Modeling the Role of Passive Dynamics of Hands in Grasping and Manipulation

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Workshop on

"Representations for object grasping and manipulation"

ICRA, May 03, 2010

Hand Research Motivation

- Understanding of the biomechanics and neuromuscular controls of hands
- Design of next generation robotic hands

- What are the underlying mechanisms in hand movement control?
- What is the importance of hand features, especially, **passive behavior**?

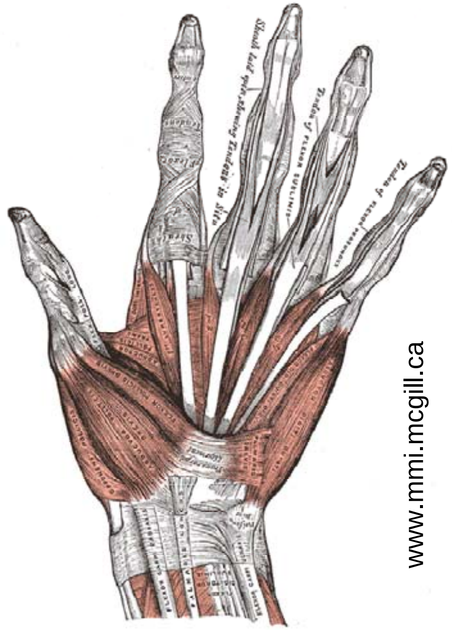
- Anaxagoras (500-428 BC) and Aristotle (384-322 BC) made arguments about relationship between human hands and mind

"Anaxagoras says that because of having hands, man grew the most intelligent among animals. (I think) it is correct to say that because of his intelligence he has hands"

[Bicchi, 95]

Human Hand- Biomechanics

- High DOF
  - Independent and coupled
- Unique tendon arrangement
  - Long tendons
  - Network of tendons that slides over bones
- Multi-articulate muscles
  - Intrinsic and extrinsic



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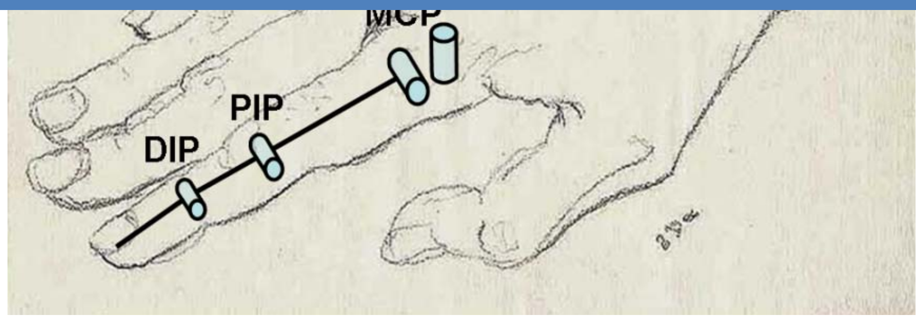
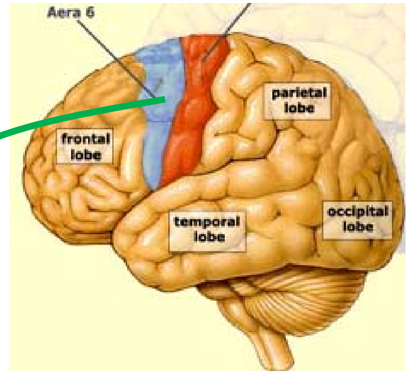
- What are the pros and cons of the complex biomechanics?



Human Hand- Neuromuscular controls

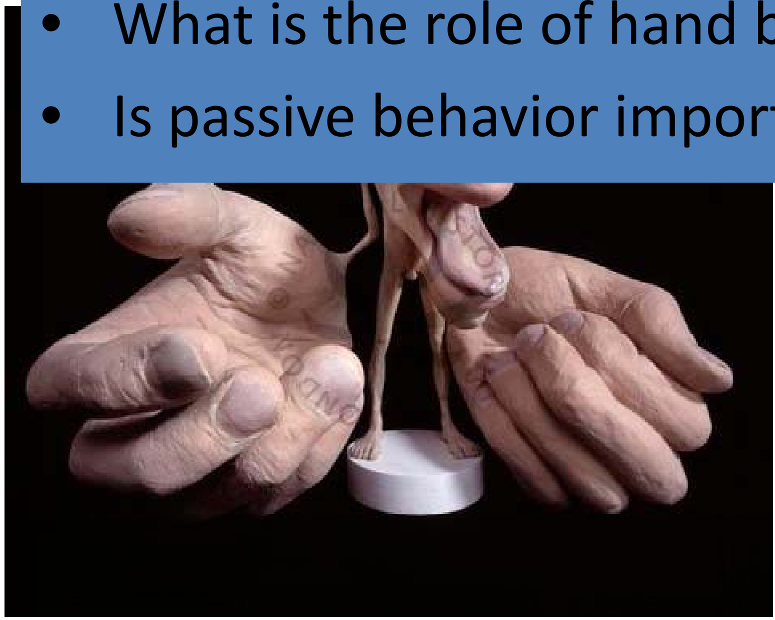
- A large portion of the primary motor cortex is devoted to hand control
- Tens of thousands of tactile sensors



Sensing

Movements

- What is the role of hand biomechanics in controls?
- Is passive behavior important in controls?



