IIT ROORKEE

NPTEL ONLINE CERTIFICATION COURSE

Redundancy Resolution of the Human Fingers in Cooperative Object Translation-II

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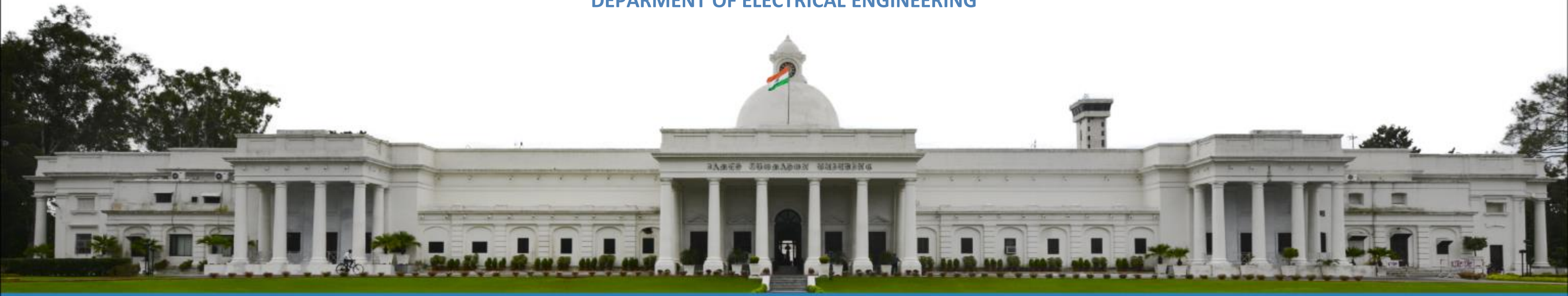
DEPARMENT OF ELECTRICAL ENGINEERING



Outline

1. Introduction

2. Finger Kinematics

   - Forward Kinematics
   - Inverse Kinematics

3. Redundancy Resolution

4. Results and Discussion

Introduction – Motivation – Major Finding

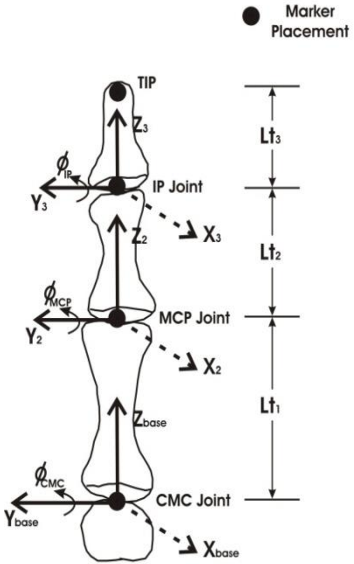
- This research study explores how humans resolve the redundancy in their thumb, index and middle fingers during object translation motion.

- We observe that humans actively employ a secondary subtask of utilizing instantaneous manipulability when performing the primary subtask of tip trajectory following.

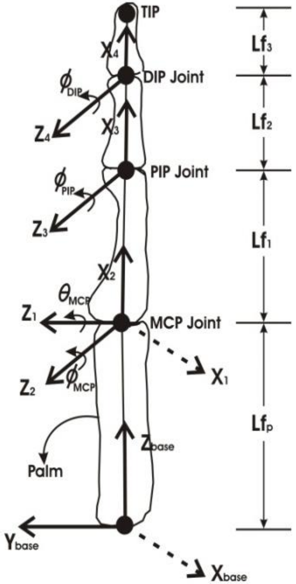
- This behavior is accurately captured by an inverse kinematic model based on a single redundancy parameter which take negative values too as per the finger configurations and it varies significantly across the 12 subjects performing the same task.

- The findings are considered to be of significant importance in reference to the challenges in design and control of finger exoskeletons for cooperative manipulation.

