Development of a 25-DOF Hand Forward Kinematic Model Using Motion Data

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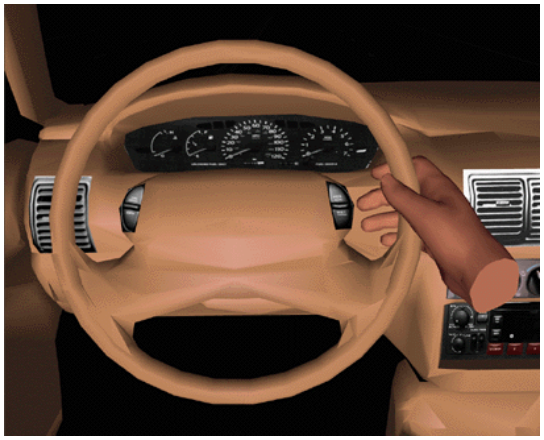
Agenda

- Background
- Objectives of the Study
- Hand Forward Kinematic Model Development
- Model Evaluation
- Discussion

Ergonomic Design with Digital Hand Models

- Hand-held device development in digital environment

Cell phone



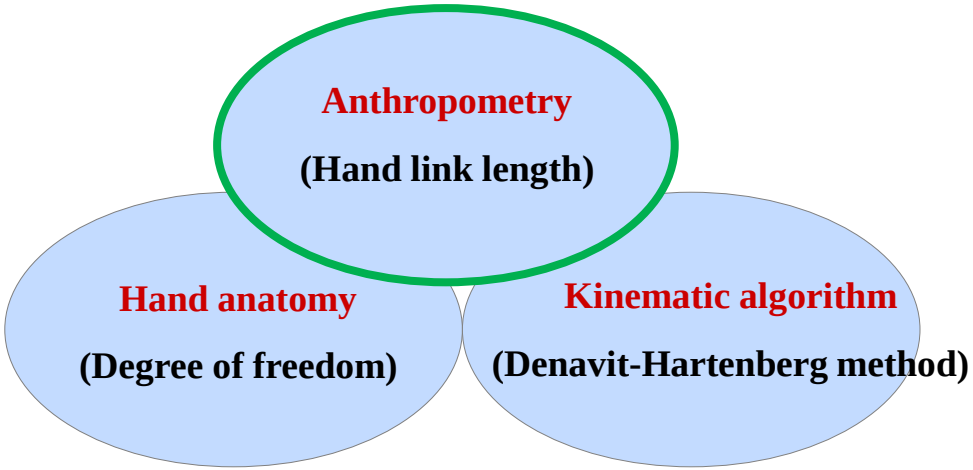
Car interior design

Helicopter controller

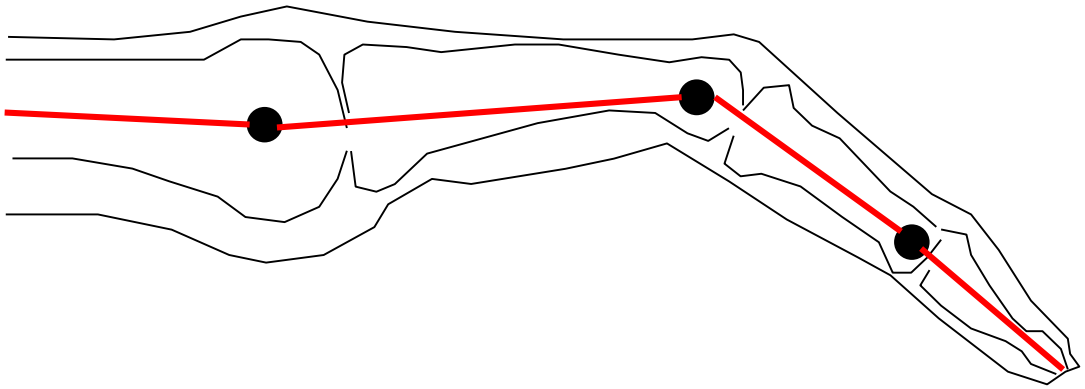
- Benefits
  - Better fit to the grip posture
  - Easily evaluate physical workloads such as grip force & torque
  - Reduce the number of physical prototypes
  - Reduce development time

Digital Hand Kinematic Modeling

- Three key issues



- Hand link length



Hand Link Length Estimation

- Two-step Procedure
  - S1. Determine joint center of rotation (COR)
  - S2. Calculate link length (distance between adjacent joint CORs)

