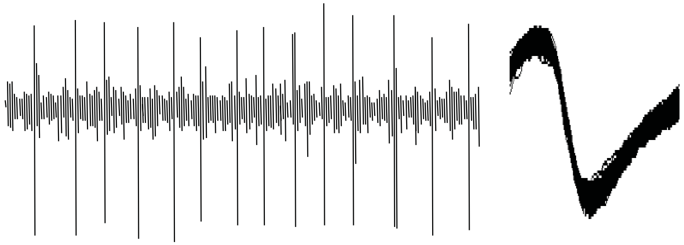


Our research aims to understand the neural mechanisms underlying hand control and investigate clinical applications.

Neural Control of Movement Laboratory: Research questions and approaches

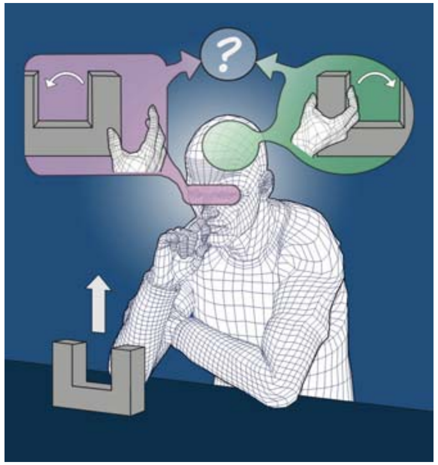
Neuromuscular control
Coordination of hand muscles



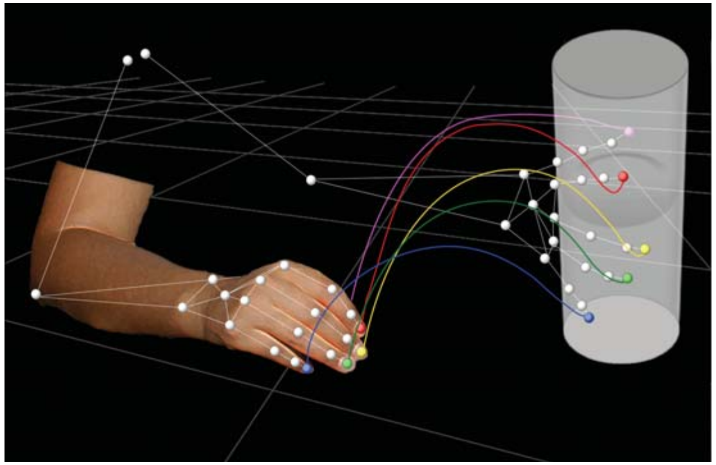


Single-unit EMG

Sensorimotor learning of dexterous manipulation
Transfer, retention, generalization

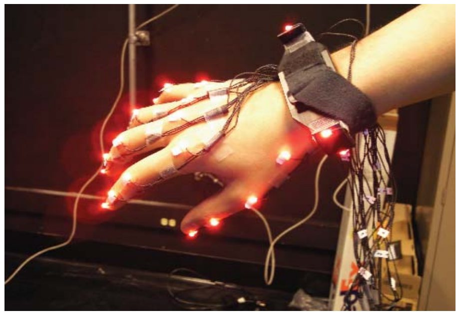


Task planning

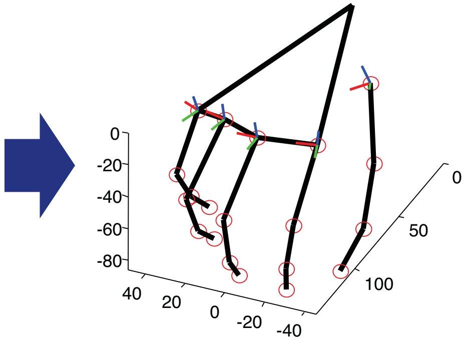


Hand trajectory and digit placement planning

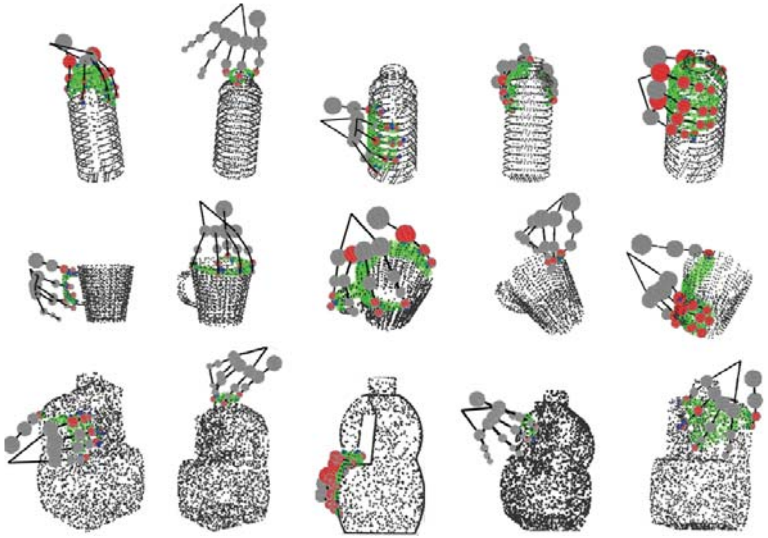
Control of grasping and manipulation
Motion-to-force transition