Biomechanical Investigations

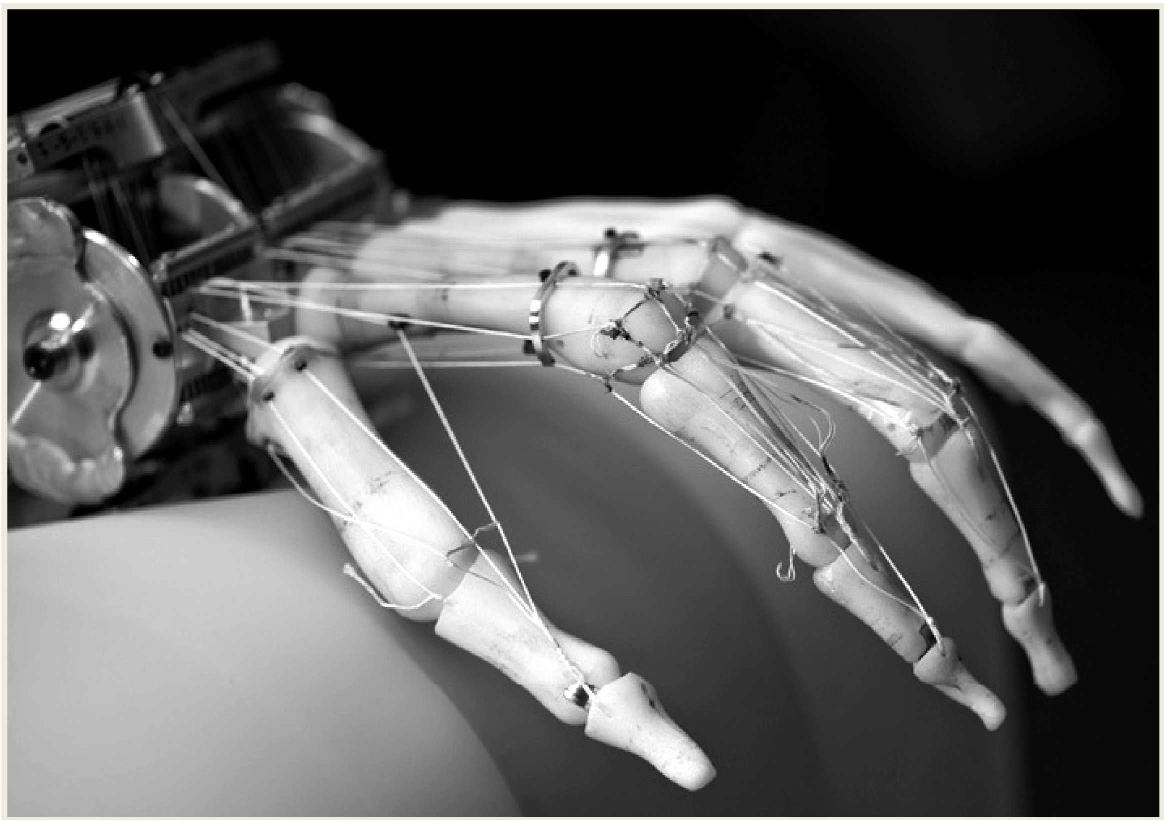
- Many unanswered questions in biomechanics and neural controls
- Our approach
  - Human subject studies
  - Mathematical modeling
  - Robot hand design and development

- What are the contributions of passive hand properties in movement control?

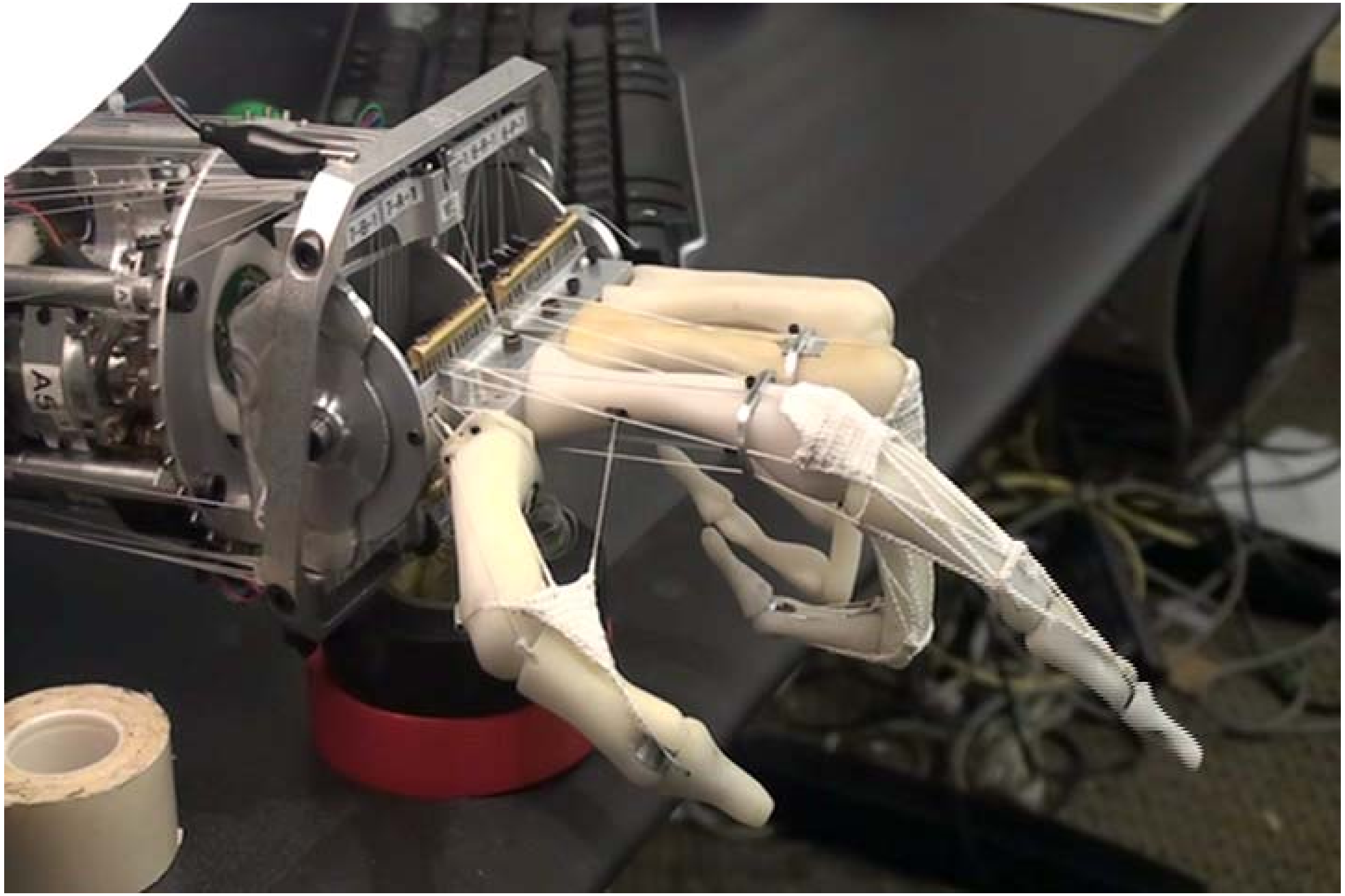
Anatomical Robotic Hand

- Our approach is fundamentally different from any other existing approaches
- A robotic hand with all anatomical features