- Existing joint COR estimation method
  - Buchholz et al. (1992)
    - Method
      - Attach markers to the fingers
      - Capture 3 or 4 X-ray images of the movement trajectory of makers
      - Estimate joint COR based on the trajectory
      - Do regression analysis based on 6 cadaver hands to derive the relation between hand link length (HLL) & hand length (HL): HLL = 0.32 HL (R^2 = 0.43)
    - Limitations
      - Limited number of X-ray images used
      - Small sample size (6 hands), R^2 value

Objectives of the Study

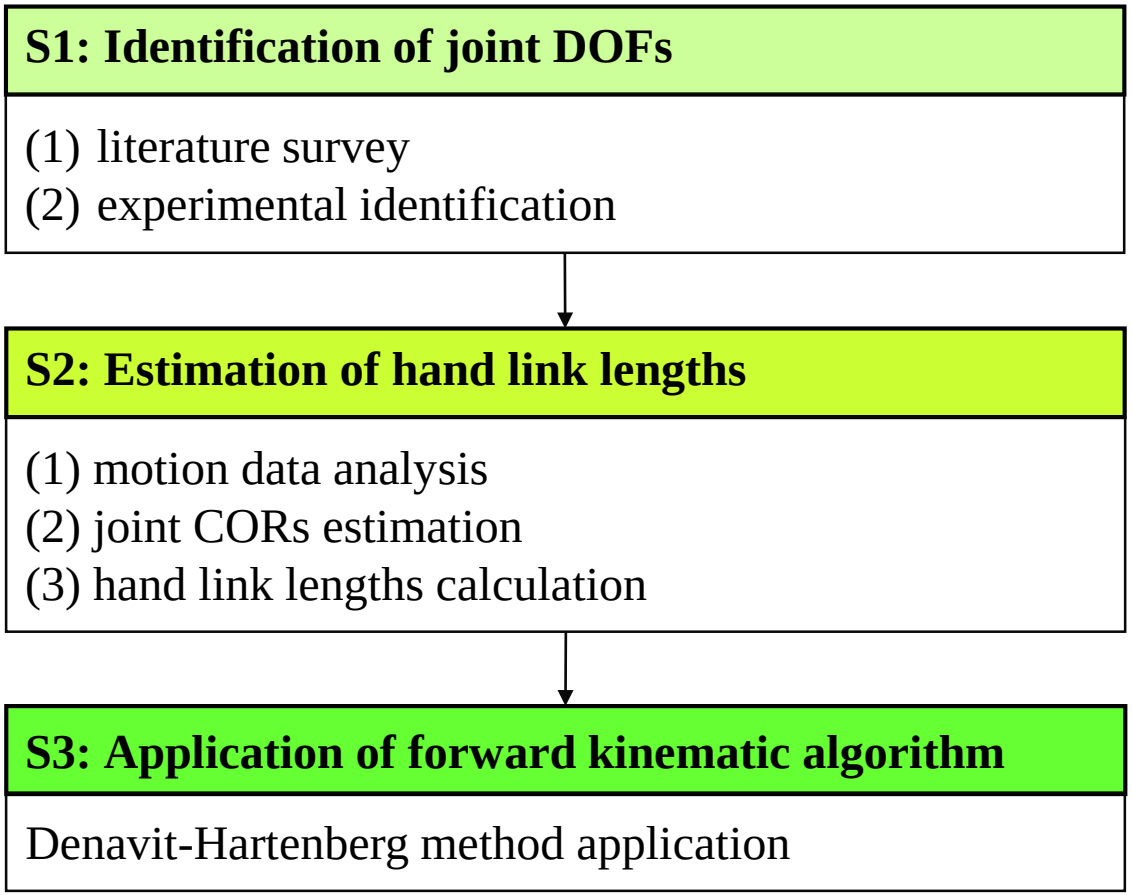
- Development of an optimization-based method for hand link length (HLL) estimation using 3D motion data collected by an optoelectronic motion capture system

- Development of a 25-DOF hand forward kinematic model for product design based on estimated HLL

- Evaluation of the model using motion data by comparing with SANTOS™ hand model which applies regression equations proposed by Buchholz et al. (1992) to estimate HLL