Hand tracking

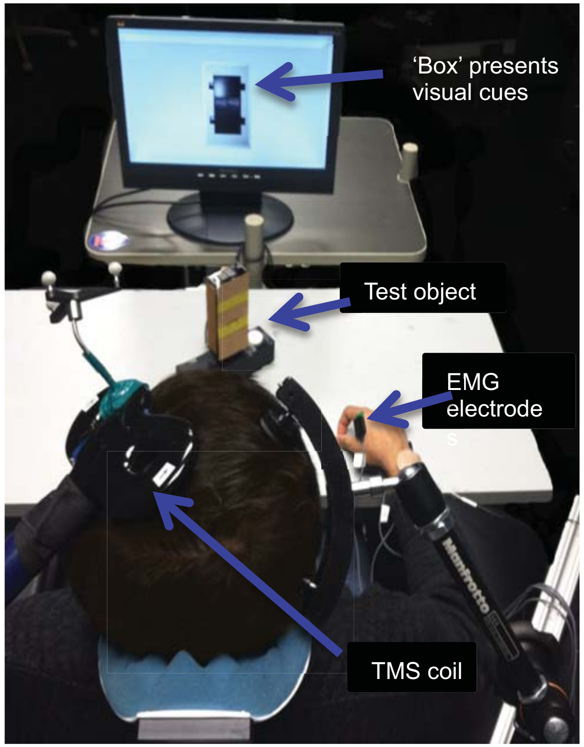


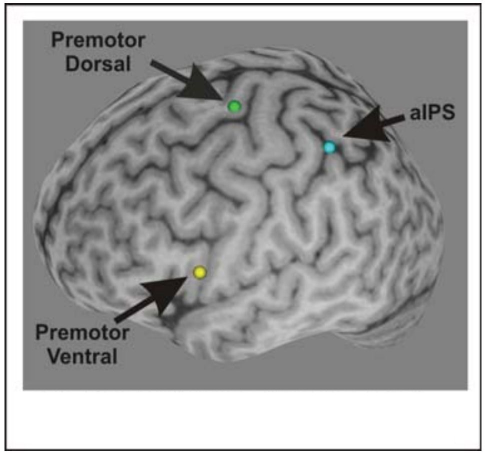
Hand model



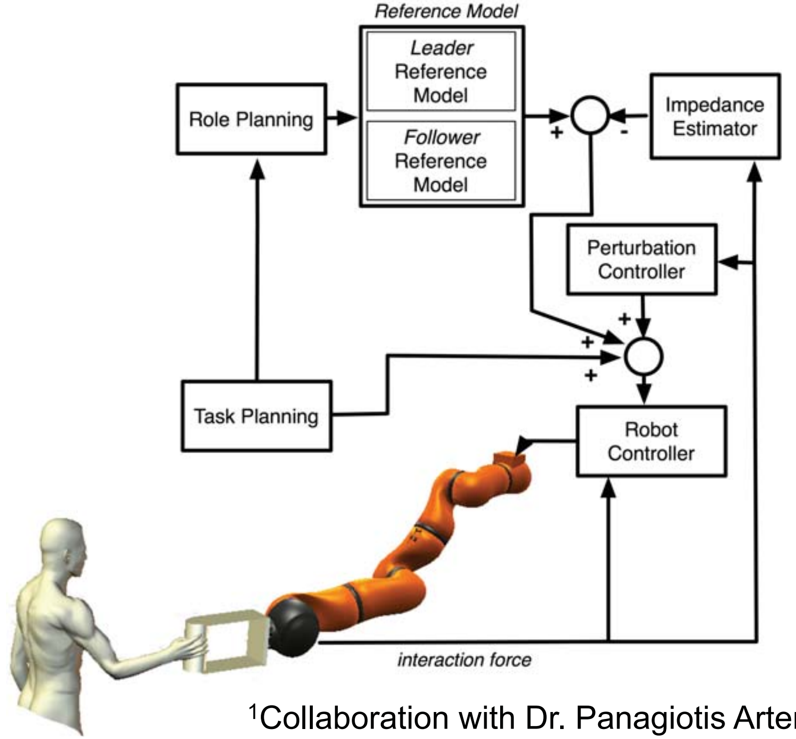
Hand-object interaction models

Non-invasive brain stimulation (TMS)
Dexterous manipulation: Cortical mechanisms



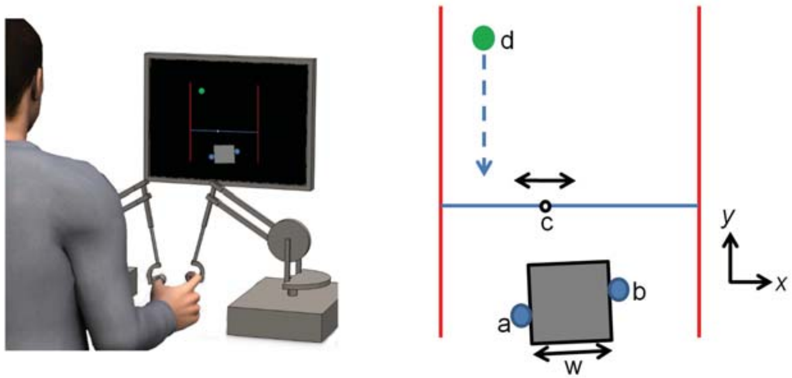


Human-machine physical interactions
Rules underlying cooperative motor actions[1]

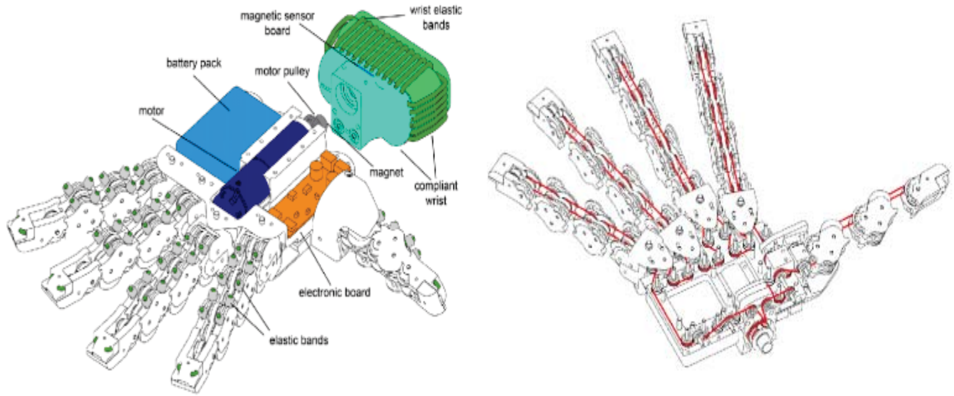


[1]Collaboration with Dr. Panagiotis Artemiadis

Virtual reality environments
Multisensory integration

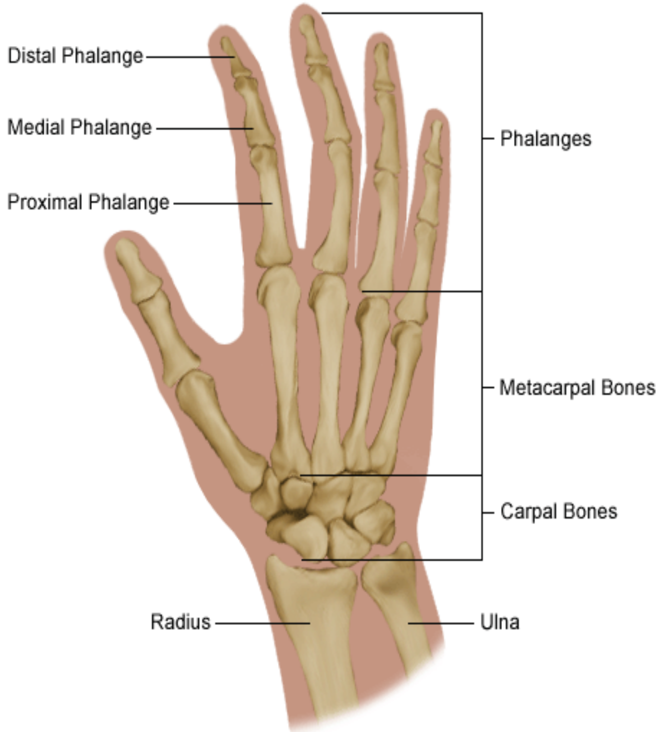


Hand prosthetics
Control of PC-based myoelectric hand prosthesis[2]



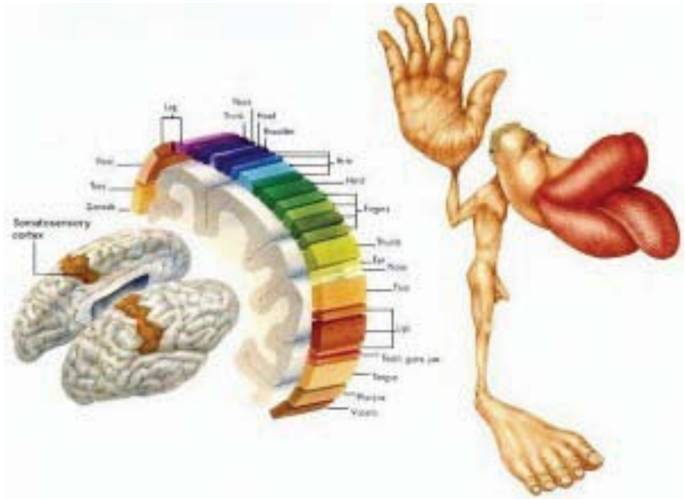
[2]Collaboration with Drs. A. Bicchi, Andrews, Terzic