- Unique challenges in hardware and software
- Potential pay-offs:
  - Human-level dexterity
  - Understanding of human hand



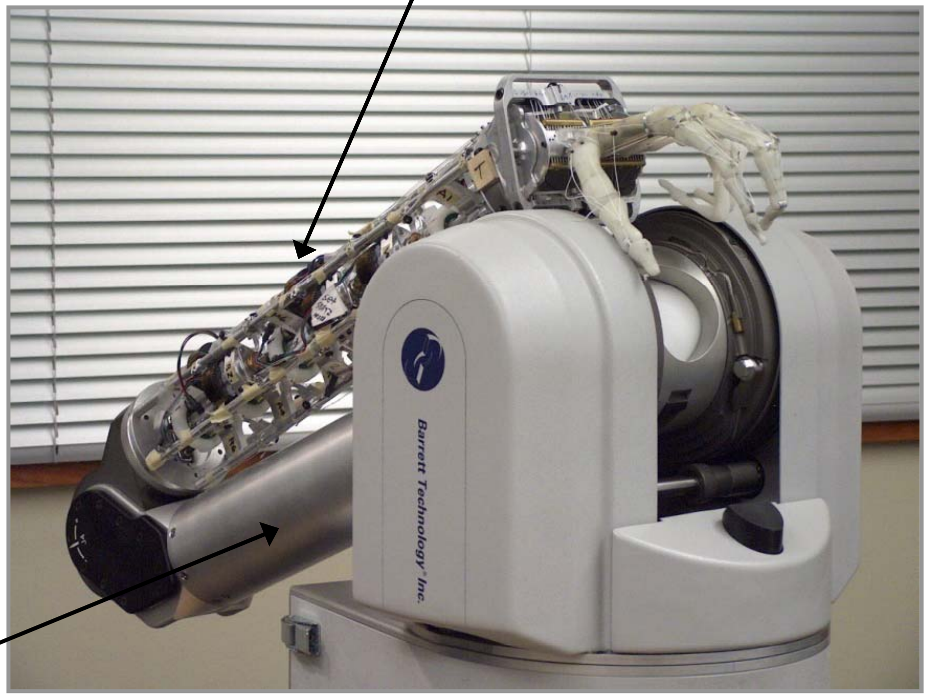
ACT Video



Passive Behavior in the ACT Hand

- What is the model of human passive behavior?
- How do we implement passive behavior?
  - Software or hardware

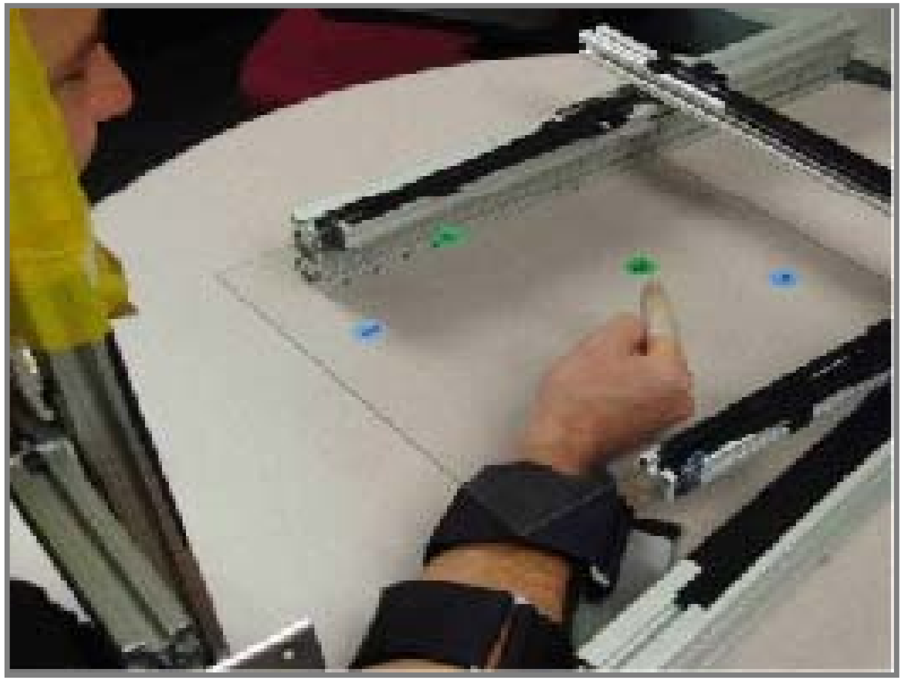
actuators



WAM arm

Study 1: Contribution of Passive Torques

- Coordinated hand and finger movements



- Conducted experiments with human subjects
    - 5 male and 5 female subjects
    - More than 50 trials for each subject
- Modeling to passive and dynamic torques

- Goal is to determine what is the contribution of passive torques to the total torque

[Deshpande et al., submitted, '10]

Mathematical model of torques at MCP joints

- Total torques at MCP joint is composed of dynamic and passive (visco-elastic torques)
- Torque are functions of finger and wrist angles