Hand Forward Kinematic Model Development

- Three-step procedure to develop the model

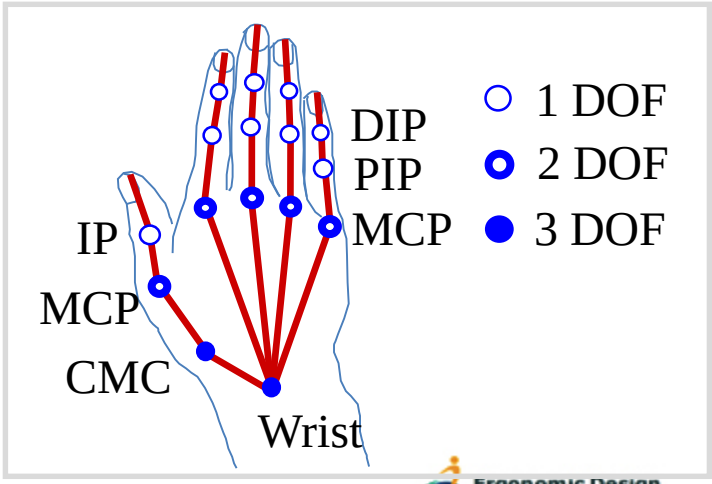


S1: Joint DOF Identification

- Survey of joint DOF

Joints	Fingers					Wrist Joint	Total
	Thumb	Index	Middle	Ring	Little		
Carpometacarpal (CMC)	2[3*] (3)					2(3)	22(25)
Metacarpophalangeal (MCP)	2[1**](2)	2	2	2	2		
Interphalangeal (IP)	1						
Proximalinterphalangeal (PIP)		1	1	1	1		
Distalinterphalangeal (DIP)		1	1	1	1		

*Buchholz, 1989; **Jack™
(): DOF of the new model



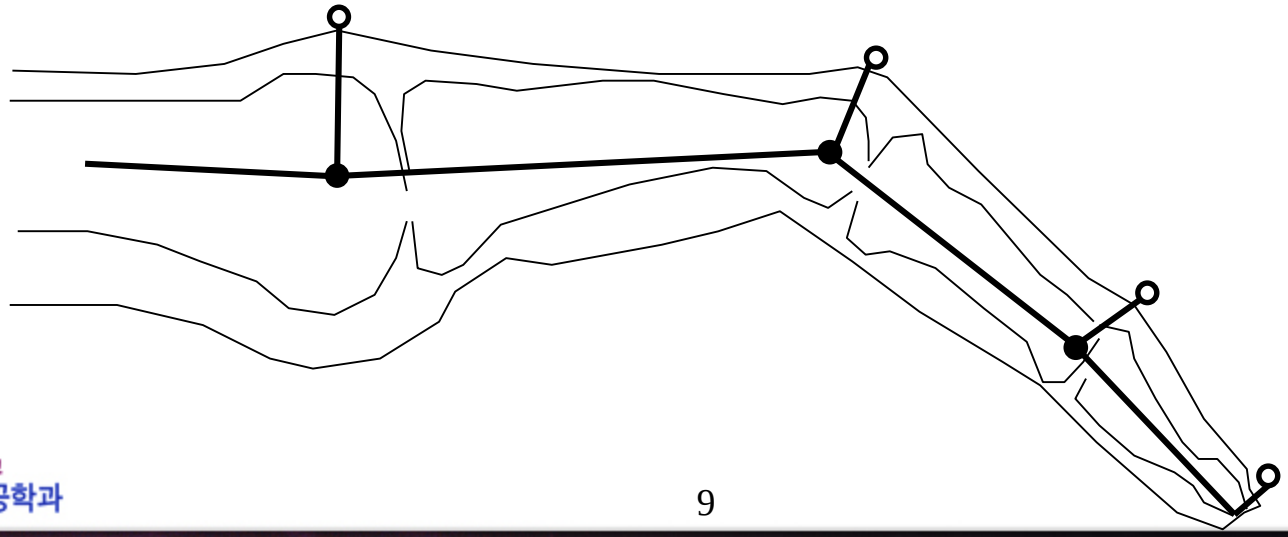
- Feature of the new model
  - Comprehensive DOFs (25 totally)

S2: Hand Link Length Estimation

- Assumption
  - Rigid linkage representation of the hand
  - Spherical trajectory of marker movement around joint COR

