Passive Properties of Human Hand:

Applications to Prosthetics, Rehabilitation and Assistive Robots

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Human Hand Biomechanics

- Kinematic intricacies are critical for hand functionality
  - Independent and coupled
- Complex tendon arrangement
  - Long tendons
  - Network of tendons that slide over bones
- Multi-articulate muscles
  - Intrinsic and extrinsic

- High DOF
- Arrangement of bones, soft tissues, tendons and muscles leads to the hand kinematics
- Exploration of hand biomechanics and neuromuscular controls
  - by building a robotic hand
  - by conducting human subject studies

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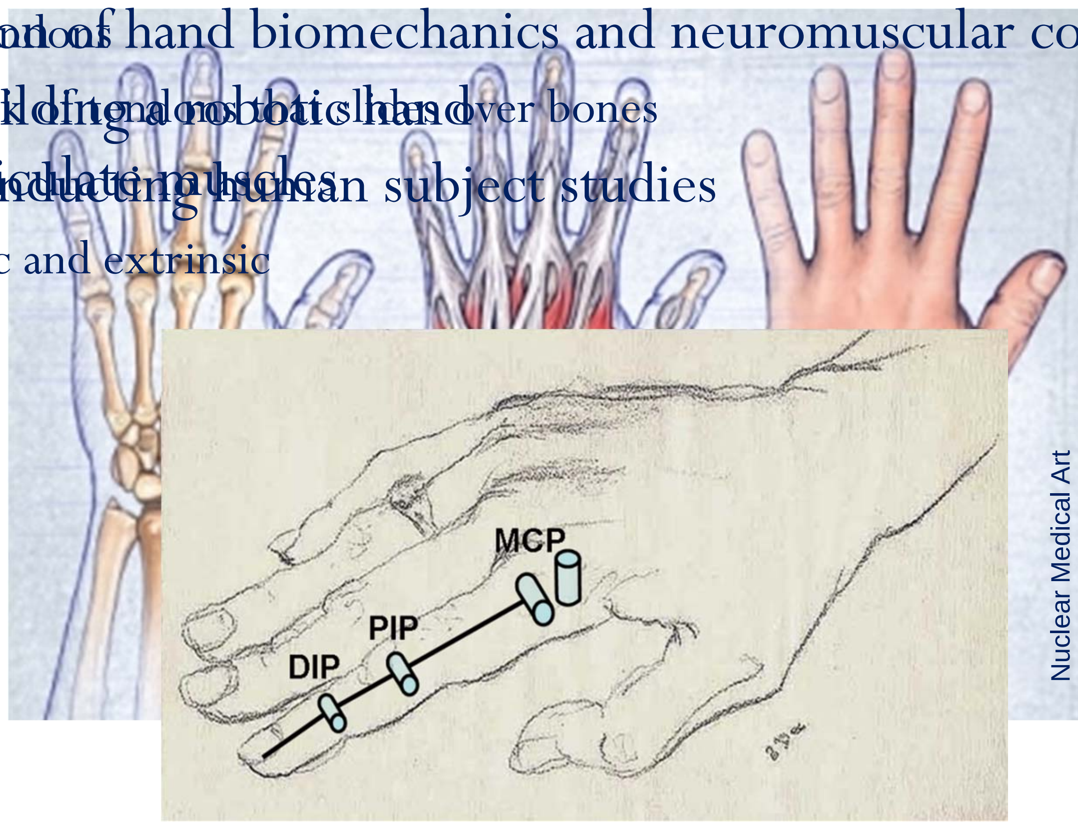
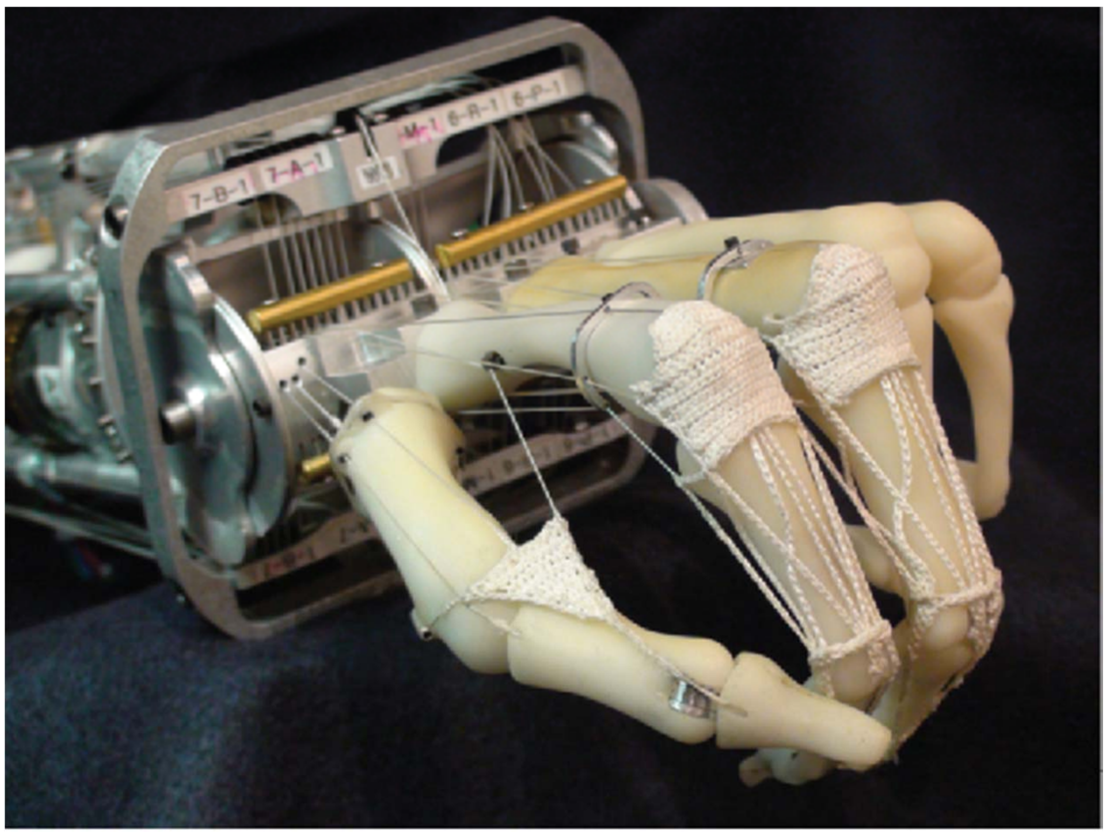


Nuclear Medical Art

[Bourdet et. al, 01; Franklin and Milner 2004, Deshpande et al 2010]

Anatomically Correct Test-bed (ACT) Hand

- Scientific goals are to achieve:
  - Versatile manipulation by copying human-like controls
    - **Muscle-to-joint relationships**
  - Understanding of human hand biomechanics and motor control