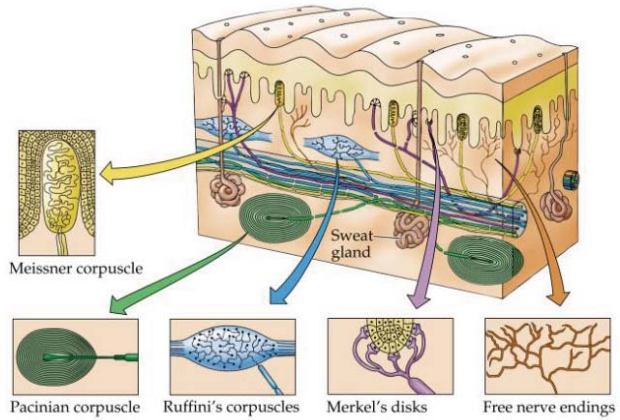
The human hand: A complex system



skeletal structure
{27 bones}

muscle architecture
{35 muscles}

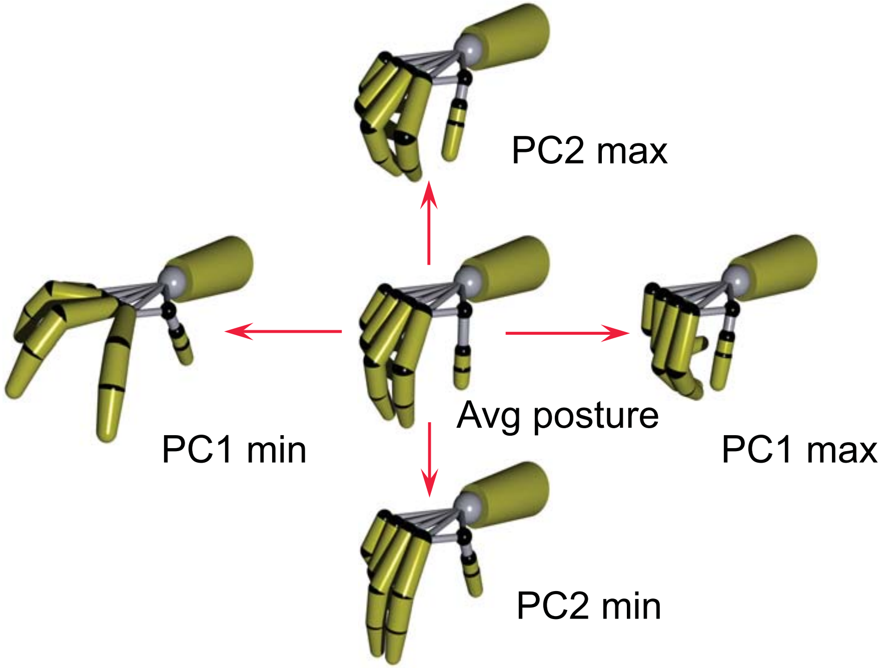




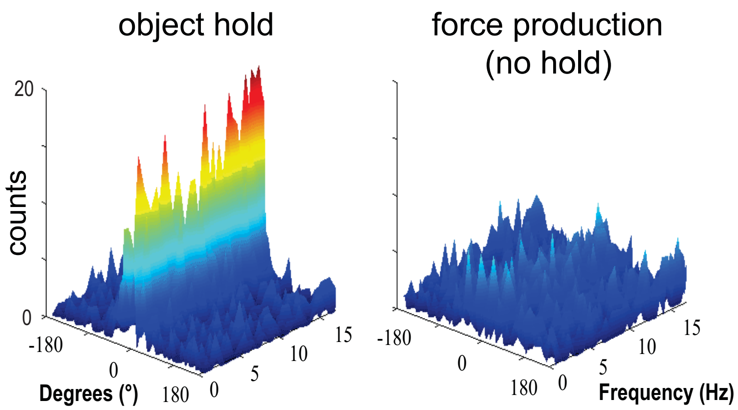
neural
{large # of motor units
and sensory receptors}

Synergies: Neuroscience

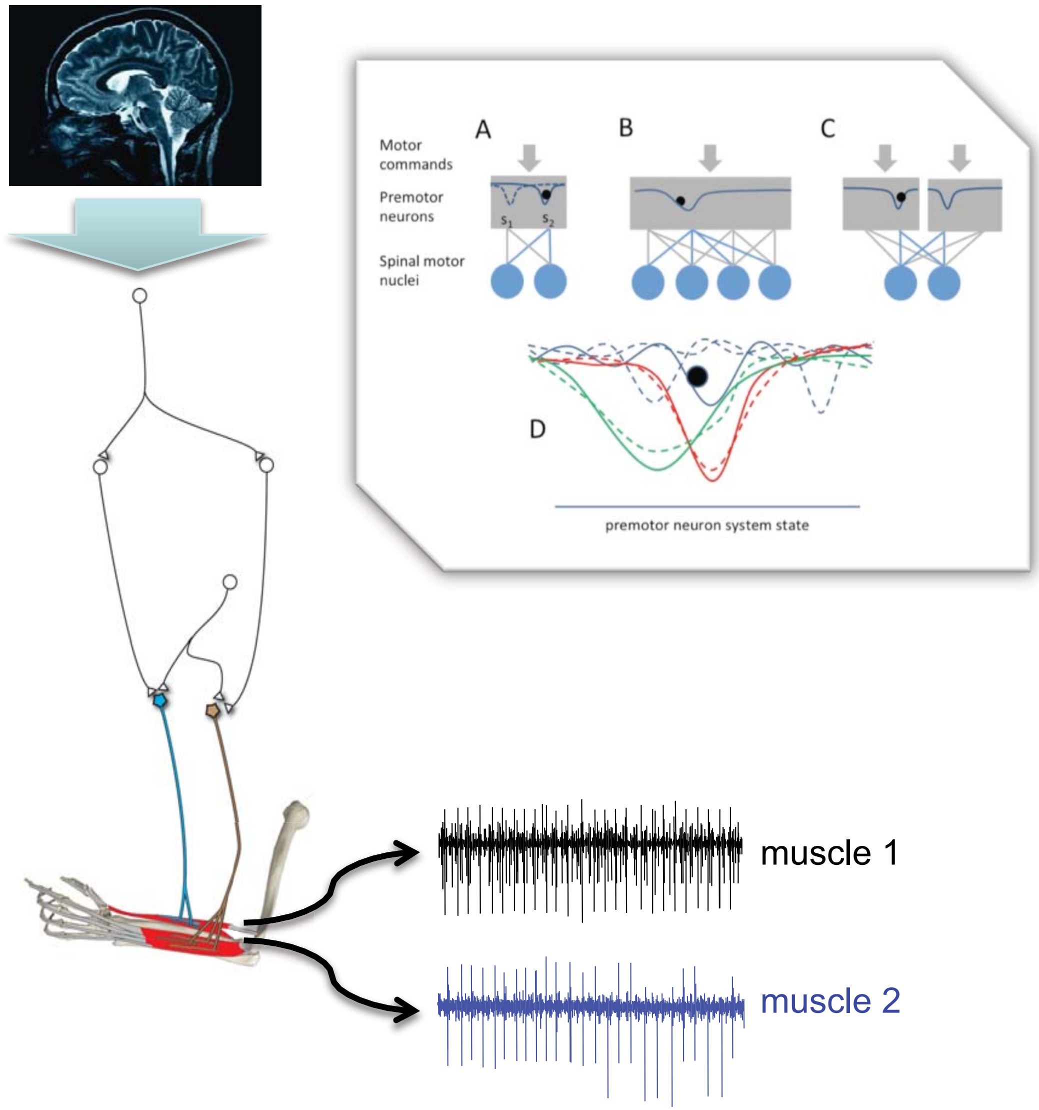
Kinematics



Kinetics



Electromyography (EMG)



[1]Reviewed in Schieber and Santello (2004); Santello et al. (2013)

Synergies: Robotic applications

The concept of synergies has been developed for grasp planning and design of robotic hands.

Artificial hands

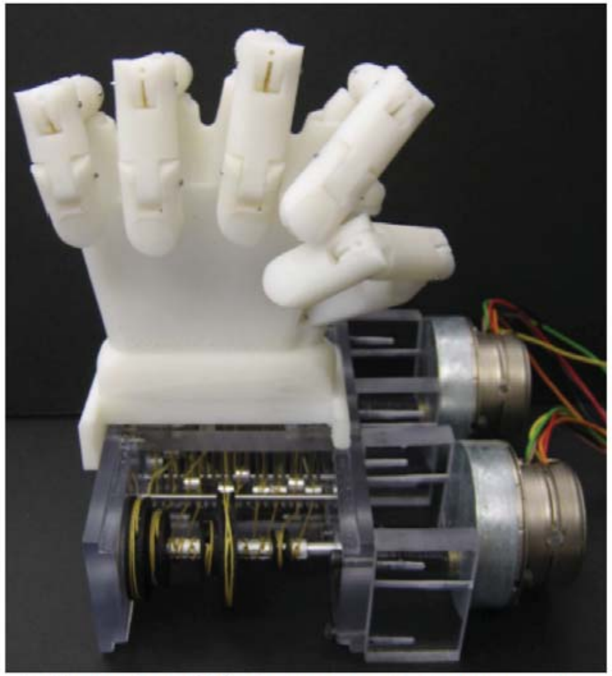


Fig. 8. Front view of final prototype. 2 stepper motors, on the right, control the eigenposture shafts.