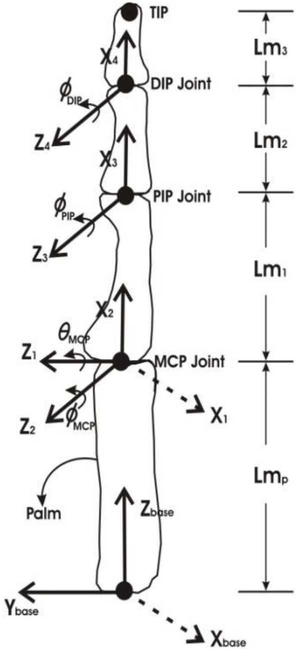
Finger Kinematic Model



Thumb



Index Finger



Middle Finger

Finger Kinematic Model (cont'd)

Thumb Tip Position:

$$T_X = Lt_1 \sin(\phi_{CMC}) + Lt_2 \sin(\phi_{CMC} + \phi_{MCP}) + Lt_3 \sin(\phi_{CMC} + \phi_{MCP} + \phi_{IP})$$
$$T_Y = 0$$
$$T_Z = Lt_1 \cos(\phi_{CMC}) + Lt_2 \cos(\phi_{CMC} + \phi_{MCP}) + Lt_3 \cos(\phi_{CMC} + \phi_{MCP} + \phi_{IP})$$

Index Finger Position:

$$I_X = \sin(\theta_{MCP})(Lf_1 \cos(\phi_{MCP}) + Lf_2 \cos(\phi_{MCP} + \phi_{PIP}) + Lf_3 \cos(\phi_{MCP} + \phi_{PIP} + \phi_{DIP})$$
$$I_Y = Lf_1 \sin(\phi_{MCP}) + Lf_2 \sin(\phi_{MCP} + \phi_{PIP}) + Lf_3 \sin(\phi_{MCP} + \phi_{PIP} + \phi_{DIP})$$
$$I_Z = Lf_p + Lf_1 \cos(\theta_{MCP})\cos(\phi_{MCP}) + Lf_2 \cos(\theta_{MCP})\cos(\phi_{MCP} + \phi_{PIP}) + Lf_3 \cos(\theta_{MCP})\cos(\phi_{MCP} + \phi_{PIP} + \phi_{DIP})$$

Middle Finger Position:

$$M_X = L_{depth} + Lm_1 \sin(\theta_{MCP})\cos(\phi_{MCP}) + Lm_2 \sin(\theta_{MCP})\cos(\phi_{MCP} + \phi_{PIP}) + Lm_3 \sin(\theta_{MCP})\cos(\phi_{MCP} + \phi_{PIP} + \phi_{DIP})$$
$$M_Y = Lm_1 \sin(\phi_{MCP}) + Lm_2 \sin(\phi_{MCP} + \phi_{PIP}) + Lm_3 \sin(\phi_{MCP} + \phi_{PIP} + \phi_{DIP})$$
$$M_Z = Lm_p + Lm_1 \cos(\theta_{MCP})\cos(\phi_{MCP}) + Lm_2 \cos(\theta_{MCP})\cos(\phi_{MCP} + \phi_{PIP}) + Lm_3 \cos(\theta_{MCP})\cos(\phi_{MCP} + \phi_{PIP} + \phi_{DIP})$$

Finger Kinematic Model (cont'd)