Grasping with ACT Hand

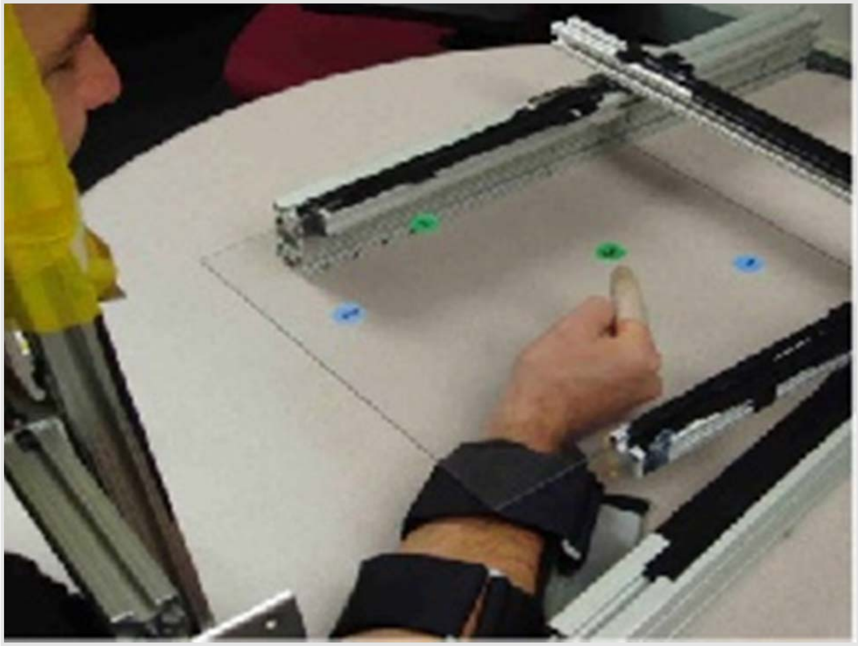
Exploration of Passive Properties

- Passive behavior – stiffness & damping – prominent in the human hand
- Improvements in robot hand capabilities by incorporating key features of passive behavior
- What is the model of human passive behavior?
  - Role in hand control
  - Implementation in robotic devices
- Experiments with human subjects to model and analyze passive properties
  1. What role do the passive properties play during movements?
  2. What is the contribution of joint tissues to passive properties?
  3. Model of joint damping

Study 1: Contribution of passive torques

- Hypothesis: passive joint torques dominate over dynamic torques during free hand movements

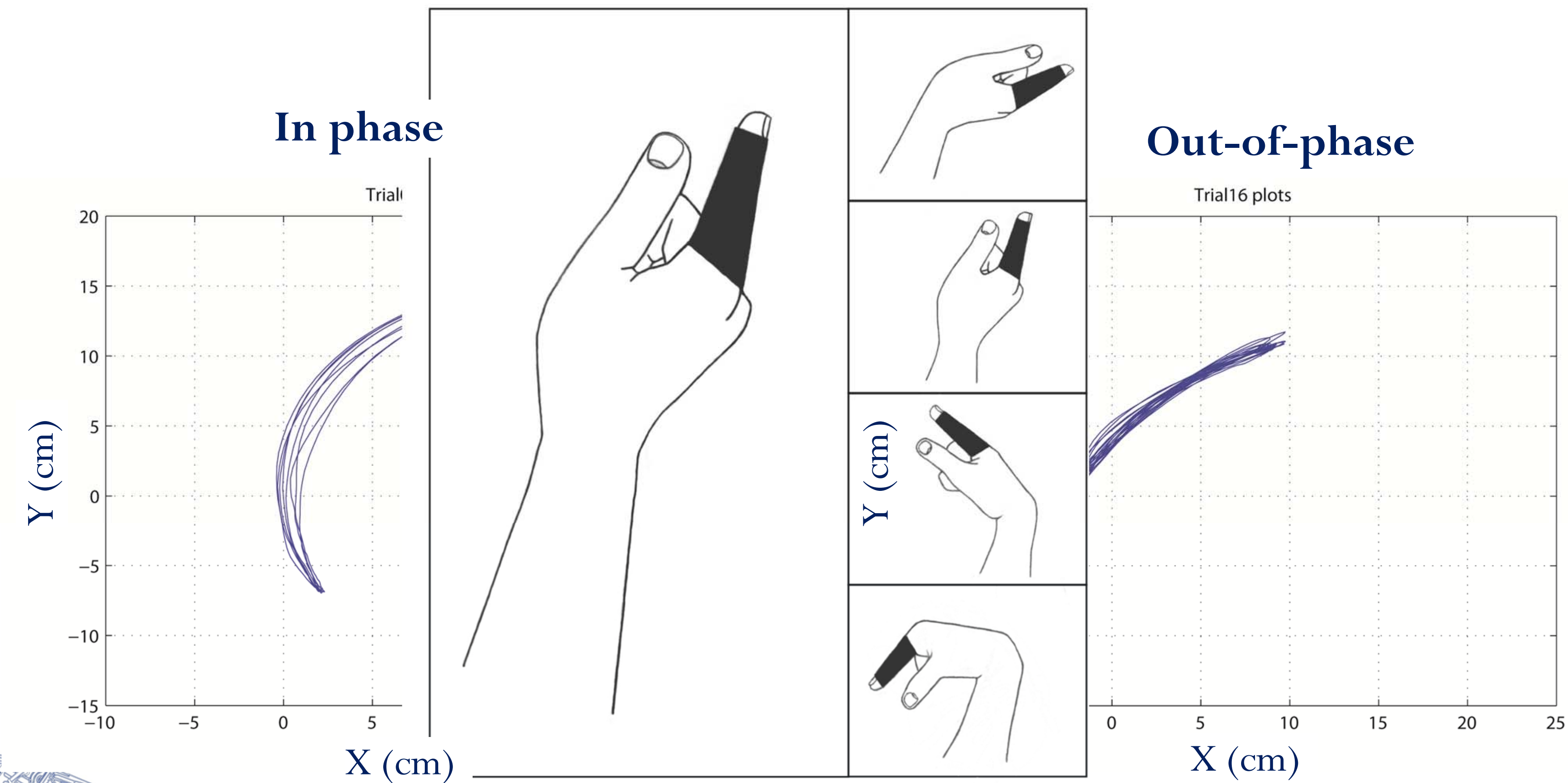
- Coordinated hand and finger movements
- Conducted experiments with human subjects
  - 5 male and 5 female subjects
  - More than 50 trials for each subject
- Models of passive and dynamic torques



[Dounaskaia 2000] [Deshpande et al.,TBME 2010]

Coordinated Finger-Wrist Movements

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



Mathematical model of torques at MCP joints

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

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

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

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

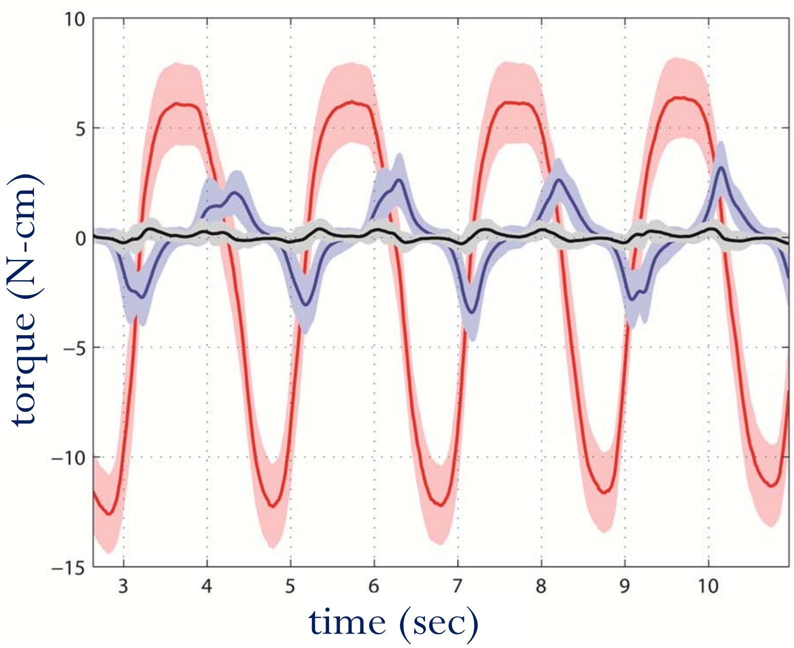
$$\tau_{stiff}(\theta_f, \theta_w) = A(e^{-B(\theta_f - E + G.\theta_w)} - 1) - C(e^{D(\theta_f - F + H.\theta_w)} - 1)$$