$$\tau_{Total} = \tau_{dyn} + \tau_{passive}$$

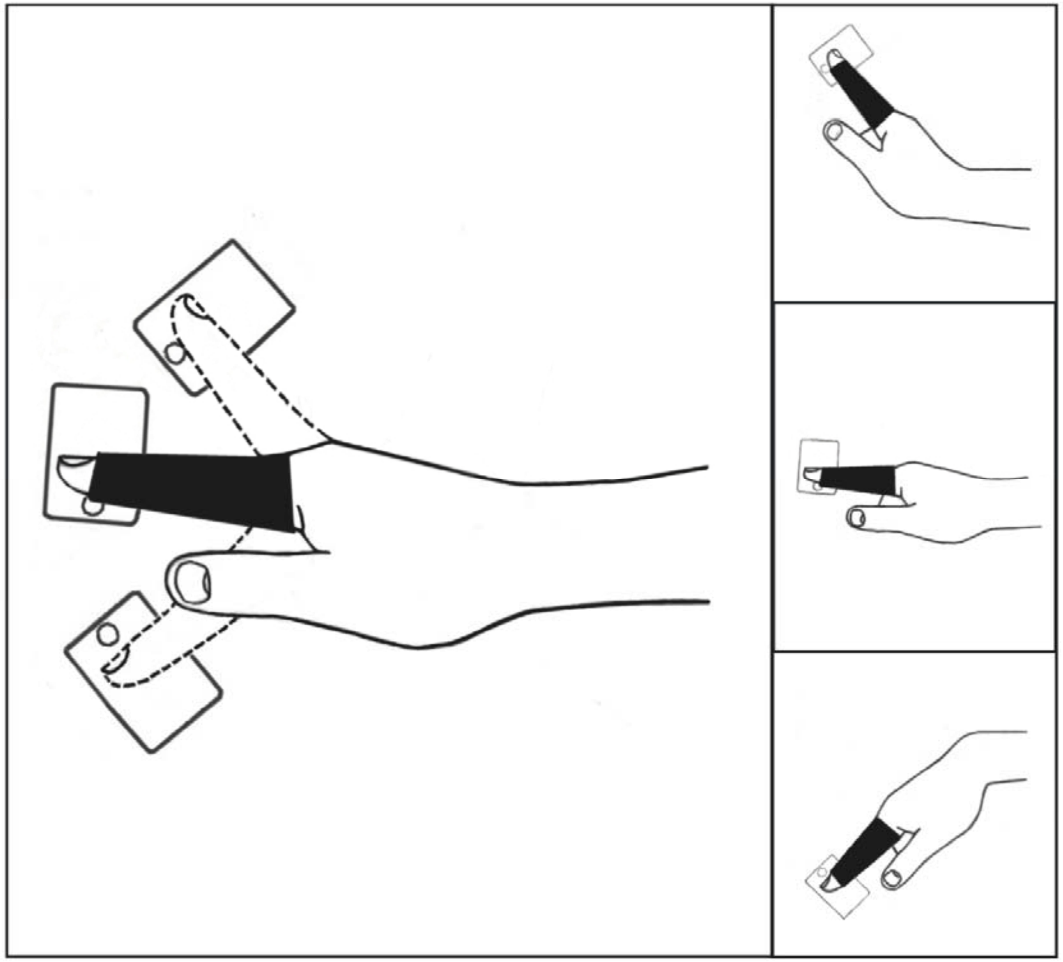
$$\tau_{passive} = \tau_{stiff} + \tau_{damp} = \tau_{stiff} + b\dot{\theta}_f,$$

$$\tau_f = \ddot{\theta_w}\left(I_f + \frac{m_f l_h l_f}{2}\cos\theta_f + \frac{m_f {l_f}^2}{4}\right) + \ddot{\theta_f}\left(I_f + \frac{m_f {l_f}^2}{4}\right) + \dot{\theta_w}^2\left(\frac{m_f l_h l_f}{2}\sin\theta_f\right)$$

$$\tau_{stiff}(\theta_f, \theta_w) = A(e^{-B(\theta_f - E + G.\theta_w)} - 1) - C(e^{D(\theta_f - F + H.\theta_w)} - 1)$$

Modeling of Stiffness Torque

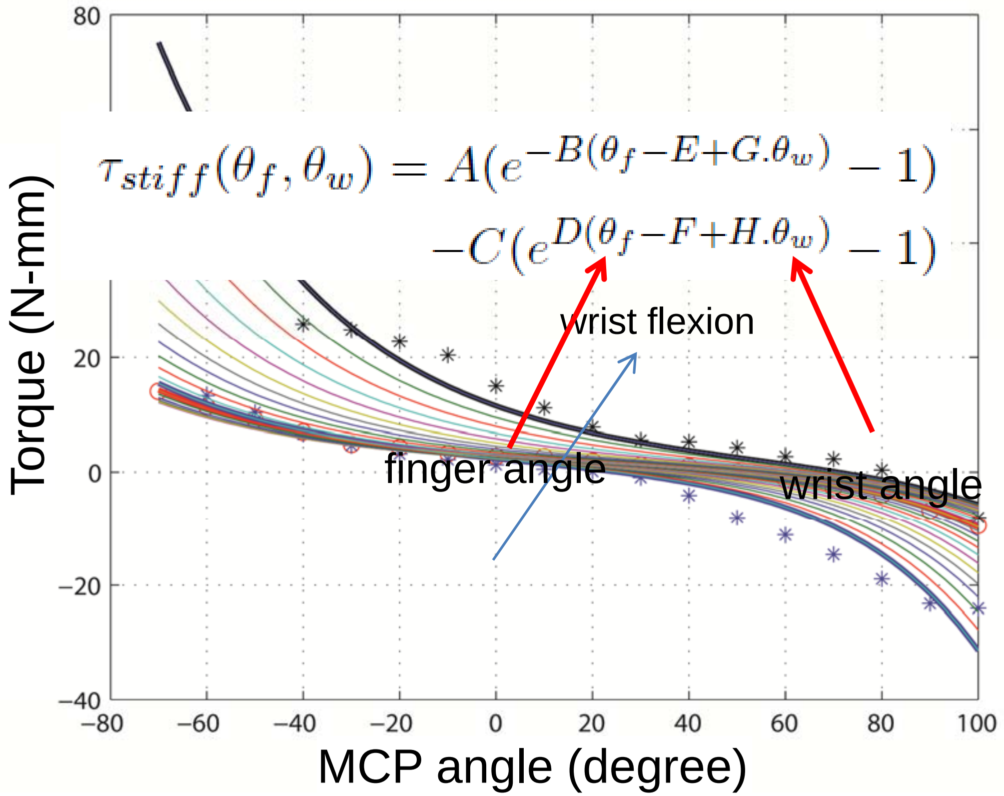
- Measured finger tip forces at various finger and wrist angles
- Flexion-extension of both wrist and finger