$$\mathbf{x}_k = \mathbf{f}(\boldsymbol{\theta}_k)$$

$$\dot{\mathbf{x}}_k = \mathbf{J}_k \dot{\boldsymbol{\theta}}_k$$

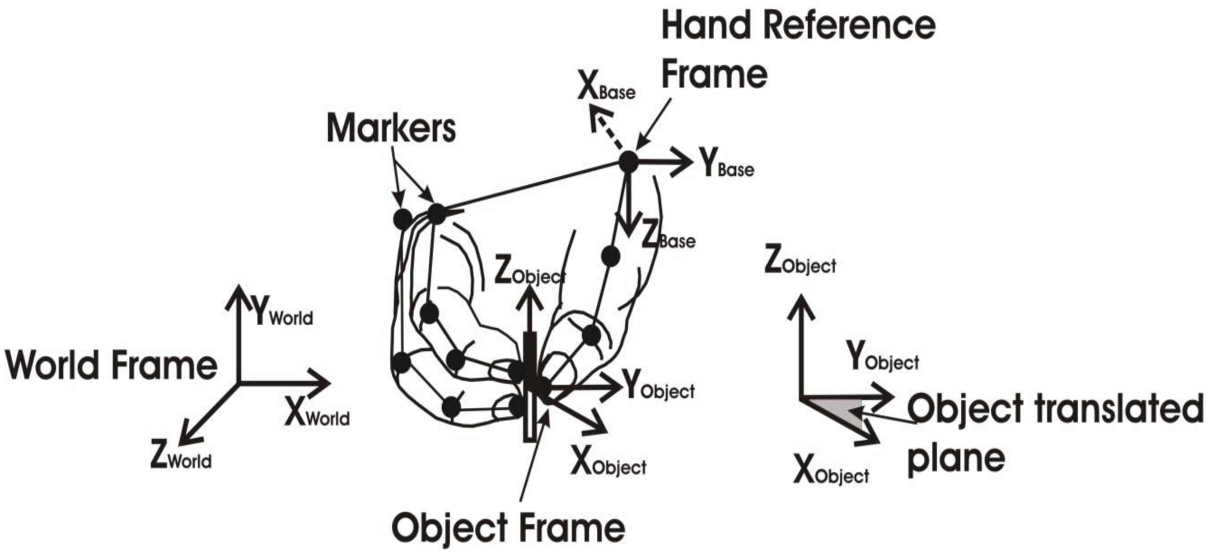
$$\mathbf{J}_k = \frac{\partial \mathbf{f}(\boldsymbol{\theta}_k)}{\partial \boldsymbol{\theta}_k}$$

$$\dot{\boldsymbol{\theta}}_k = \mathbf{J}_k^{+} \dot{\mathbf{x}}_{kd} + (\mathbf{I} - \mathbf{J}_k^{+}\mathbf{J}_k)\mathbf{N}$$

where, $\mathbf{J}_k^{+} = \mathbf{J}_k^{T}(\mathbf{J}_k\mathbf{J}_k^{T})^{-1}$ is the Pseudo Inverse and **N** is an arbitrary vector

$$\dot{\boldsymbol{\theta}}_k = \mathbf{J}_k^{+} \dot{\mathbf{x}}_{kd} + (\mathbf{I} - \mathbf{J}_k^{+}\mathbf{J}_k) k_p \frac{\partial M(\boldsymbol{\theta}_k)}{\partial \boldsymbol{\theta}_k}; \qquad M(\boldsymbol{\theta}_k) = \sqrt{\det(\mathbf{J}_k\mathbf{J}_k^{T})}$$

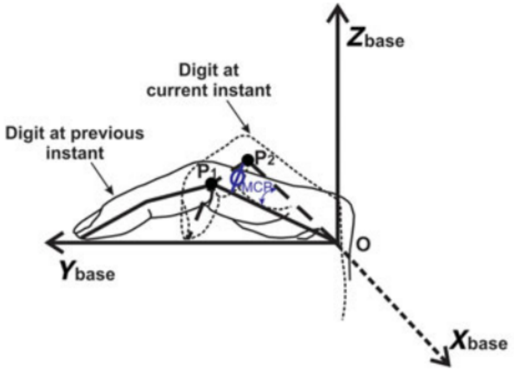
Schematics of the hand reference frame, object frame and plane of motion



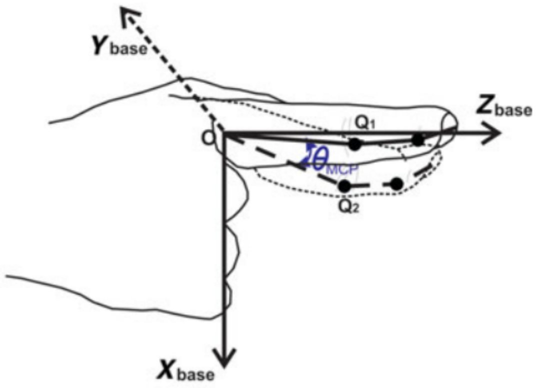
Joint angle computation from the experimentally obtained marker positions

$$\phi_{\mathrm{MCP}} = \sin^{-1}\left(\frac{\mathrm{OP}_1 \times \mathrm{OP}_2}{\|\mathrm{OP}_1\|\,\|\mathrm{OP}_2\|}\right)$$

$$\theta_{MCP} = \sin^{-1}\left(\frac{\mathrm{OQ}_1 \times \mathrm{OQ}_2}{\|\mathrm{OQ}_1\|\,\|\mathrm{OQ}_2\|}\right)$$