[Deshpande et al.,TBME 2011][Munson 2002; Esteki et al 1999]

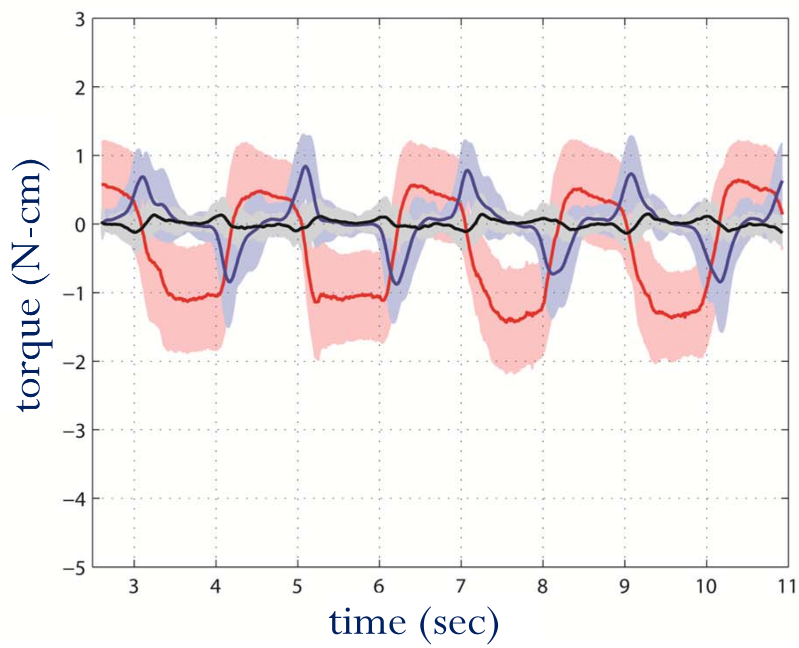
Stiffness Torques Dominate

- Dynamic torque contribution is very low
- red – stiffness, blue - damping, black – dynamic
- Total torque is much higher (~700%) during IP than OP

In phase



Out-of-phase



[Deshpande et al.,TBME 2011]

Study 1: Summary and Implications

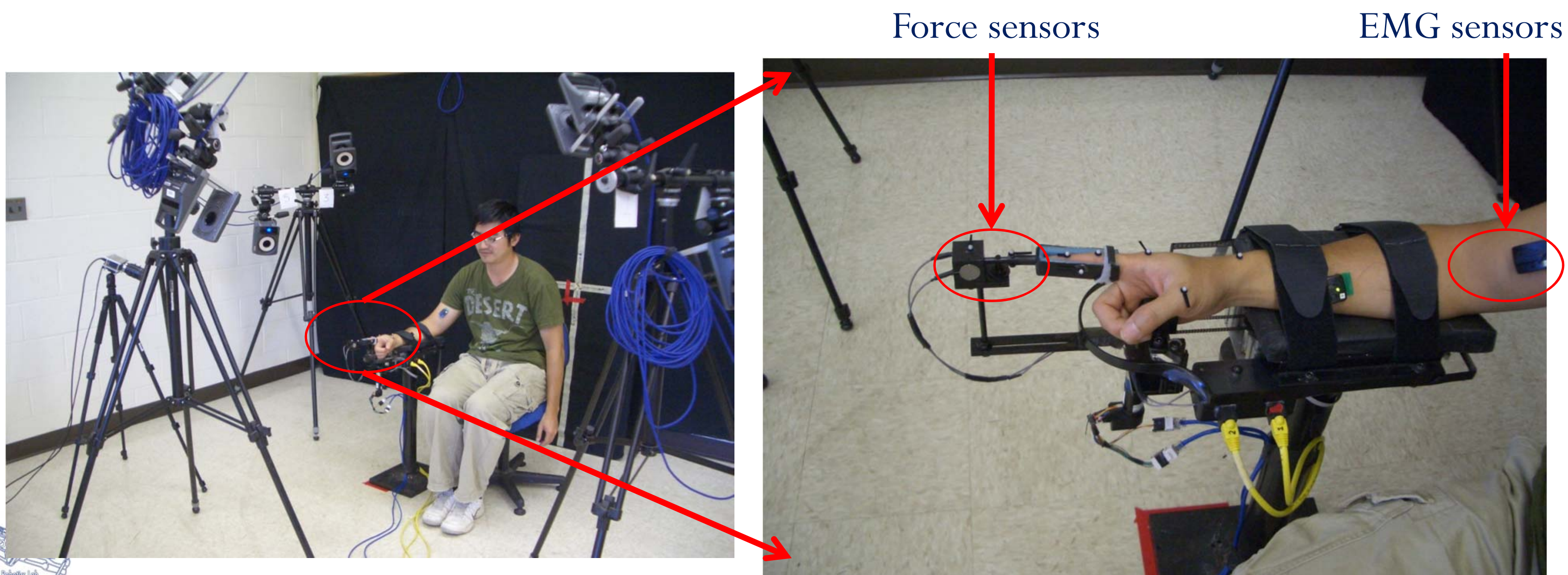
- Passive torque contribution is substantially greater (~90%) than dynamic torque contribution (~10%)
- **Human hands**
  - How does the CNS exploit these properties for controls?
  - Shoulder-elbow movements studies show that dynamic torques dominate

- **Robotic hands**
  - Incorporation of passive behavior may lead to improved performance
  - May ease the controls problem
    - Similarity with walking robot controls

[Hollerbach and Flash 1982]

Hardware for Quantification of Passive Joint Properties

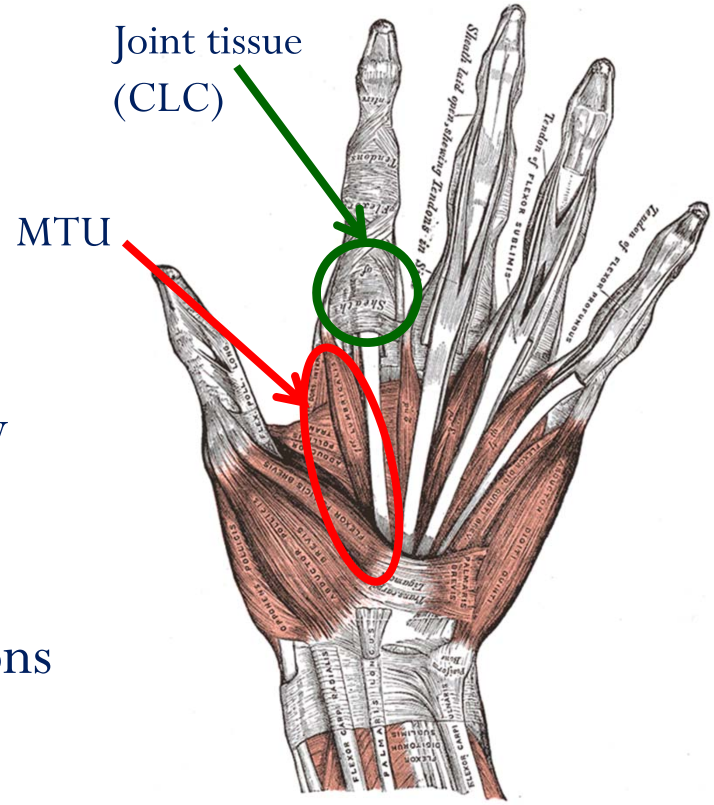
- Designed a mechanism to drive the index finger while the subjects relax
- DC motor driven system with force sensing
- Also muscle activity sensors to ensure that subjects are relaxed