Modeling of Stiffness Torque

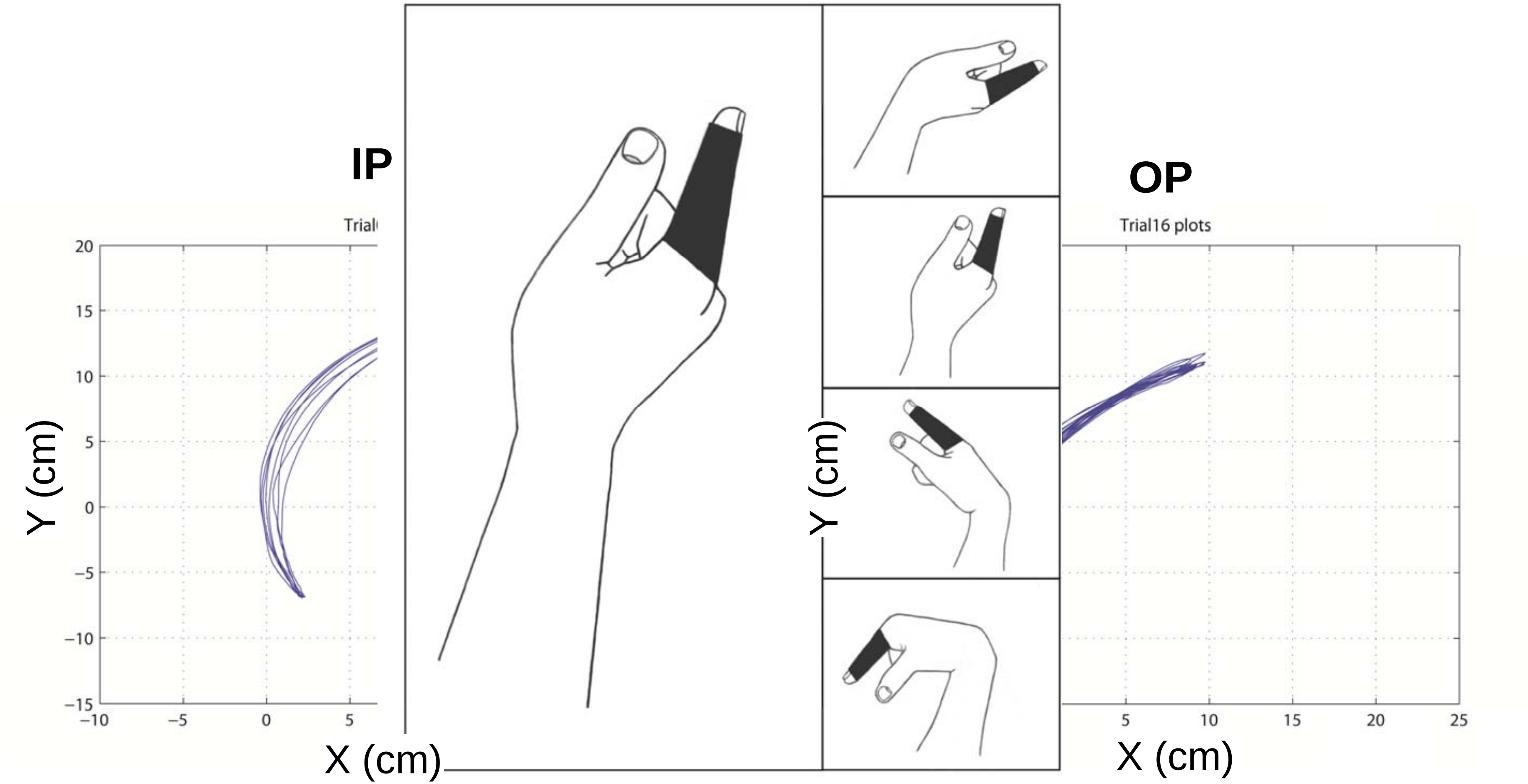
- Derived a double exponential model of stiffness torque as a function of finger and wrist angles

$$\tau_{stiff}(\theta_f, \theta_w) = A(e^{-B(\theta_f - E + G.\theta_w)} - 1) - C(e^{D(\theta_f - F + H.\theta_w)} - 1)$$



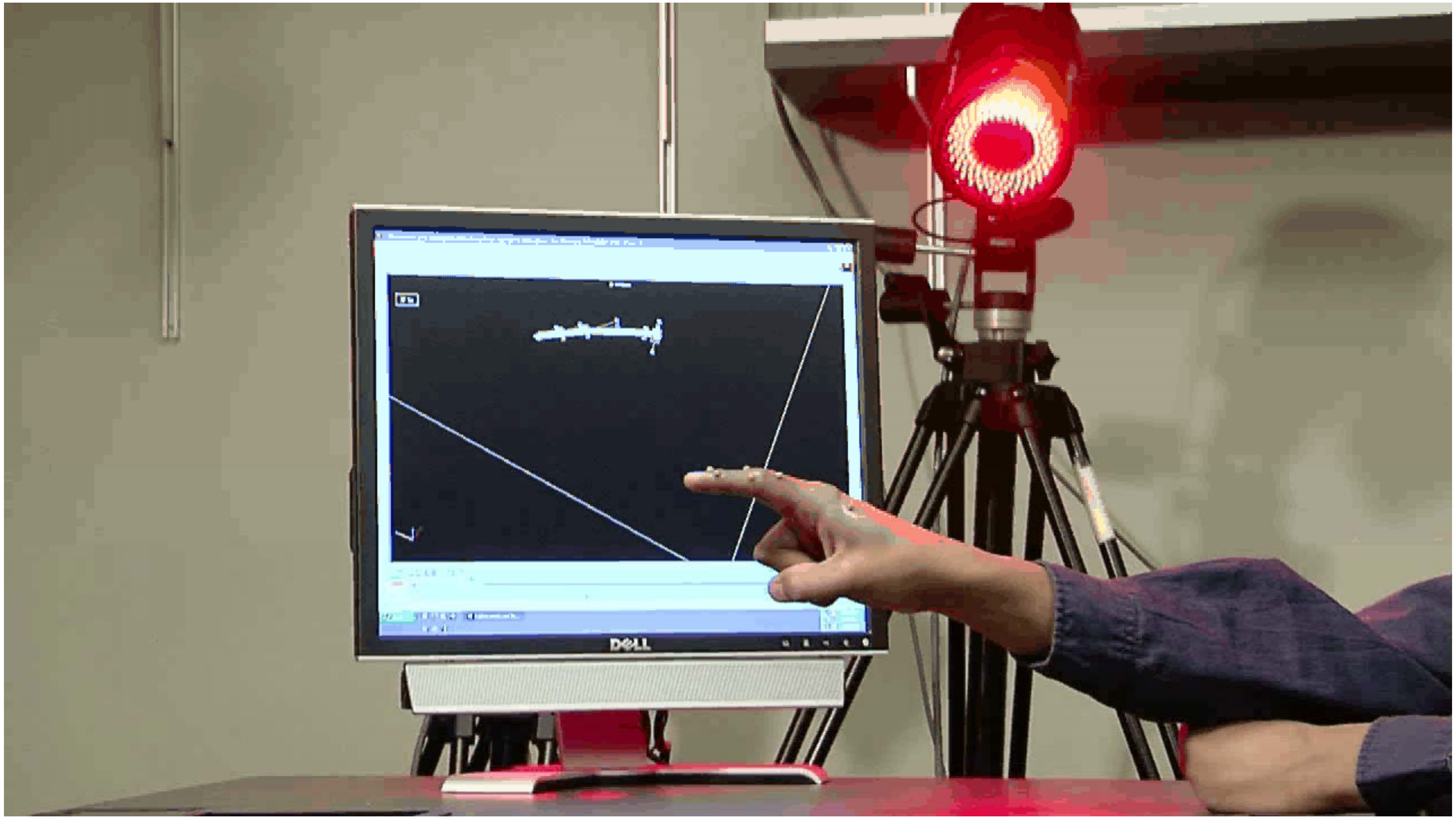
Coordinated Finger-Wrist Movements

- Moving finger and wrist together in sweeping motions
- In-phase (IP) and out-of-phase (OP)