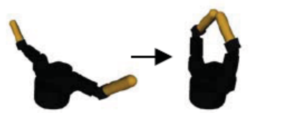
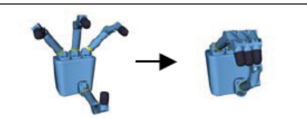
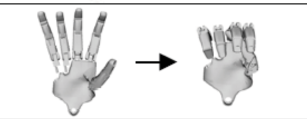
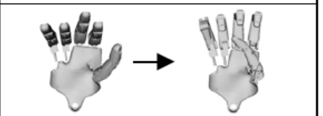
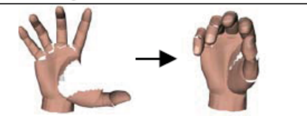
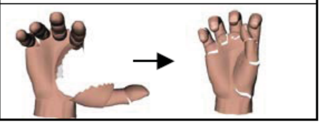
Brown and Asada (2007)

(a) one synergy (b) four synergies

Fig. 8. A modular hand prototype with adaptive synergies. (a) An assembly with two 4-phalanx fingers, a 2-phalanx thumb and a single adaptive synergy. (b) A prototype with three equal fingers and four adaptive synergies.

Catalano, Grioli, Farnioli, Serio, Piazza, Bicchi (2014)

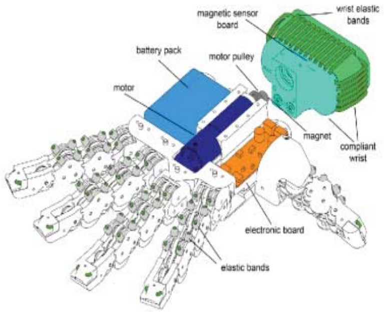
Grasp planners

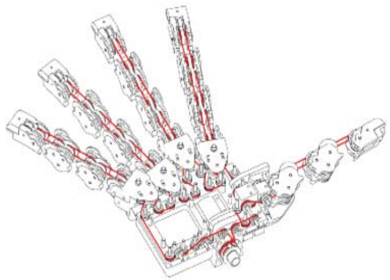
Model	DOFs	Eigengrasp 1			Eigengrasp 2		
		Description	min	max	Description	min	max
Gripper	4	Prox. joints flexion			Dist. joints flexion		
Barrett	4	Spread angle opening			Finger flexion		
DLR	12	Prox. joints flexion Finger abduction			Dist. joints flexion Thumb flexion		
Robonaut	14	Thumb flexion MCP flexion Index abduction			Thumb flexion MCP extension PIP flexion		
Human	20	Thumb rotation Thumb flexion MCP flexion Index abduction			Thumb flexion MCP extension PIP flexion		

Ciocarlie, Goldfeder, Allen (2007)

Synergies: Prosthetic applications

The concepts of synergies and soft robotics are currently being investigated for prosthetic applications in trans-radial amputees.[1]





[1]Collaboration among Arizona State University, Italian Institute of Technology, and Mayo Clinic, MN

Supported by: NIH, Grainger Foundation, INAIL

Ajoudani, Godfrey, Bianchi, Catalano, Grioli, Tsagarakis, Bicchi (2013)
Catalano, Grioli, Farnioli, Serio, Piazza, Bicchi (2014)

From robotics to neuroscience (and viceversa)

Robotic studies of the problem of 'noisy' and incomplete sensing of Hand Posture Reconstruction (HPR) systems take inspiration from and inspire neuroscience research on the extent to which the central nervous system exploits biomechanical and neural constraints for sensing hand posture.[1]

5DT Data Glove - www.5dt.com

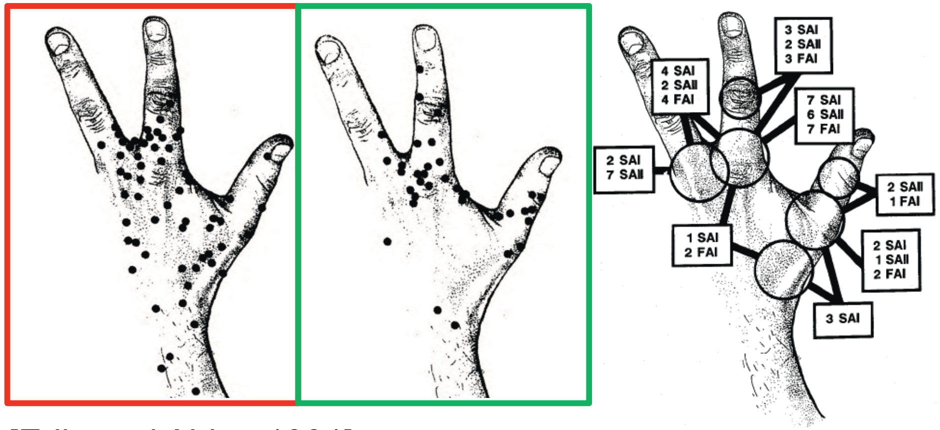
[Dipietro et al.,2008]

The problem of correct hand pose estimation:

- ❑ complexity of human hand biomechanics, measurement inaccuracies
- ❑ widespread use of glove-based HPR systems

Bianchi, Salaris, Bicchi. *Int J Rob Res* (2013a)

If you were the designer…



[Edin and Abbs, 1991]