Study 2: Modeling of Passive Joint Stiffness

- Hypothesis: joint stiffness is the result of muscle-tendon elasticity

- Two separate contributors to passive stiffness torques at a joint
  - Musculotendon units (MTUs)
  - Joint soft tissues (CLC)
- Literature speculates that MTU elasticity leads to joint stiffness
- Goal is to determine relative contributions of MTUs and joint soft tissues



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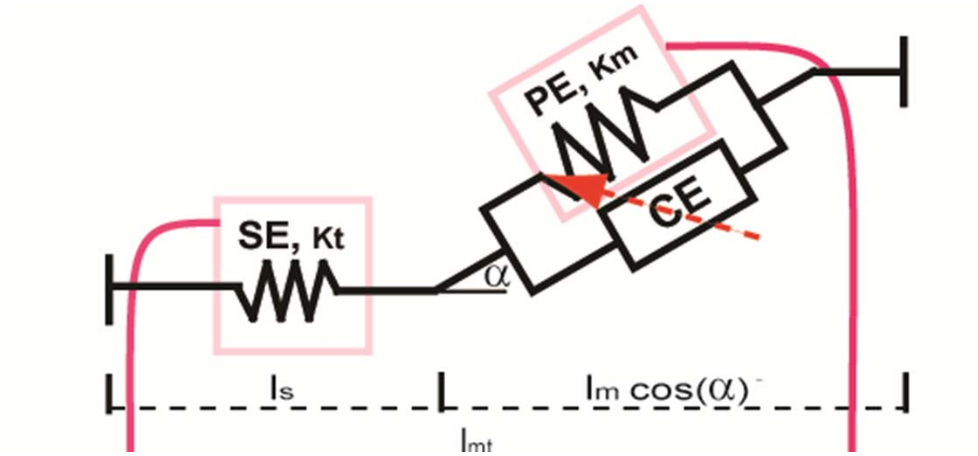
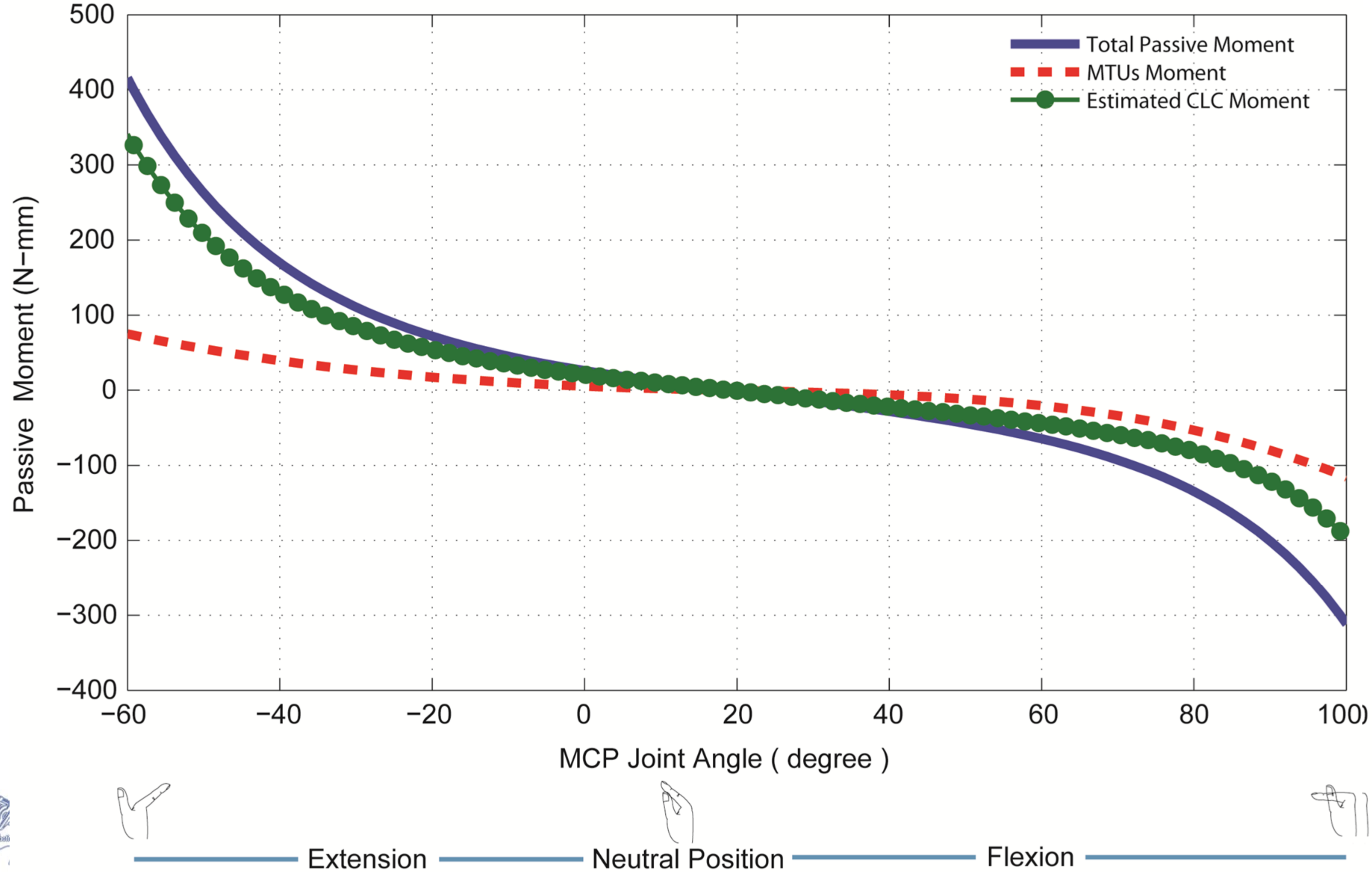
[Esteki et al 1999; Hogan 2007]