- Optimization routine
  - Cost function: variation of hand link length and depth from marker to joint COR during entire grip motion

$$C_i = \sum_{t=1}^{T} \left\{ \sum_{k=0}^{3} \left[\left\| \vec{l}_{i,k}(t) \right\| - \left\| \vec{l}_{i,k} \right\| \right]^2 + \sum_{m=0}^{4} \left[\left\| \vec{D}_{i,m}(t) \right\| - \left\| \vec{D}_{i,m} \right\| \right]^2 \right\}$$



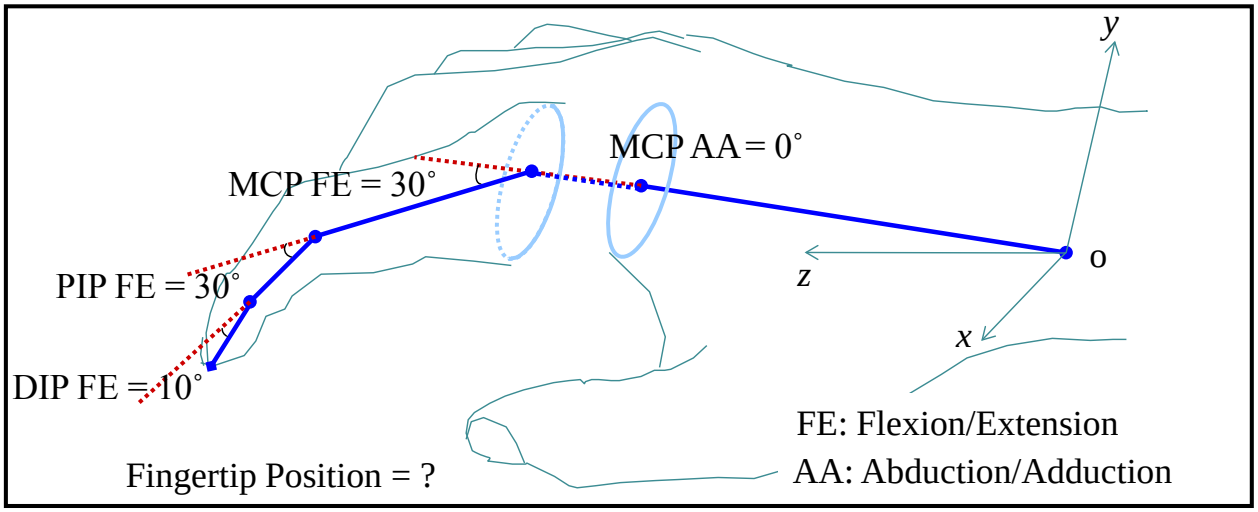
S3: Forward Kinematic Method Application

- Denavit-Hartenberg method provides the transformation relationship between joint angles and fingertip position.