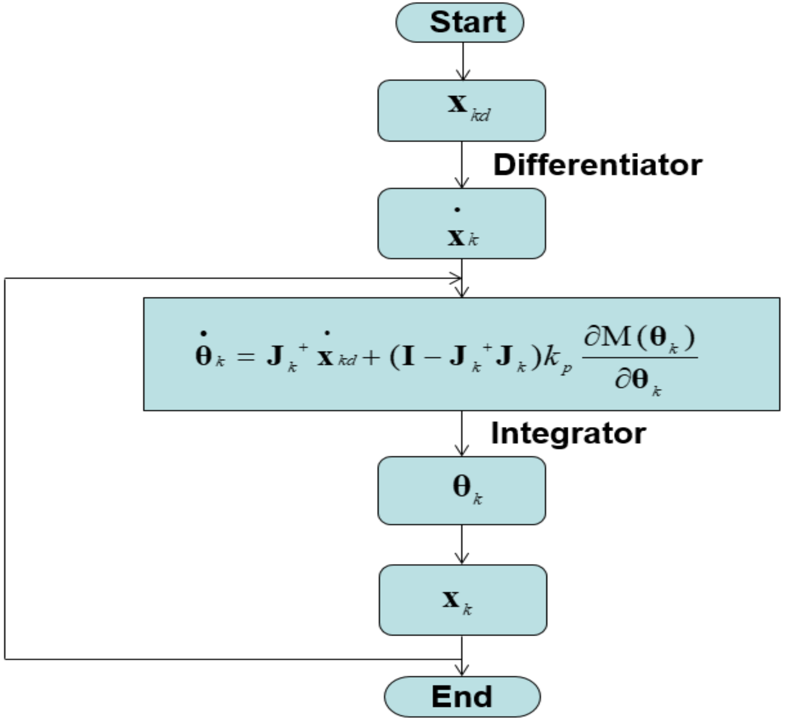


(a)



(b)

Joint angle computation from Inverse Kinematic Model



Redundancy Resolution

- Assumed the cubic dependence of $k_p(t)$ on the normalized time

$$k_p(t) = k_{p0} + k_{p1}t + k_{p2}t^2 + k_{p3}t^3$$

- The coefficients are obtained by minimizing the Root Mean Square Error (RMSE) between the desired experimental and actual inverse kinematics data

$$E_{\theta_j} = \sqrt{\frac{1}{A}\sum_{k=1}^{A}(\theta_{je}(t_A) - \theta_{ji}(t_A))^2}$$