Coordinated Finger-Wrist Movements Joint Angles

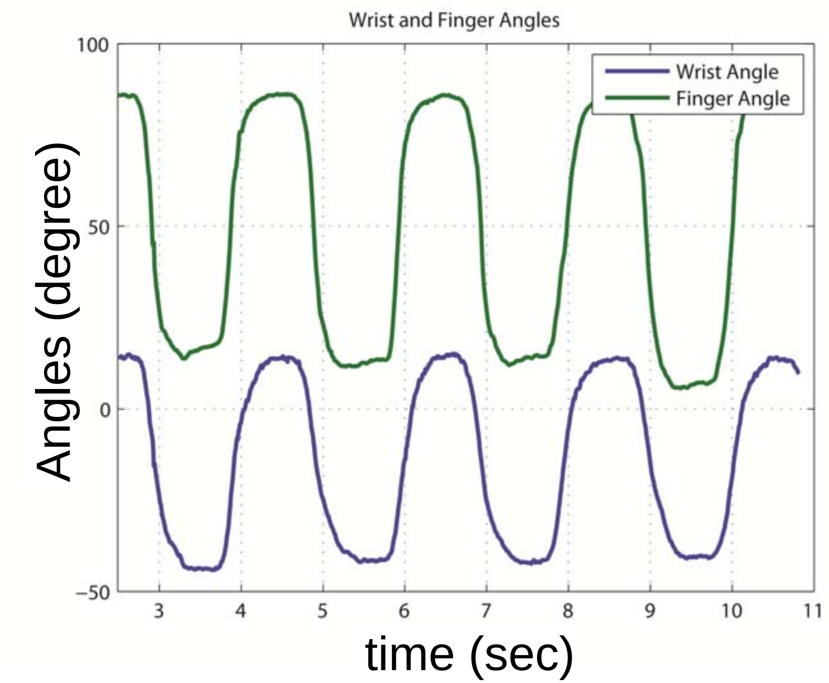
- Recorded data with Vicon motion capture system



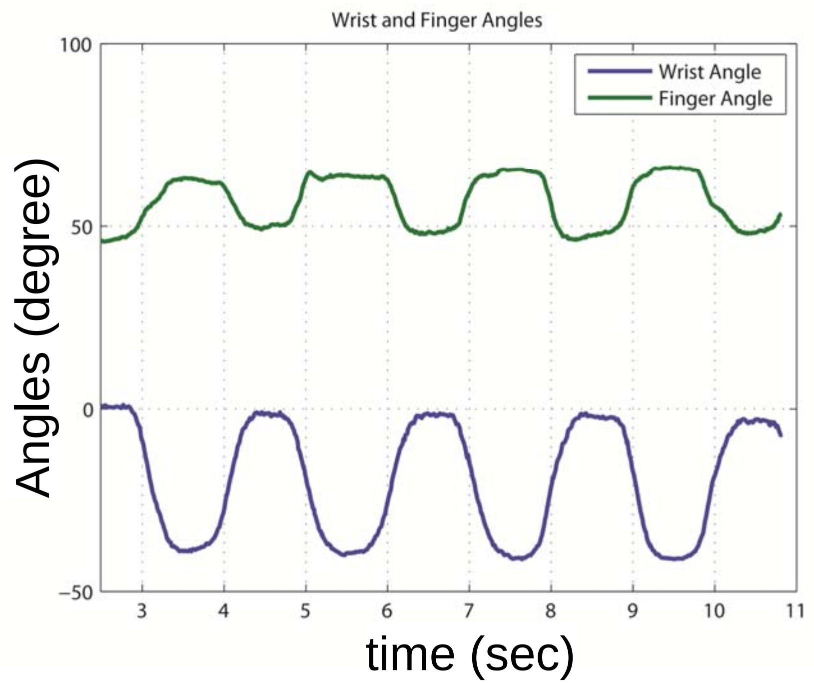
Coordinated Finger-Wrist Movements Joint Angles