Muscle-Tendon Unit Model



MTU contributions to passive torque < 50%

- Results reveal explicit contributions of MTUs and joint tissues



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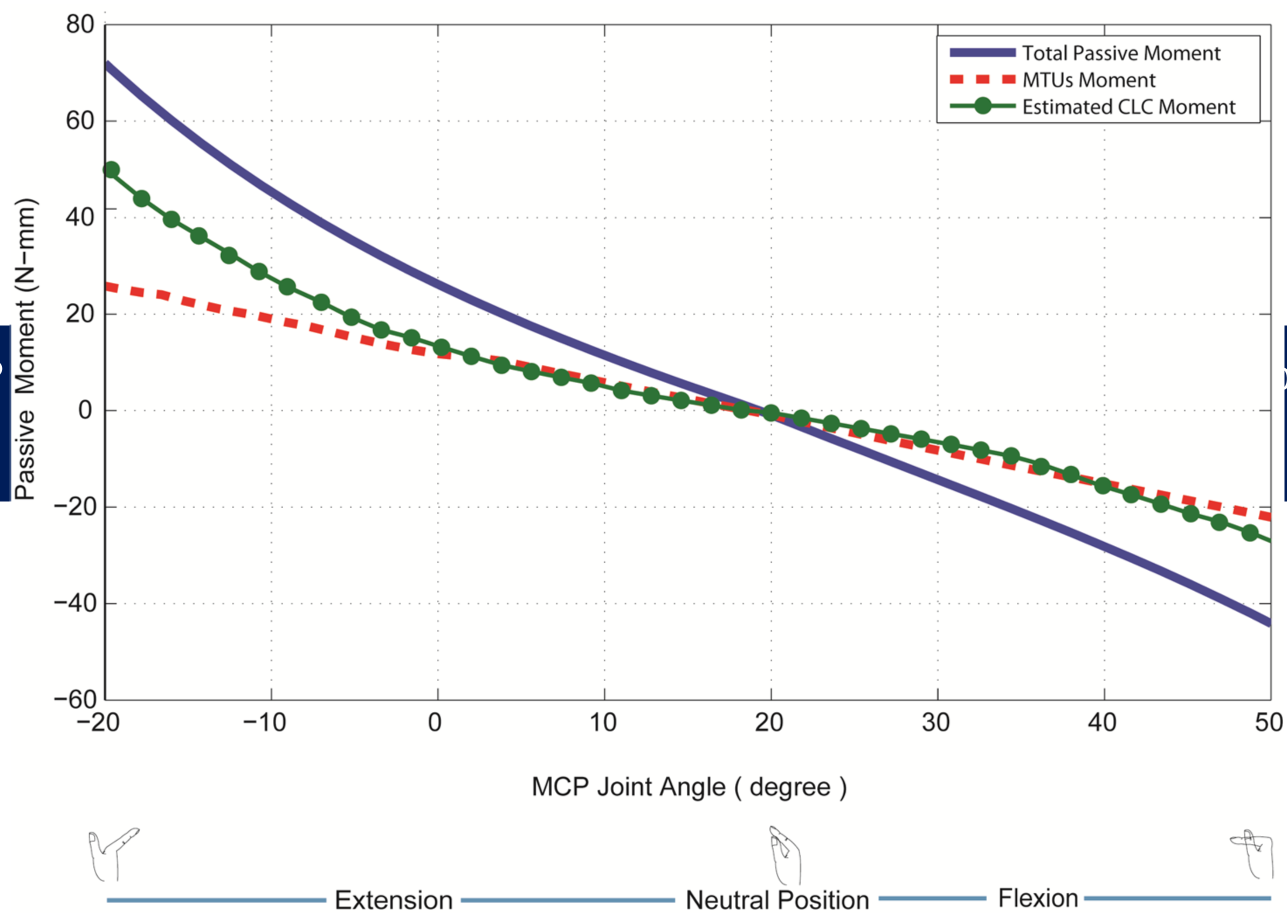


[Kuo and Deshpande in BioRob 10]

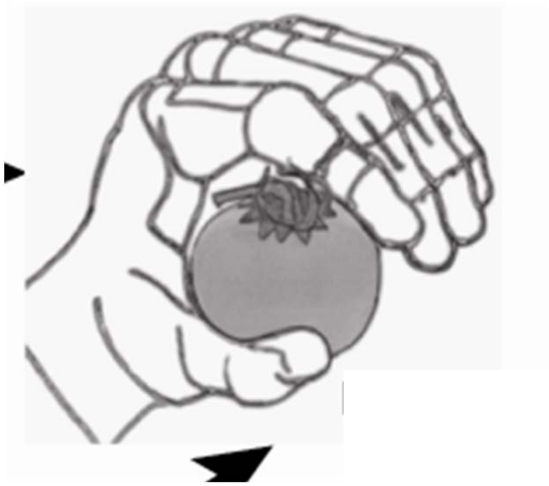
Study 2: Implications

⦿ Human Hands

- Soft tissue stiffness can provide injury projection
- Soft tissue stiffness is NOT controllable
  - MTU can compensate by active stiffness control through co-contraction
- Is there an internal model representation of the passive behavior in CNS?

⦿ Robotic Hands

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



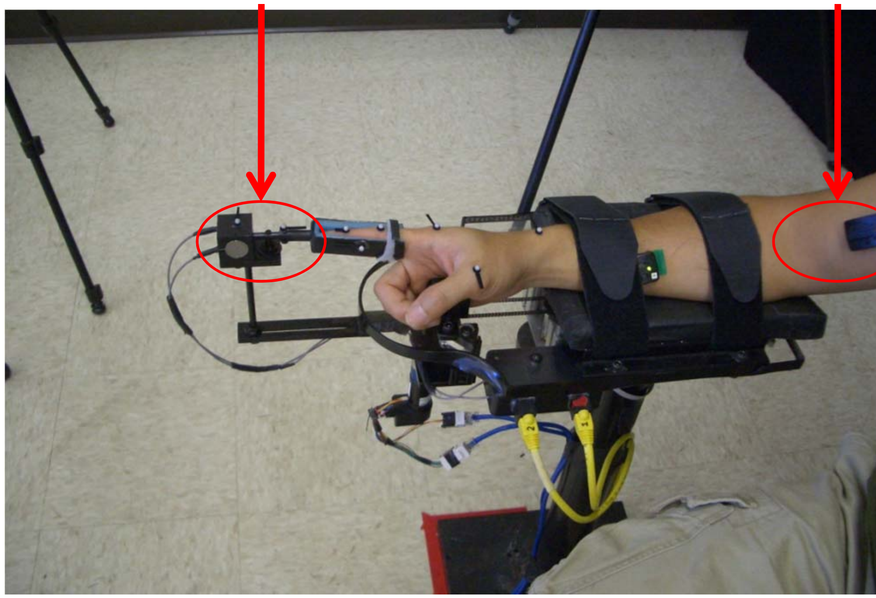
Study 3: Model of Damping in Hand Joints

- Existing models of damping are simplistic

τ_{Total} … $+ b\dot{\theta}_f,$

- Mathematical models of joint damping to determine dependency on joint angle and joint velocity