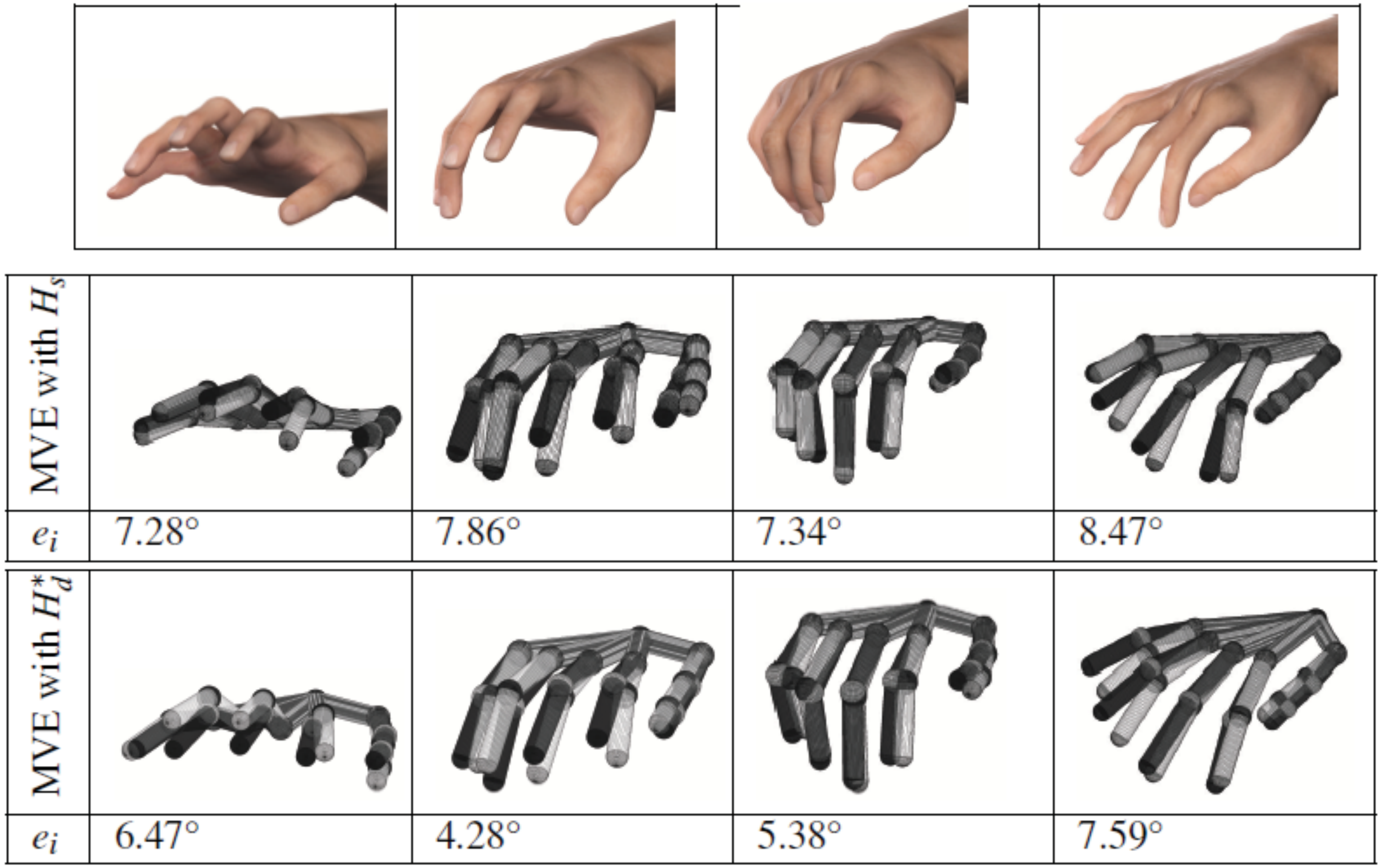
- ❑ **SA units (SAI, SAII):**
  - ❑ non-localized response (several joints involved);
  - ❑ rather uniformly distributed
- ❑ **FA units (FAI):**
  - ❑ localized response to one/ two joints;
  - ❑ higher density near the joints

Different typologies of proprioceptive sensors are distributed in the dorsal skin with different densities

A non–uniform map of sensitivities to joint angles

Is there a preferential distribution and density of different sensors, which optimizes the overall accuracy of a glove?

Application of synergy-based optimal glove design techniques (noisy case)



Non-Optimal

Optimal

Bianchi Salaris Bicchi *Int J Rob Res* 2013b

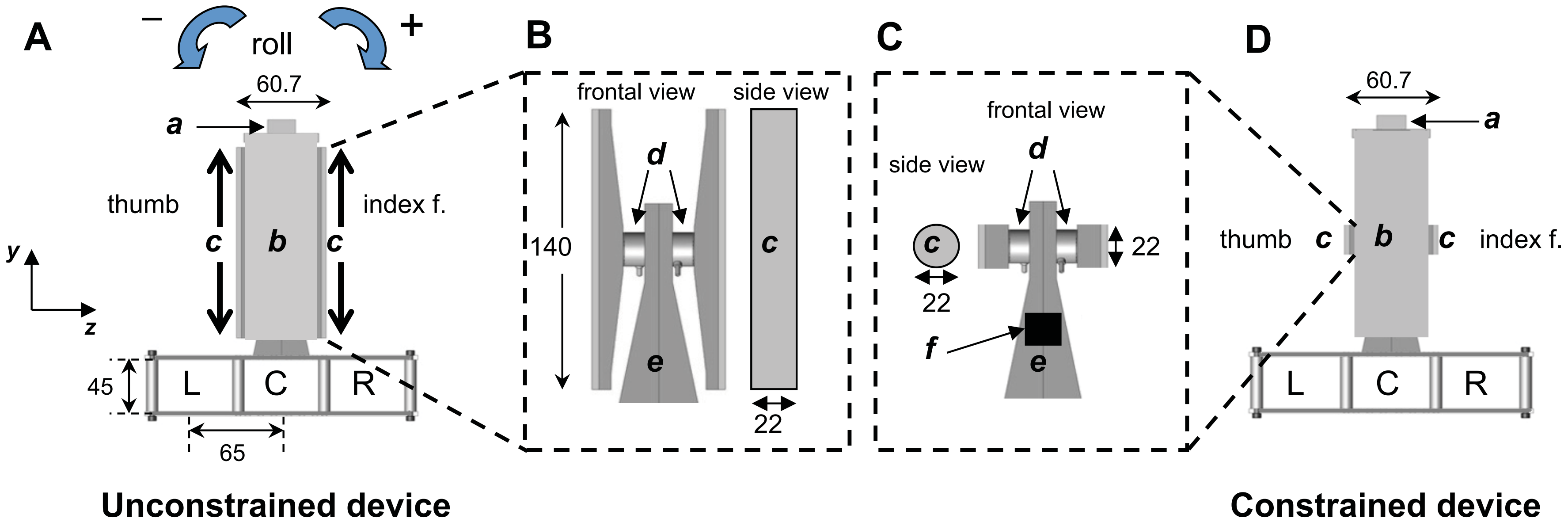
High-level representations of dexterous manipulation

The present studies were designed to infer the **neural mechanisms underlying learning of dexterous manipulation** and address the following questions:

- *What are the sensorimotor mechanisms responsible for digit force control for unconstrained grasping?*
- *What are the sensory modalities responsible for digit force modulation to position?*

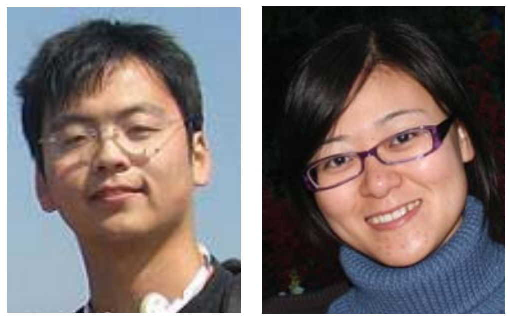
Testing dexterous manipulation: constrained vs. unconstrained grasping

When subjects can choose contact points on objects, the extent to which they can rely on sensorimotor memory of digit forces is reduced. This is a major control problem when trial-to-trial variability of digit placement occurs.



Task:

- grasp the object with the **thumb** and **index finger**
- lift the object while **preventing it from rolling**
- hold the object and replace it