- Finger and wrist angle variations

IP



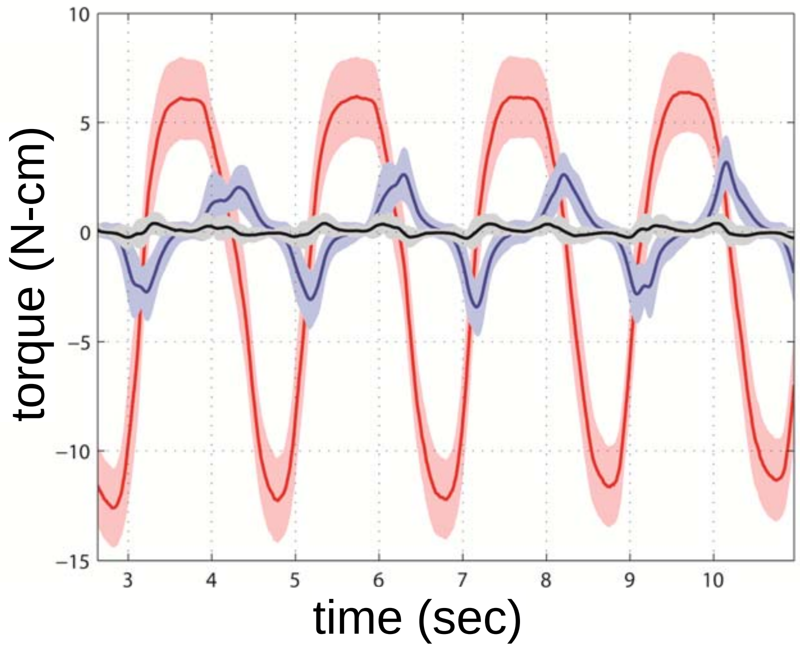
OP



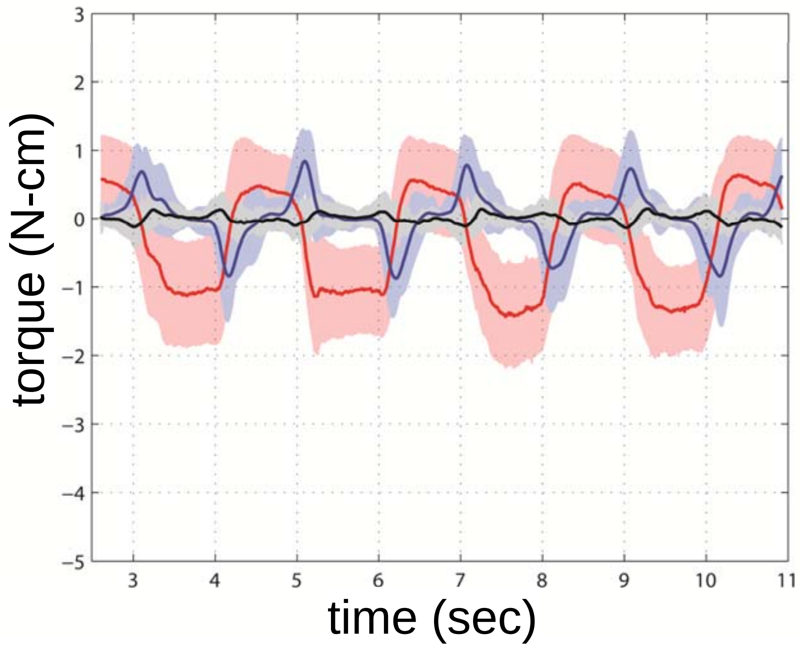
Stiffness Torques Dominate

- Total torque is much higher during IP than OP
- Dynamic torque contribution is very low
- red – stiffness, blue - damping, black - dynamic

IP



OP



Results: Passive Torques Dominate

- Passive torque contribution is substantially greater than dynamic torque contribution

$$\tau_{Total} = \tau_{dyn} + \tau_{passive}$$

$$\tau_{passive} = \tau_{stiff} + \tau_{damp} = \tau_{stiff} + b\dot{\theta}_f,$$

- Relative contributions depend on type of movements and speed
  - Dynamic torque contribution is never more than 11%

Implications: Neuromuscular Controls and Robotics

Human Hands

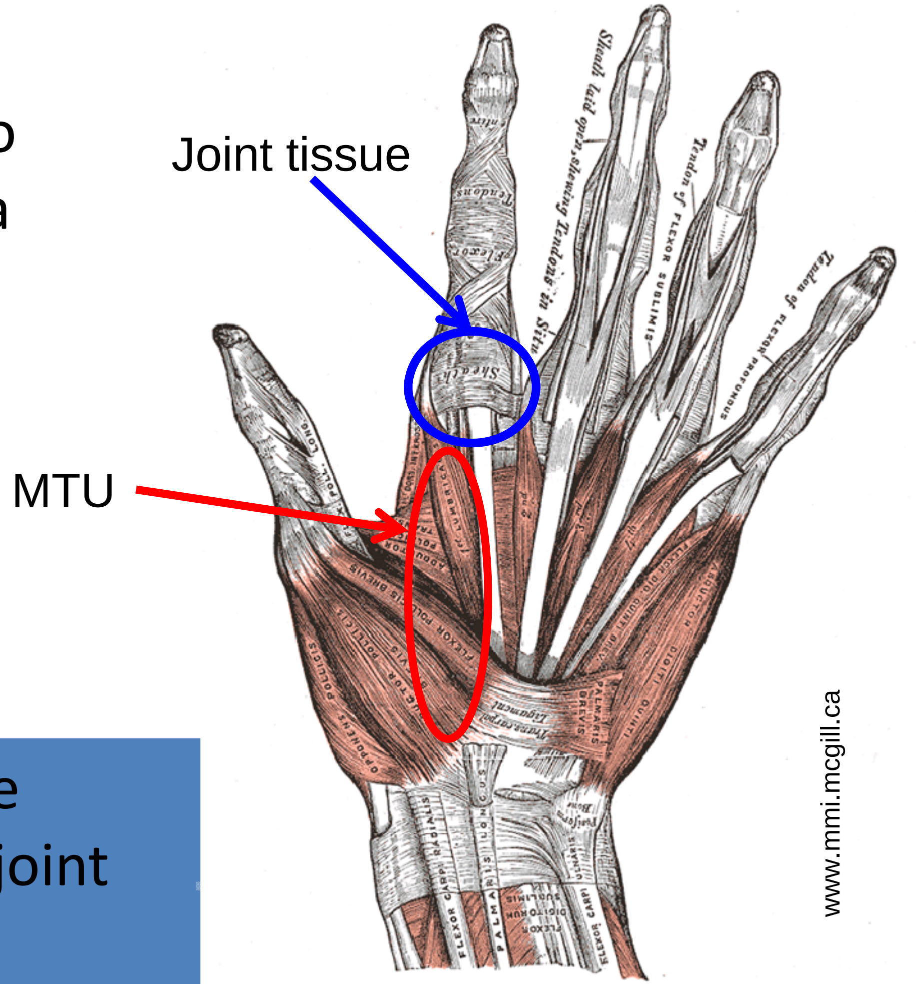
- CNS must have an internal model of passive behavior
  - Must take advantage during dynamic manipulation tasks
- Shoulder-elbow movements studies show that dynamic torques dominate
  - It is predicted that CNS models dynamic torques

Robotic Hands

- It may be necessary to incorporate passive behavior in robotic hands
- How? – software, hardware, location…