- Forward kinematic method predicts fingertip position, given joint angles

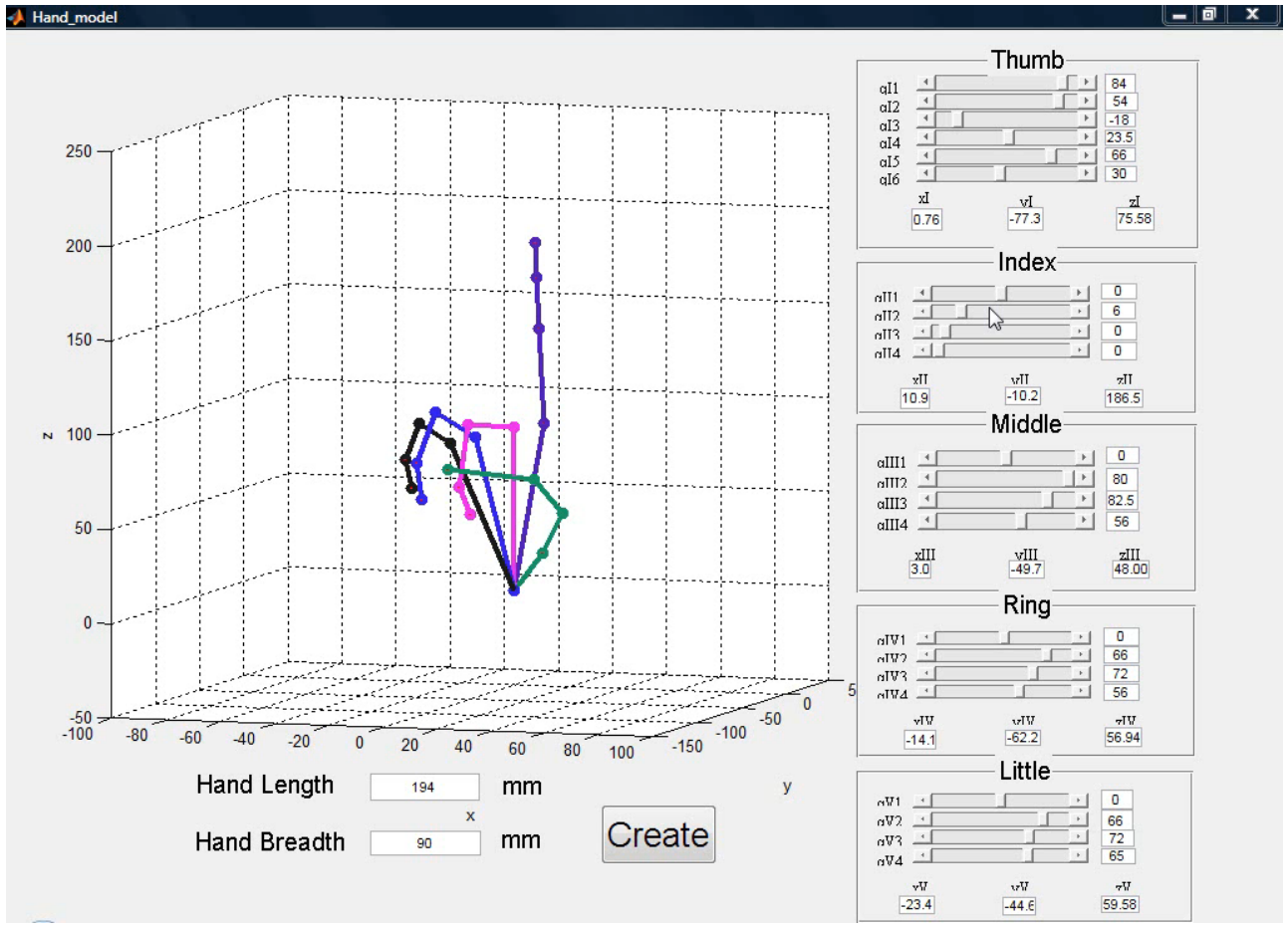
$$\mathbf{P} = f(\Theta)$$

P: Fingertip Position, Θ: Joint Angles



Proposed Hand Forward Kinematic Model

- Input: joint angles
- Output: fingertip position



Experimental Evaluation

Ball grasping Motion experiment

Data Processing

Joint Angles

Forward Kinematic Model

Measured Fingertip Positions

Predicted Fingertip Positions

Prediction Error

Participants

- Five right-handed male participants

Classification	Mean (SD)	Range
Age (years)	26.3 (2.1)	23~28
Hand length (mm)	192 (10.1)	178~206

- Selection criteria
  - No history of injuries at the hand and wrist

Apparatus

- Optoelectronic motion capture system: 6 Hawk Digital Cameras® (Motion Analysis Corporation, CA, USA)