Qiushi Fu **Wei Zhang**

Perfect anticipation at object lift onset: $M_{com} = -M_{ext}$

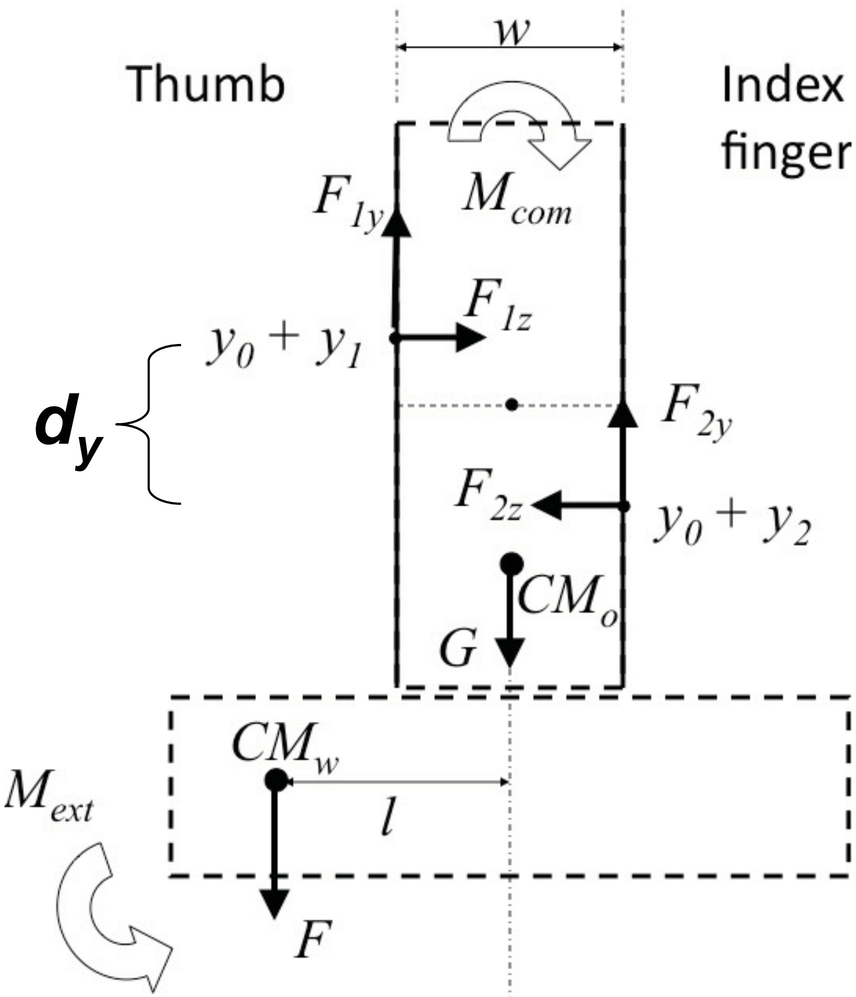
$$M_{com} = \frac{w}{2}F_{1y} - \frac{w}{2}F_{2y} + (y_1 + y_0)F_{1z} - (y_2 + y_0)F_{2z} \quad (1)$$

$$F_{1z} \approx F_{2z} \approx F_{GF} = (F_{1z} + F_{2z})/2 \quad (2)$$

$$M_{com} = \frac{w}{2}d_{LF} + d_y F_{GF} \quad (3)$$

$\boldsymbol{M_{LF}}$ — moment generated by **load forces**

$\boldsymbol{M_{GF}}$ — moment generated by **normal forces**



Unconstrained device

Perfect anticipation at object lift onset: $M_{com} = -M_{ext}$

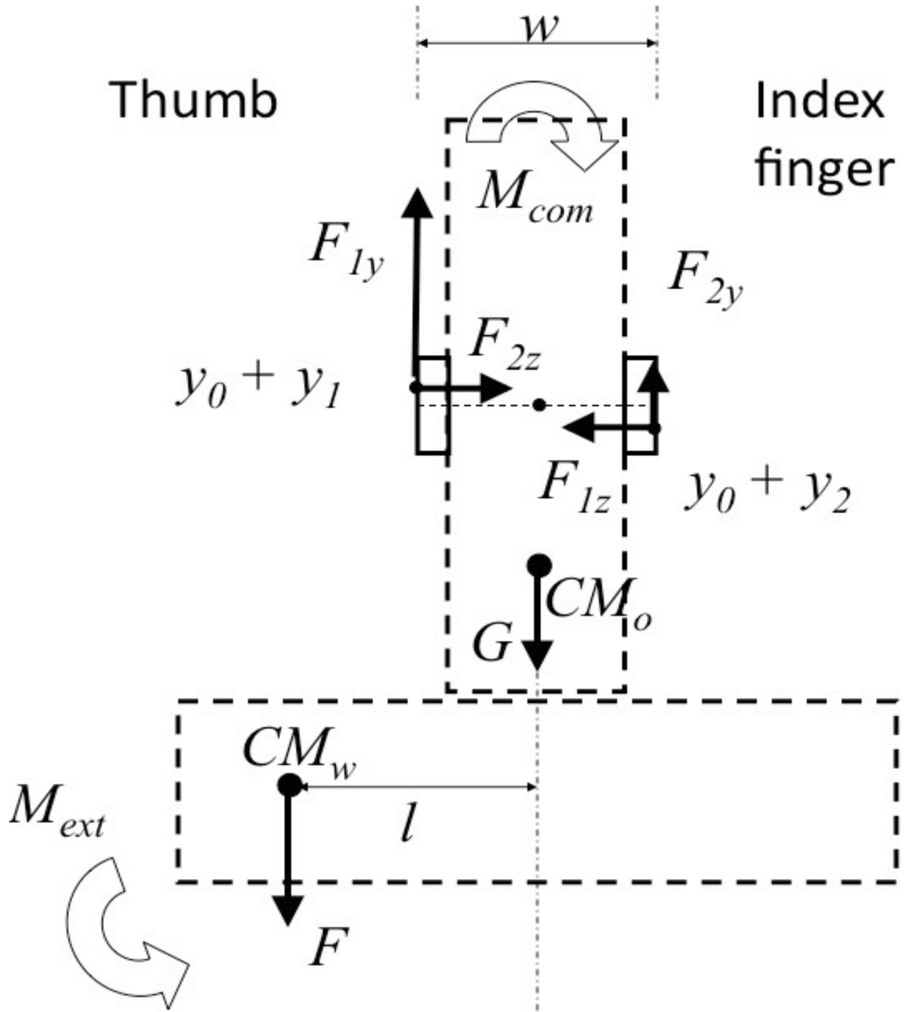
$$M_{com} = \frac{w}{2}F_{1y} - \frac{w}{2}F_{2y} + \cancelto{0}{(y_1 + y_0)}F_{1z} - \cancelto{0}{(y_2 + y_0)}F_{2z} \qquad (1)$$

$$F_{1z} \approx F_{2z} \approx F_{GF} = (F_{1z} + F_{2z})/2 \qquad (2)$$

$$M_{com} = \underbrace{\frac{w}{2}d_{LF}}_{\boldsymbol{M_{LF}}} + \underbrace{\cancel{d_y F_{GF}}}_{\cancel{\boldsymbol{M_{GF}}}}$$

moment generated by **load forces**

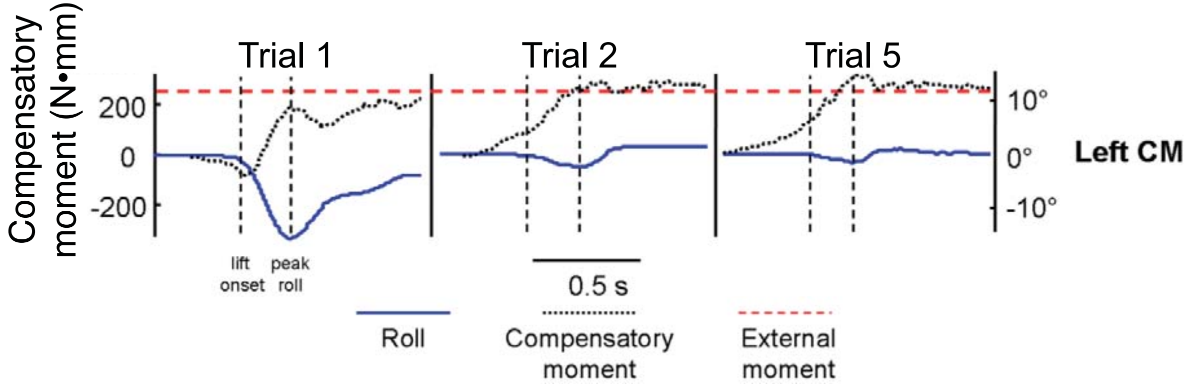
~~moment generated by **normal forces**~~