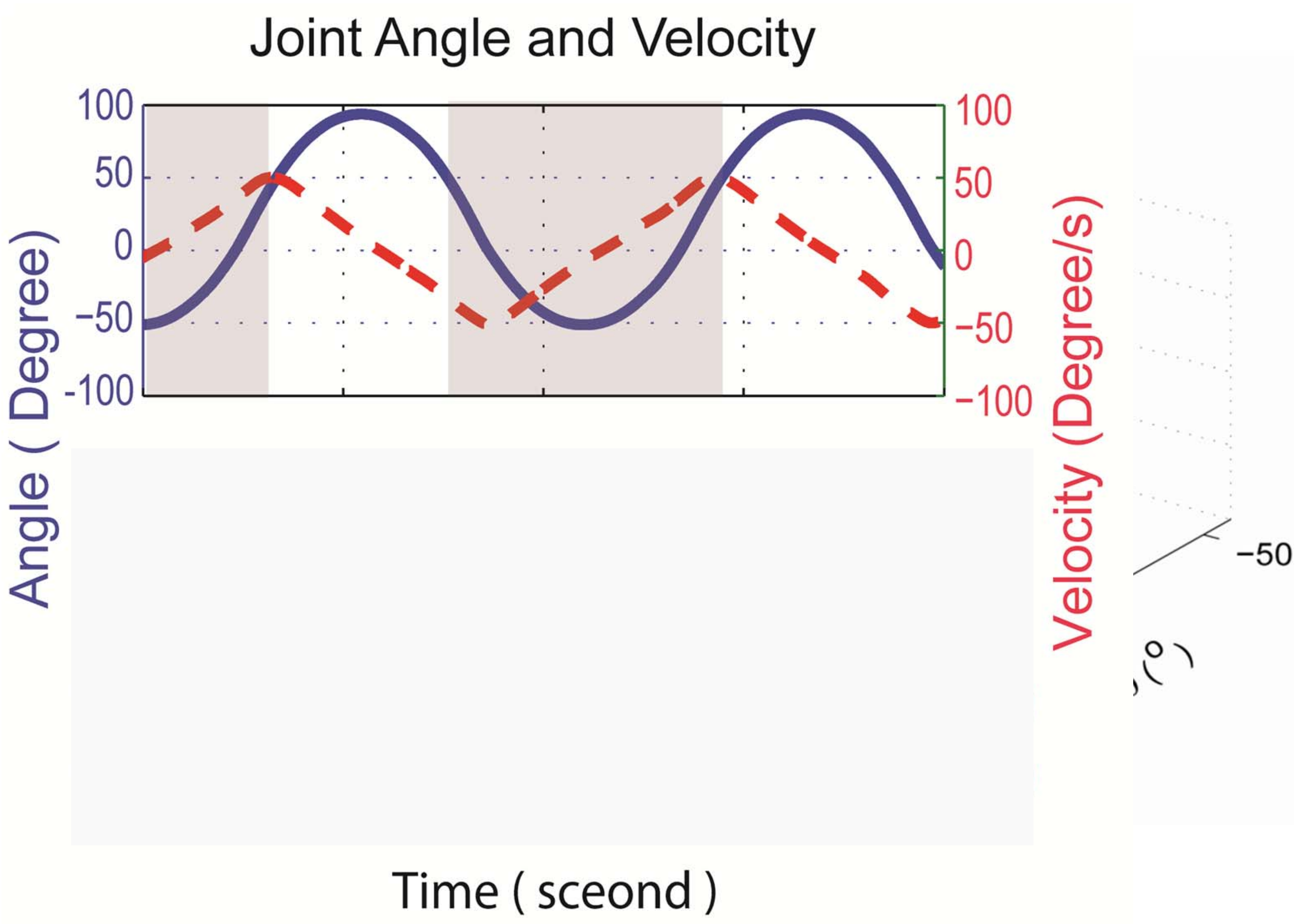
- We conducted experiments to develop more comprehensive models of the visco-elastic torque



[Kuo et al., IDETC 2011 , ASB 2011]

Model of Passive Visco-elastic Torque at MCP Joint

- Cyclic movement of the finger at various frequencies

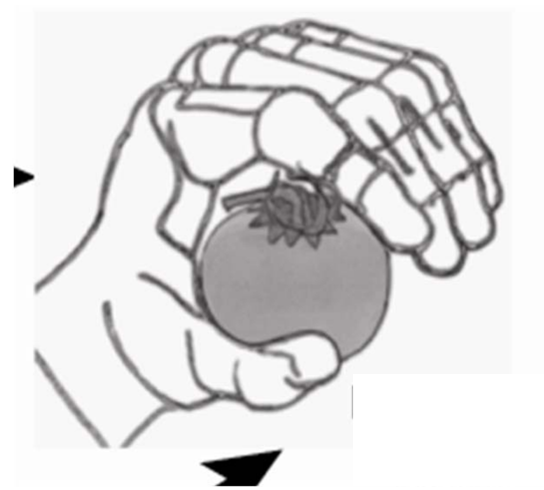


[Kuo et al., ASB 2011]

Study 3: Implications

⦿ Human Hands

- Visco-elastic torque depends on both velocity and configuration
- What is the relative contribution of MTU and joint tissues?
- Is there an internal model representation of the variable damping in CNS?

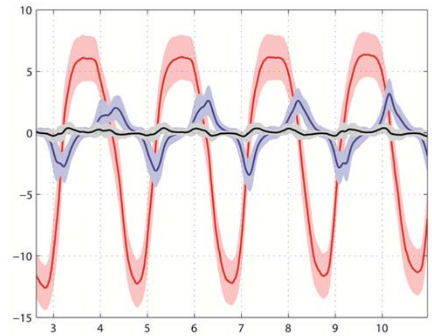


⦿ Robotic Hands

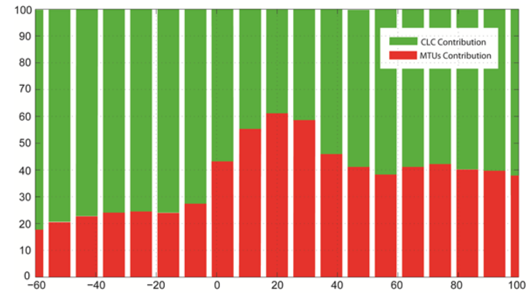
- Variable joint damping may improve contact stability
- Hardware implementation and software controls

Summary and Contributions

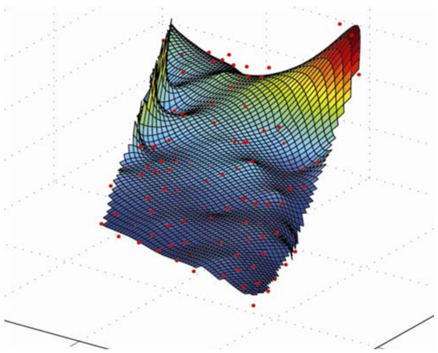
- Passive properties dominate (> 90%) during free hand movements



- Soft tissues at the MCP joint provide prominent contribution to passive stiffness



- Passive visco-elastic torque at the MCP joint varies with configuration and velocity



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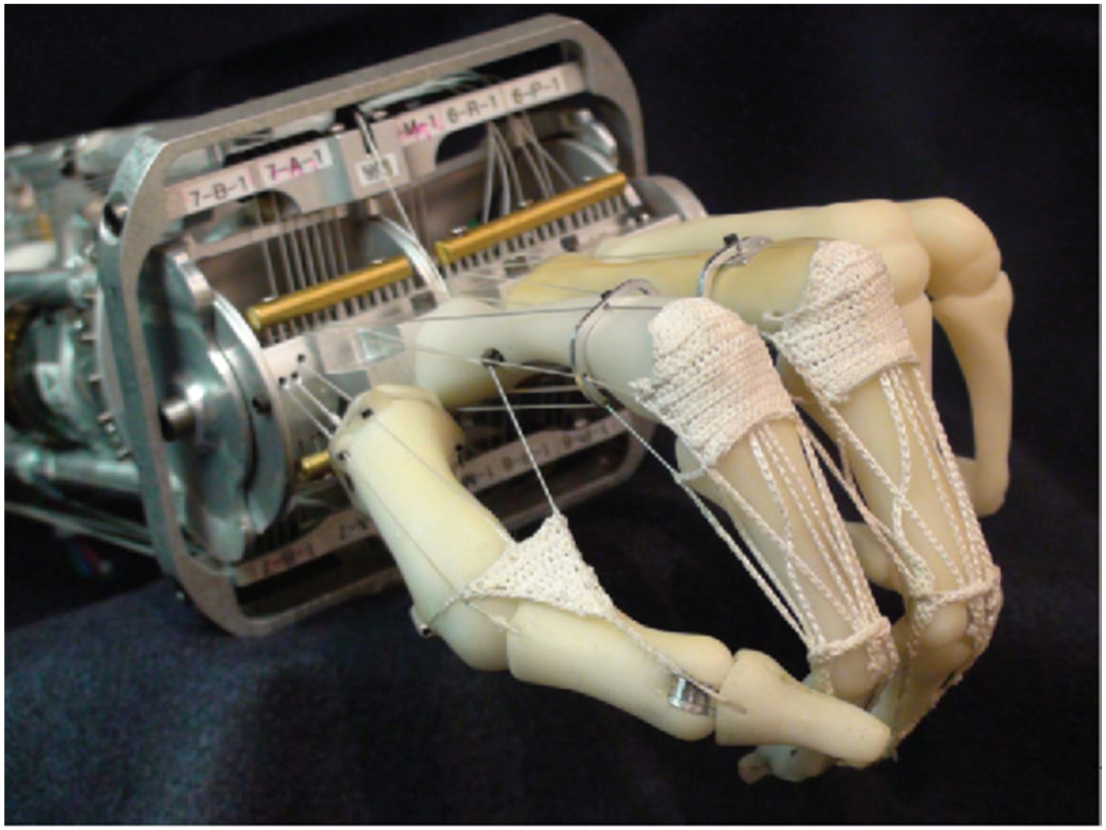
  - Understanding of human hand biomechanics and motor control