Study 2: Contributions to Passive Stiffness

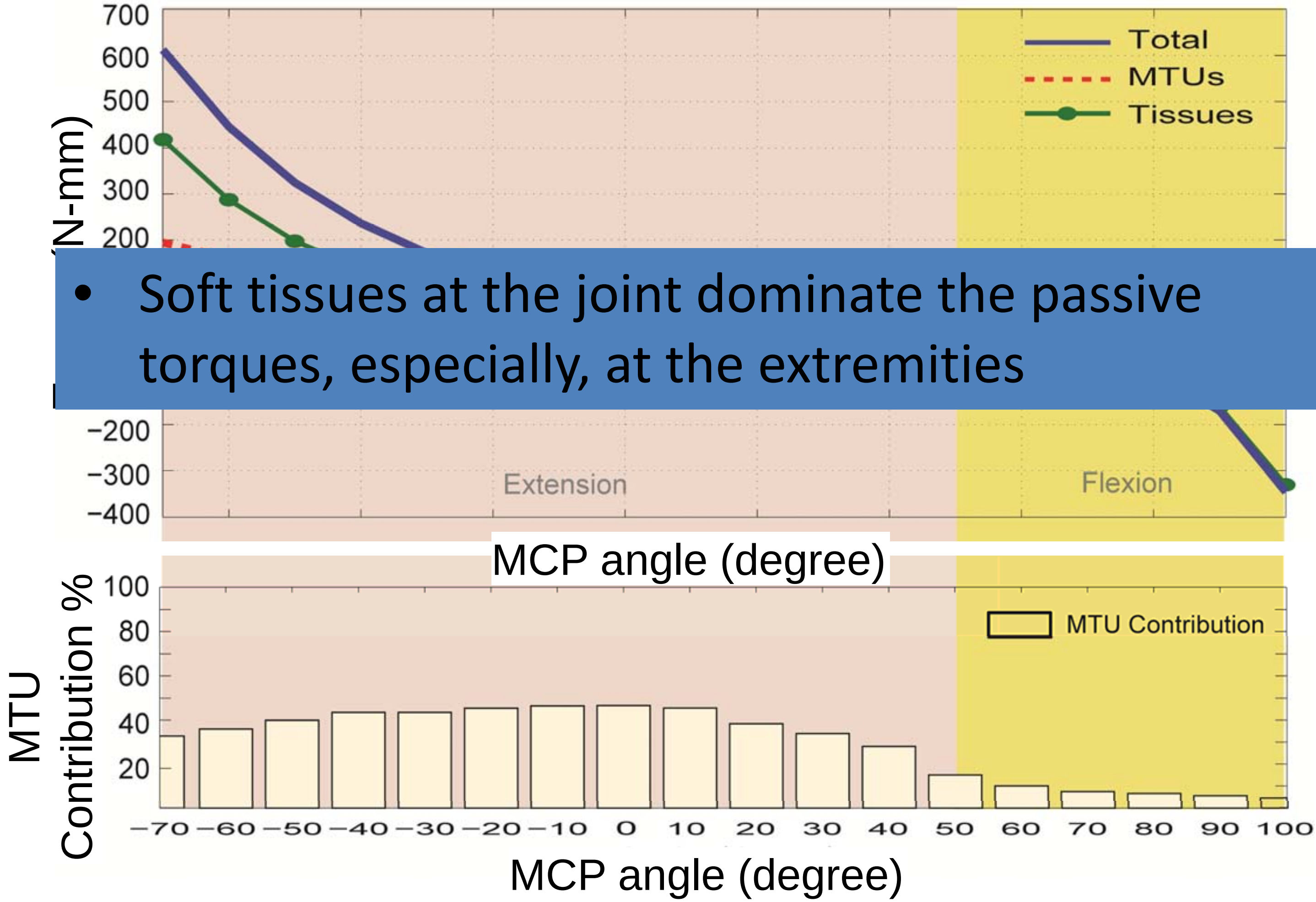
- Two separate contributors to passive stiffness torques at a joint
  - Musculotendon units (MTUs)
  - Joint soft tissues



- Goal is to determine relative contributions of MTUs and joint soft tissues

MTU contributions to passive torque < 50%

- Result reveal explicit contributions of MTUs and joint tissues



- Soft tissues at the joint dominate the passive torques, especially, at the extremities

Implications: Human and Robotic Hands

Human Hands

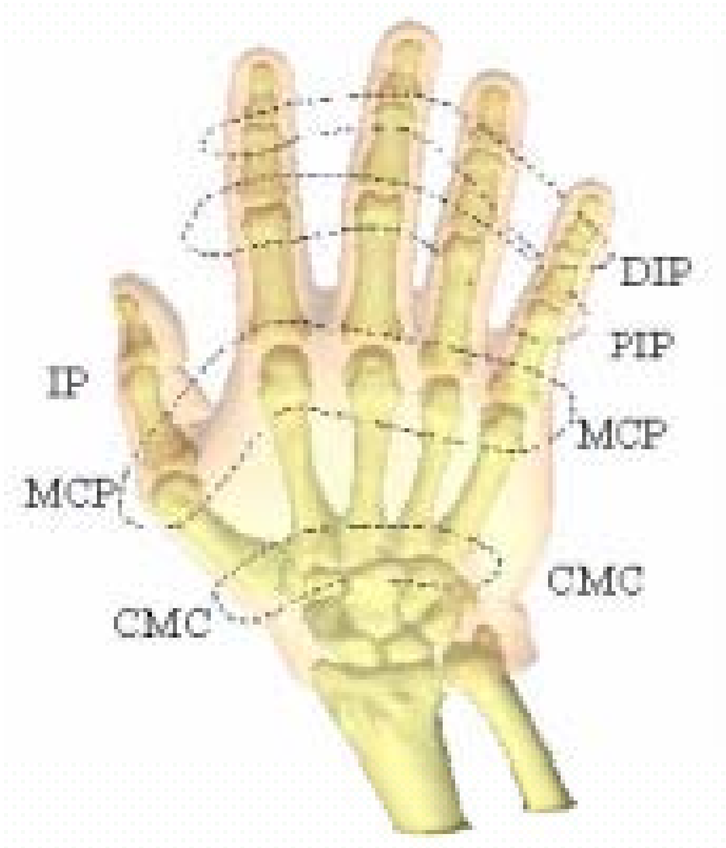
- Soft tissue stiffness may provide injury projection
- Soft tissue stiffness is NOT controllable so
  - MTU may compensate by active stiffness control – co-contraction
- CNS must have an internal model of passive behavior

Robotic Hands

- May be necessary to incorporate joint passive behavior in robotic hands
- Hardware implementation and software controls

Next Steps

- Human subject experiments to model human hand joint damping
- **Building robotic hands with compliant joints**
  - Stiffness and damping properties
  - Programmable compliance



[Deshpande et al in JBiomech]