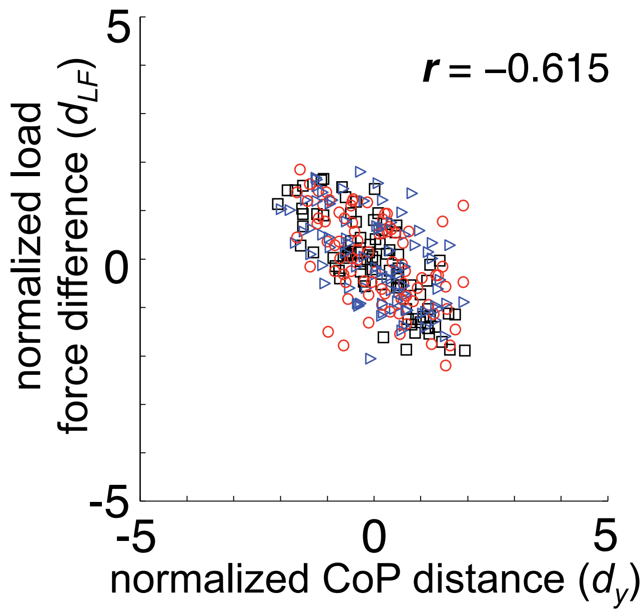
Constrained device

Anticipatory grasp control occurs through *parallel* modulation of digit position and force

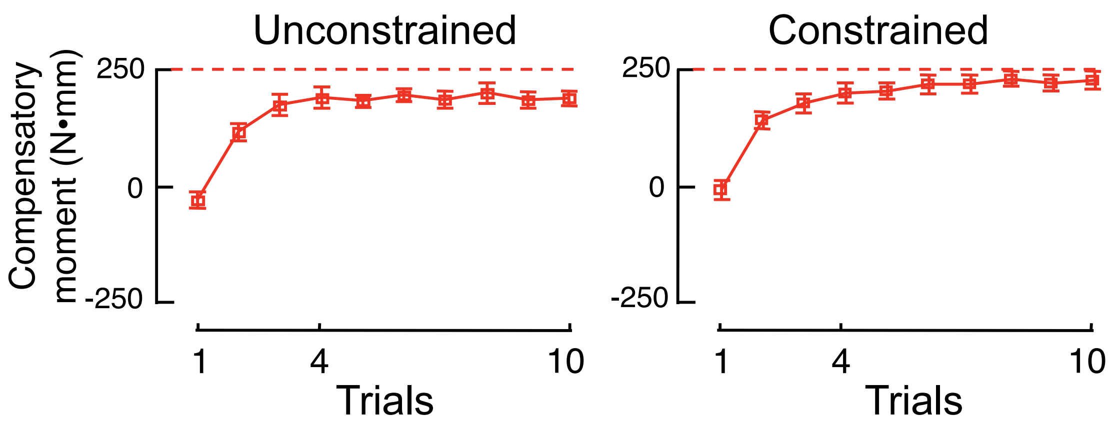
Subjects learn to exert a compensatory moment in an anticipatory fashion, i.e., *before* lifting the object



Subjects modulate digit forces as a function of digit placement



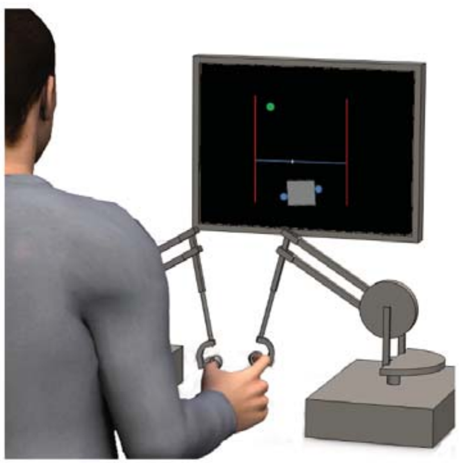
Despite *the larger trial-to-trial variability of digit placement* for the unconstrained group, *the trial-to-trial variability of compensatory moment was the same for both groups*.



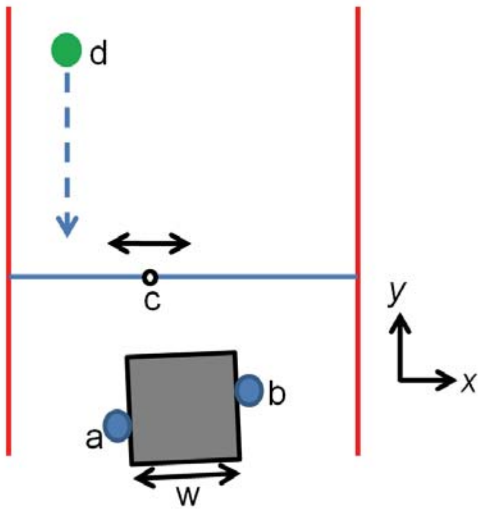
Fu, Zhang, and Santello, *J Neurosci* (2010)

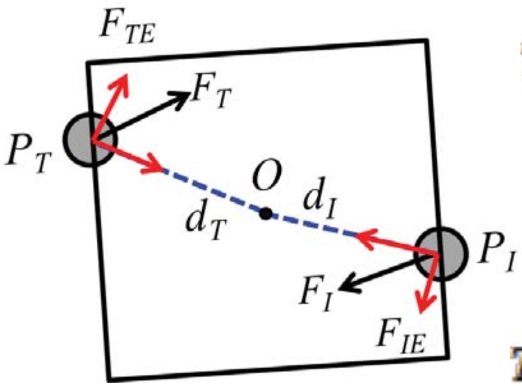
Sensorimotor mechanisms for coordination of digit force to position