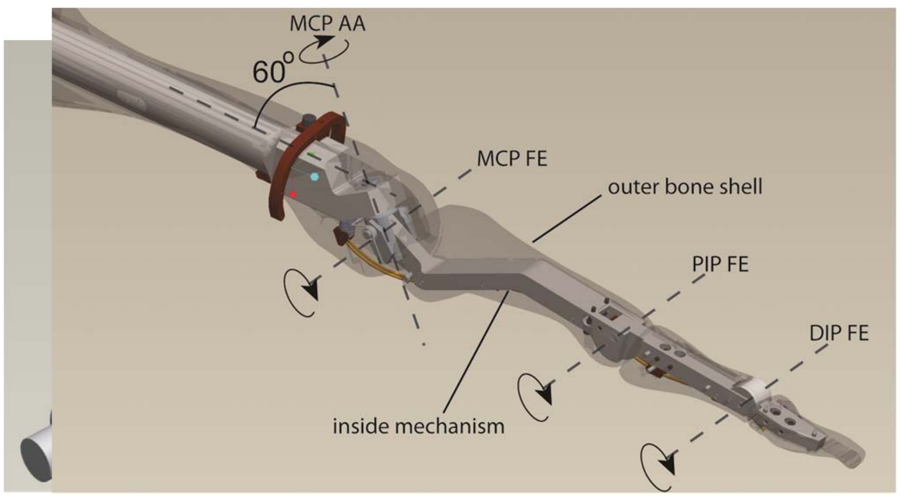


Grasping with ACT Hand

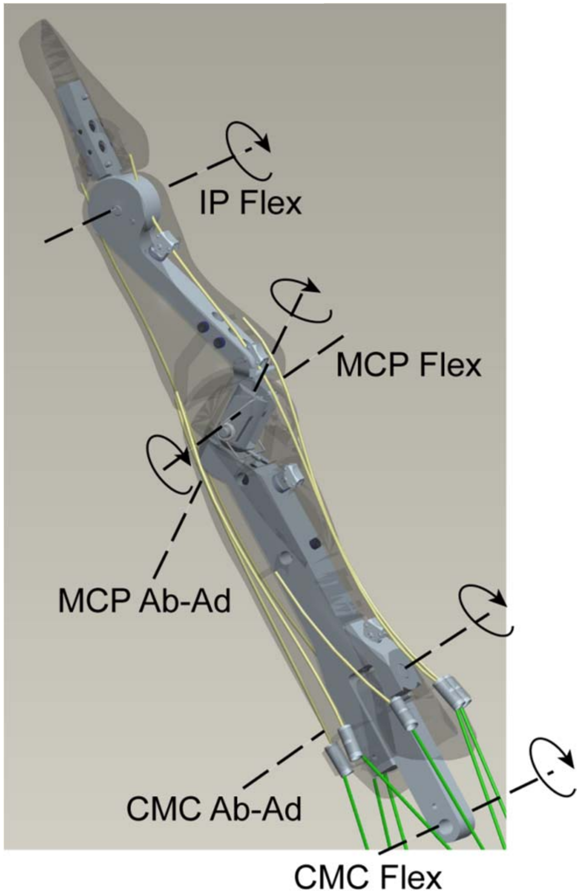
ACT Hand Bones and Joints

- Bone shapes match human bones
  - Critical for preserving hand functionality
- Joints match DOF and ranges of motions
  - Mechanism inside bone shells

Index finger



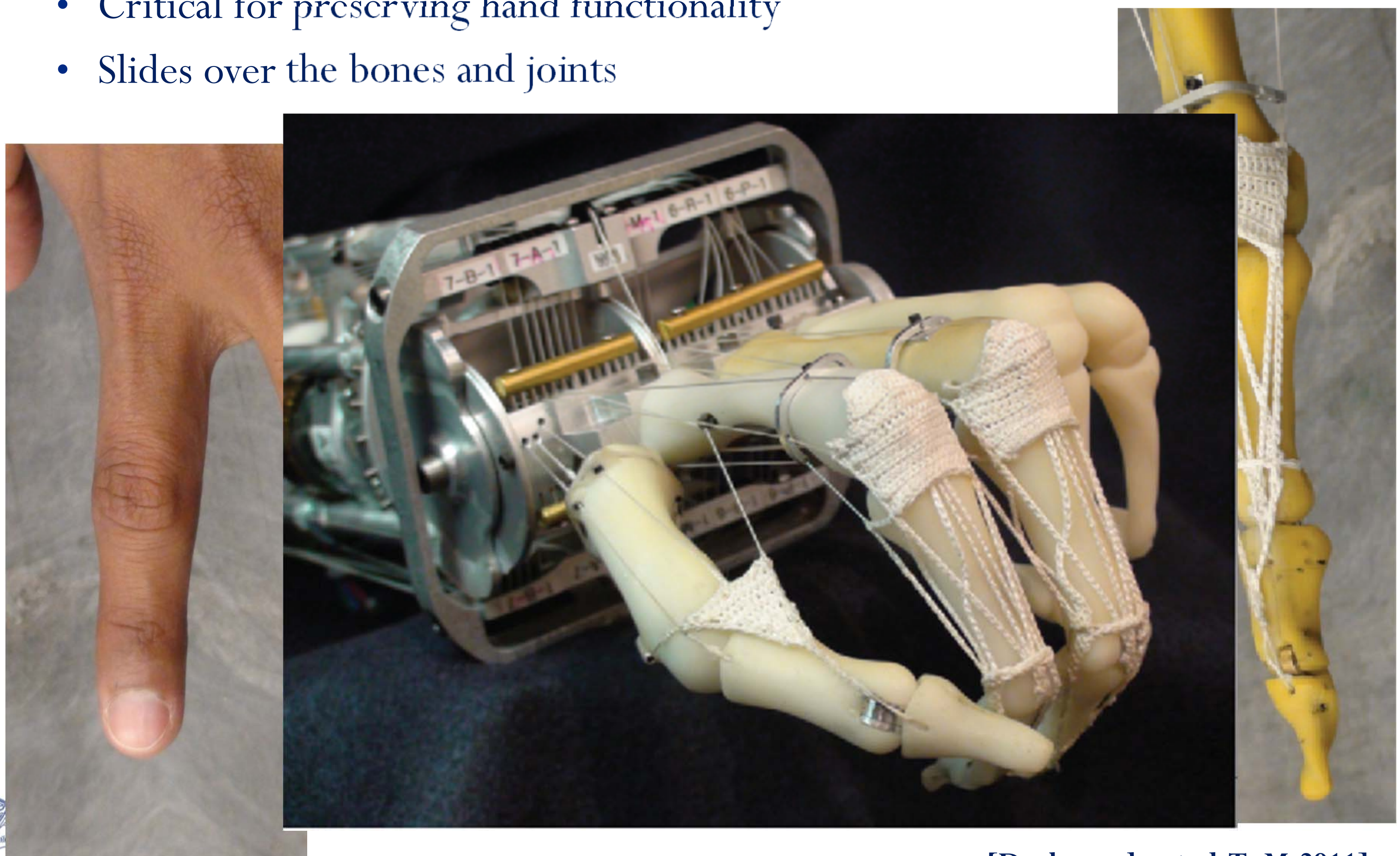
Thumb



[Deshpande et al, ToM 2011]