- 24 spherical retro-reflective markers
  - Diameter: 5 mm

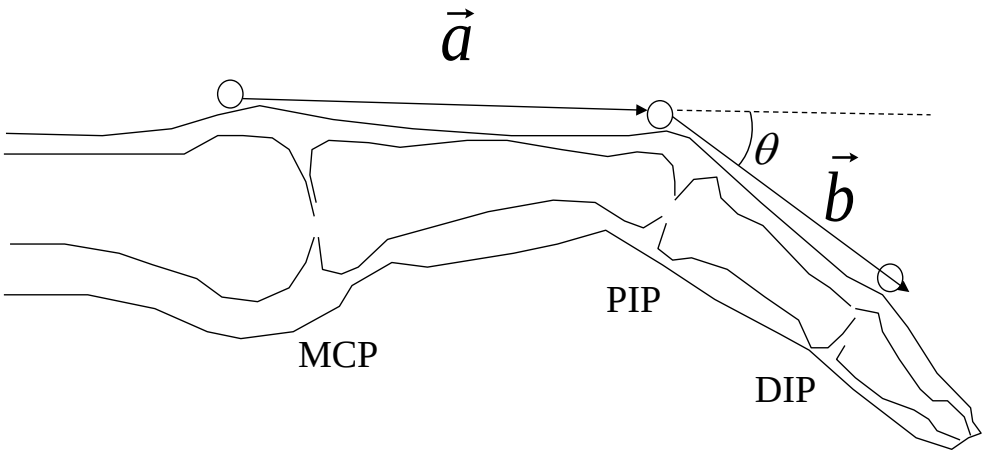
Motion capture system layout

Surface marker set

Joint Angle Calculation: 1 DOF

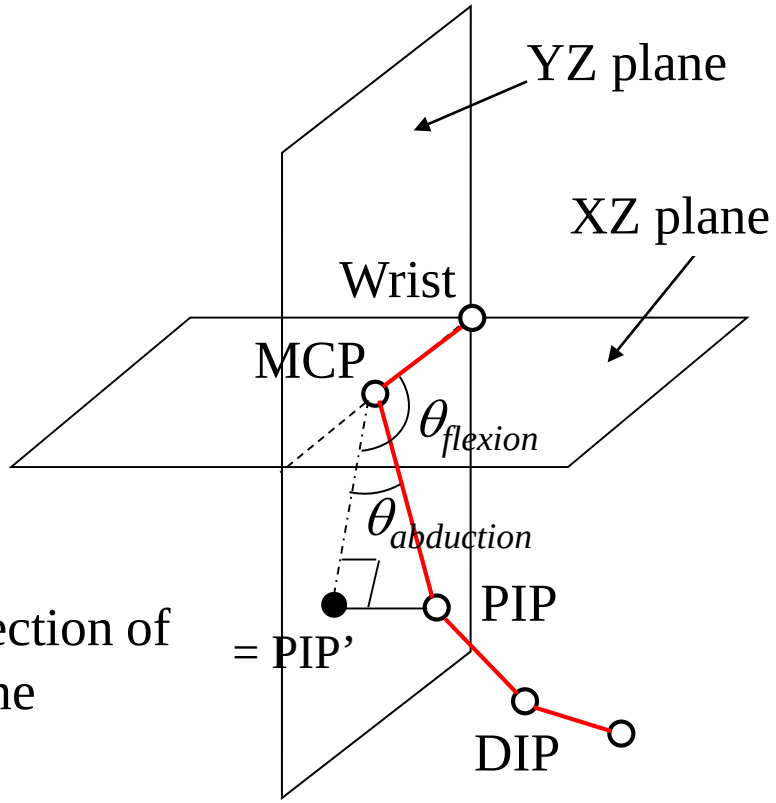
- Flexion-extension angle of PIP joint

$$\theta = \arccos\left(\frac{\vec{a}\cdot\vec{b}}{|\vec{a}||\vec{b}|}\right)$$



Joint Angle Calculation: 2 DOF

- Flexion-extension and abduction-adduction angles of MCP joint



Orthogonal projection of PIP onto YZ plane

Evaluation Criteria

- Prediction Error
  - Distance between the measured fingertip position (X_M, Y_M, Z_M) and predicted fingertip position (X_P, Y_P, Z_P)

$$\text{Prediction error} = \sqrt{(X_P - X_M)^2 + (Y_P - Y_M)^2 + (Z_P - Z_M)^2}$$

Unit: mm

Participants	Classification	Index finger position		
		X	Y	Z
P1	Measured	-8.2	-39.3	128.8
	Predicted	-7.8	-41.3	130.5
	Prediction eror	2.7		

Evaluation Result

- Fingertip prediction error at each finger

  Proposed model: Middle > Ring > Index > Little

  SANTOS™ hand model: Middle > Little > Ring > Index

- Grand mean: Proposed model (2.7 mm) < SANTOS ™ hand (5.8 mm)

Mean (SD) value (mm) of fingertip position prediction error

Hand model	Index	Middle	Ring	Little	Maximum
Proposed Model	2.2 (2.5)	3.6 (3.2)	3.1 (2.8)	1.8 (1.5)	9.7 (Middle)
SANTOS™ Hand model	5.4 (3.2)	6.3 (3.7)	5.7 (1.5)	5.9 (1.3)	15.3 (Middle)

Discussion

- The new hand model predicts fingertip position more accurate than SANTOS^{TM} hand (2~3 mm on average).
- Accuracy of proposed optimization-based HLL estimation method > regression equations proposed by Buchholz et al. (1992)
- The model has lower accuracy at middle and ring fingers
  - Smaller amount of joint rotation for middle and ring fingers during ball grasping motion
  - More amount of joint rotation leads to more accurate estimation of HLL
- Source of prediction error
  - Attaching location of markers: need to locate markers right over the joint COR

Q & A

Thank you!