A



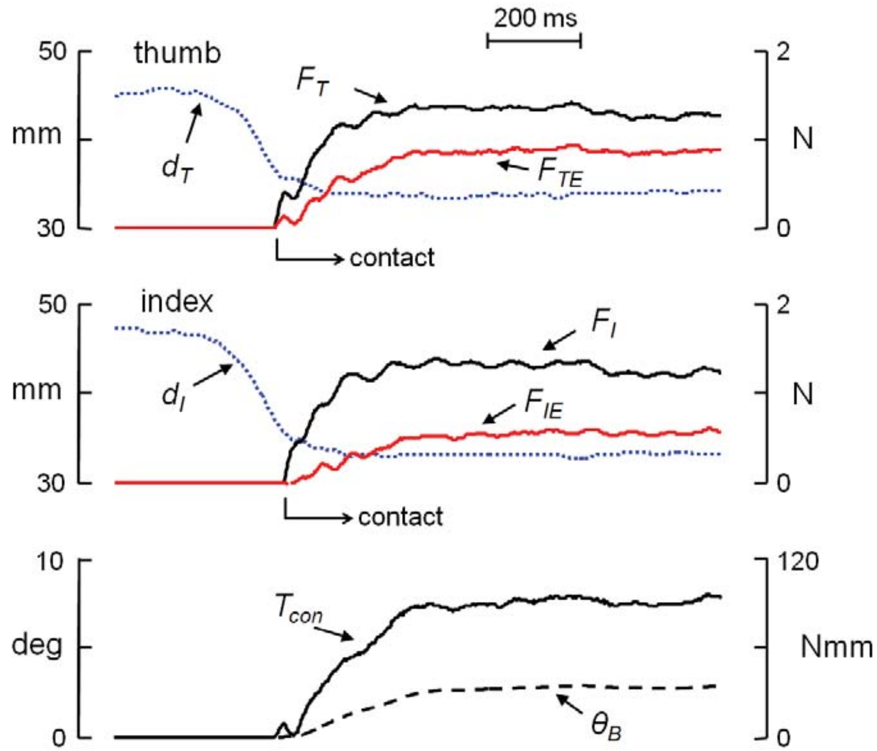
B



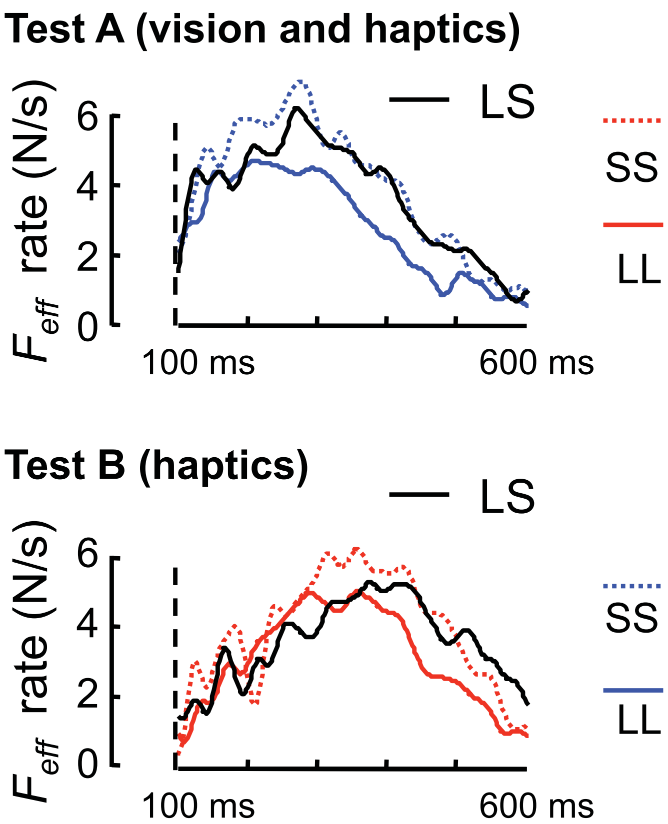


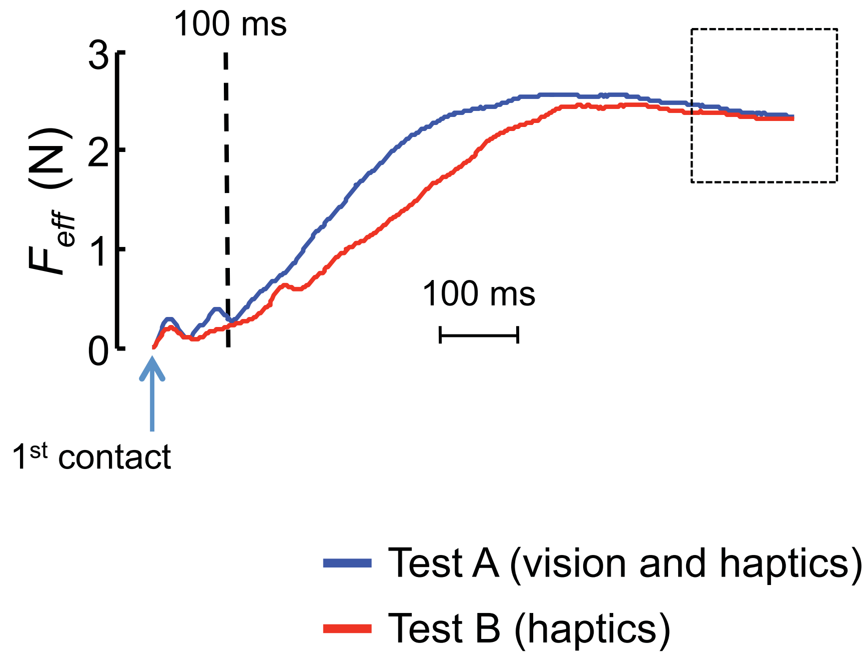
$$T_{con} = F_{TE} d_T + F_{IE} d_I$$

$$T_{con} \approx F_{TE} \frac{w}{2} + F_{IE} \frac{w}{2}$$



Haptic information alone is sufficient to modulate digit forces after contact – but with a significant delay

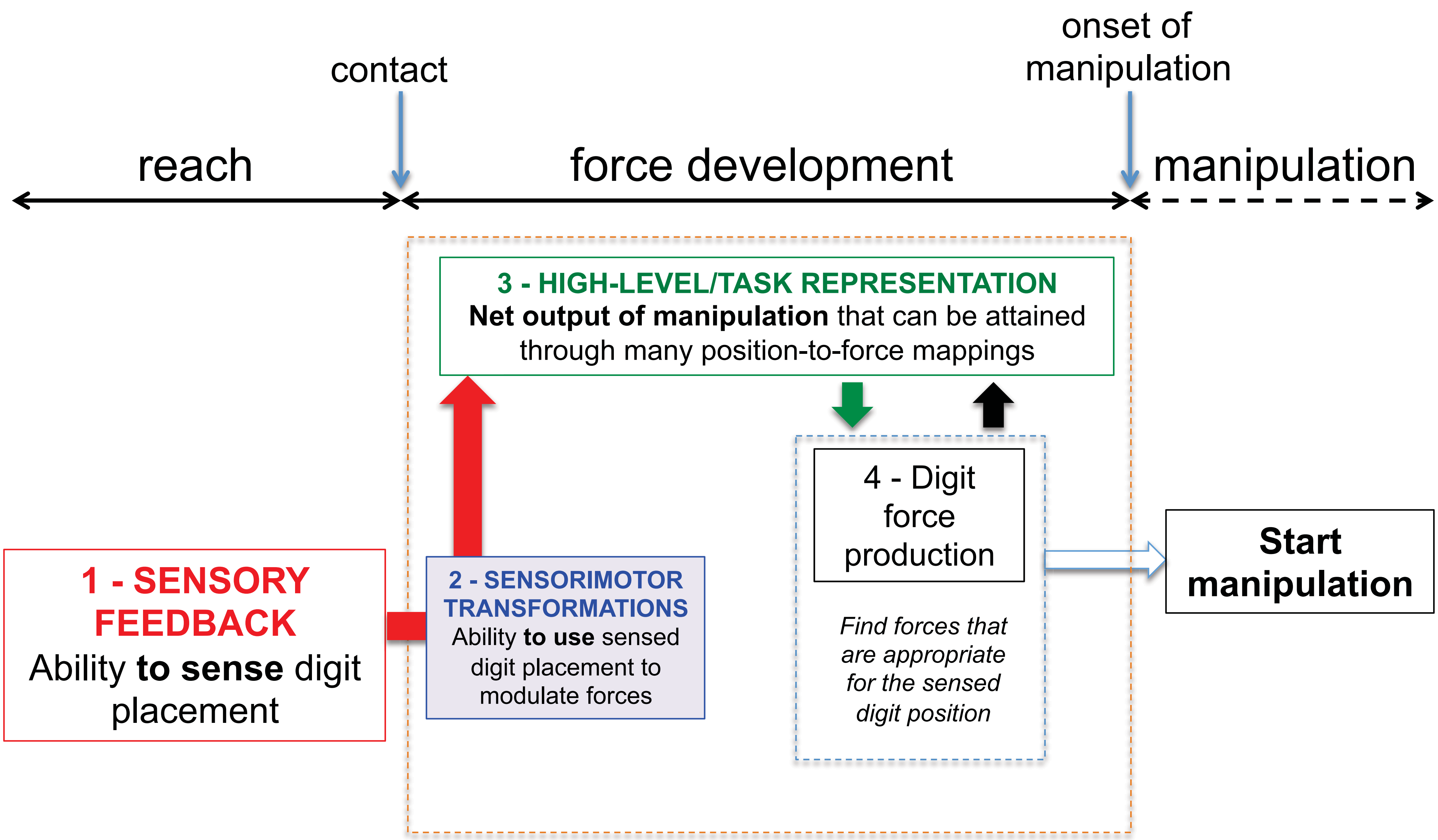




Without visual feedback, subjects **initially** use a ‘default’ force development, but **make force corrections as a function of actual objects width** after haptic information is acquired.

Fu and Santello, *J Neurophysiol* (2014)

Theoretical framework



Conclusions and open questions

Neuroscience and robotics. The interaction between these two areas have led to the development of theoretical frameworks and experimental approaches to study the human hand and robotics applications.

Sensorimotor integration. The ability to perform dexterous manipulation despite variability in digit placement has led to a theoretical framework based on the integration of high-level (task) representations with online sensory feedback of digit placement and forces.

Neural mechanisms. Ongoing work aims at identifying the cortical mechanisms that might account for the current behavioral evidence and theoretical framework as well as potential clinical applications.

Neural Control of Movement Lab NCML

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THE
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