ACT Hand Tendon Arrangements

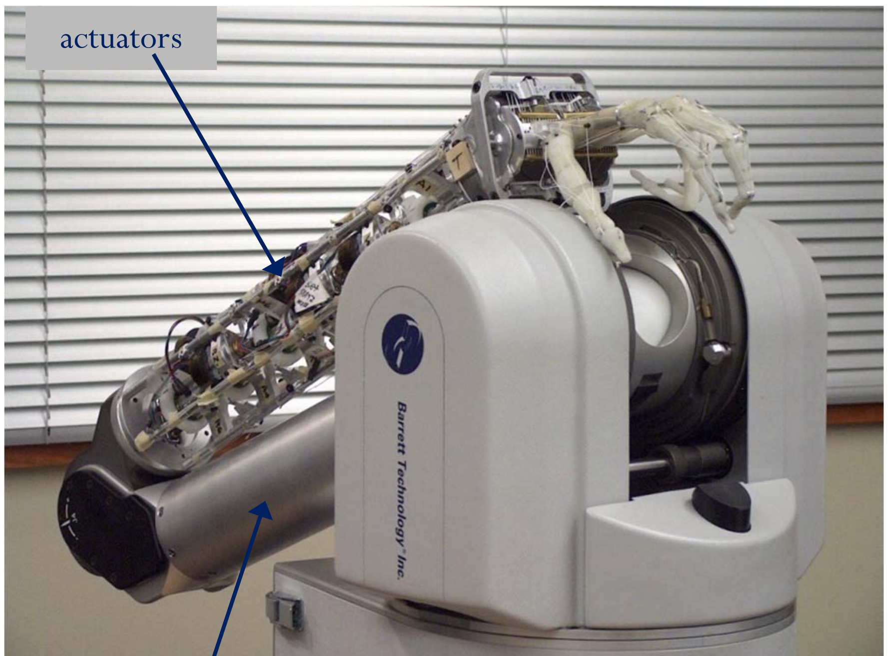
- Tendon hood structure for extensors
  - Critical for preserving hand functionality
  - Slides over the bones and joints



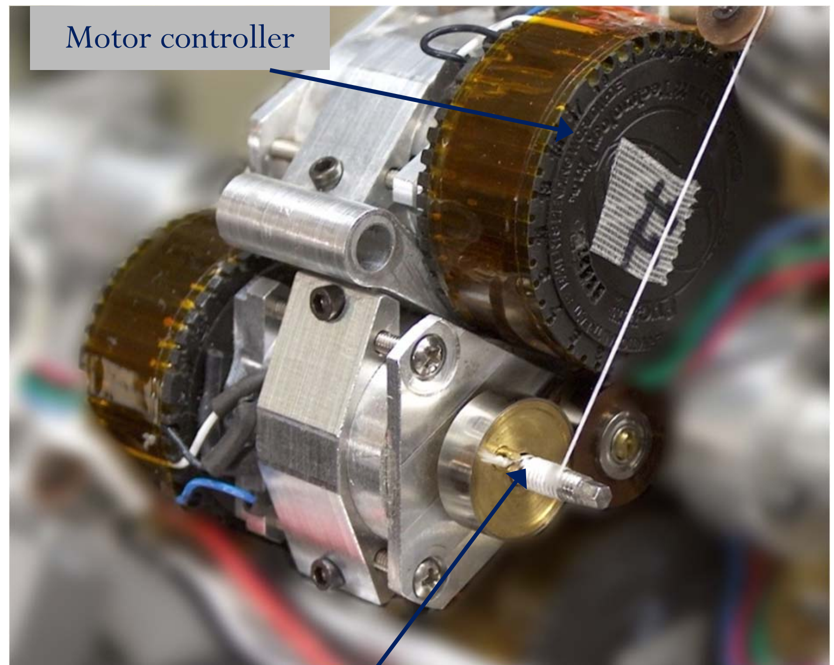
[Deshpande et al, ToM 2011]

ACT Hand Actuators

- Muscles are realized by customized DC motors
- Fast response, ranges of forces and tendon travel lengths
- Muscle-like behaviors with hardware and software



WAM arm



Motor to tendon connection

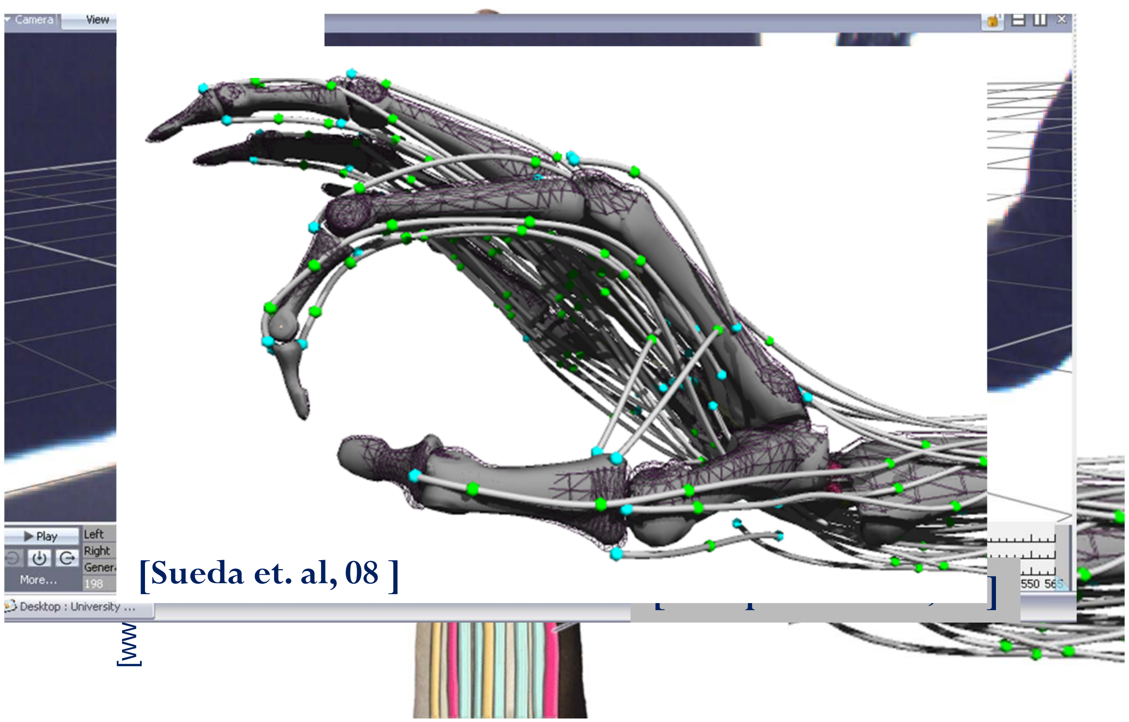
[Deshpande et al. in BioRob 2008, ICRA 09, TBME 10, ToM 2011]

Research Impacts – Artificial Hands

- Novel approach toward the development of robotic hands
  - Versatile manipulators
  - Highly functional hand prosthesis

Research Impacts – Human Hand Understanding

- Understanding of human hand biomechanics and movement control
  - Hand rehabilitation
  - Computer simulation models of hands



[Sueda et. al, 08]