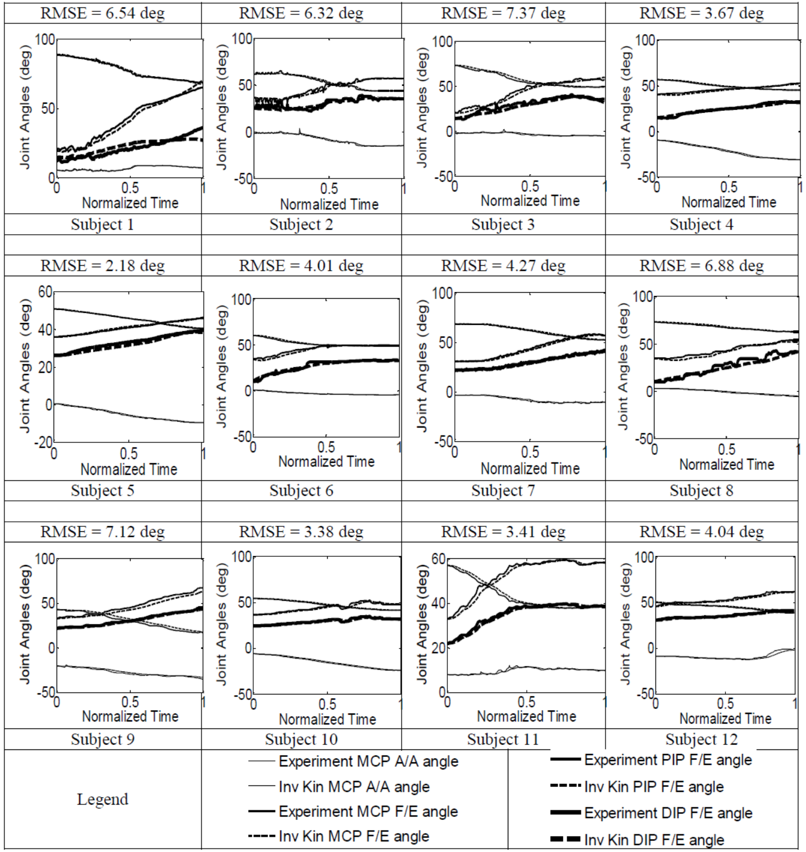
- Yoshikawa's Model:

$$\dot{\boldsymbol{\theta}}_k = \mathbf{J}_k^{+}\dot{\mathbf{x}}_{kd} + (\mathbf{I} - \mathbf{J}_k^{+}\mathbf{J}_k)k_p \frac{\partial \mathrm{M}(\boldsymbol{\theta}_k)}{\partial \boldsymbol{\theta}_k}$$

- Our Findings suggest that:

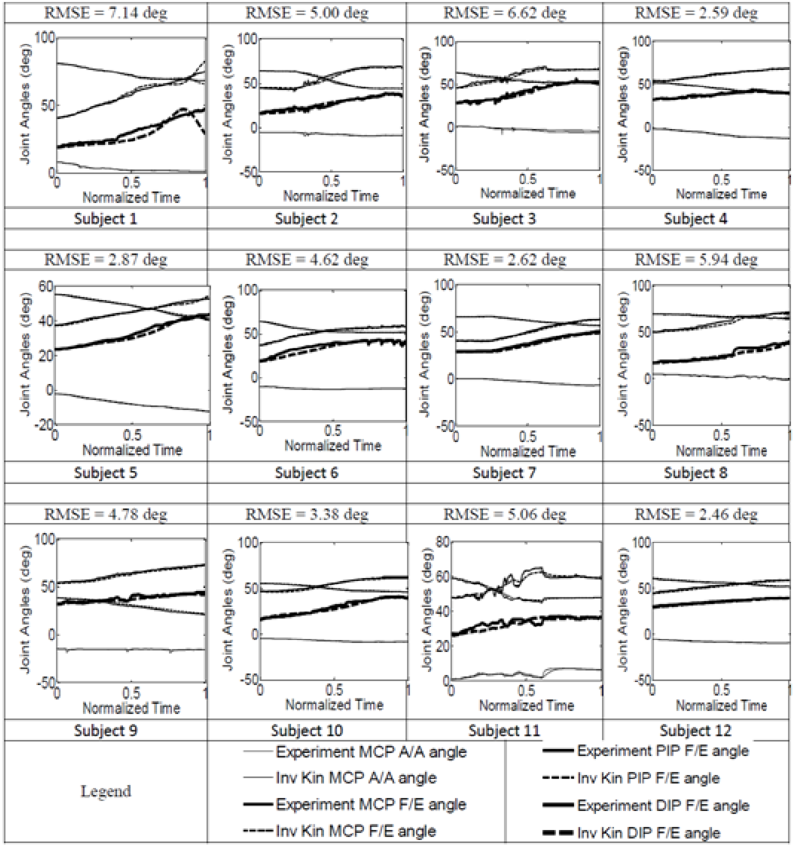
Humans accommodate redundancy by instantaneously altering the sign and magnitude of the parameter along with the utilization of the manipulability measure.

Results



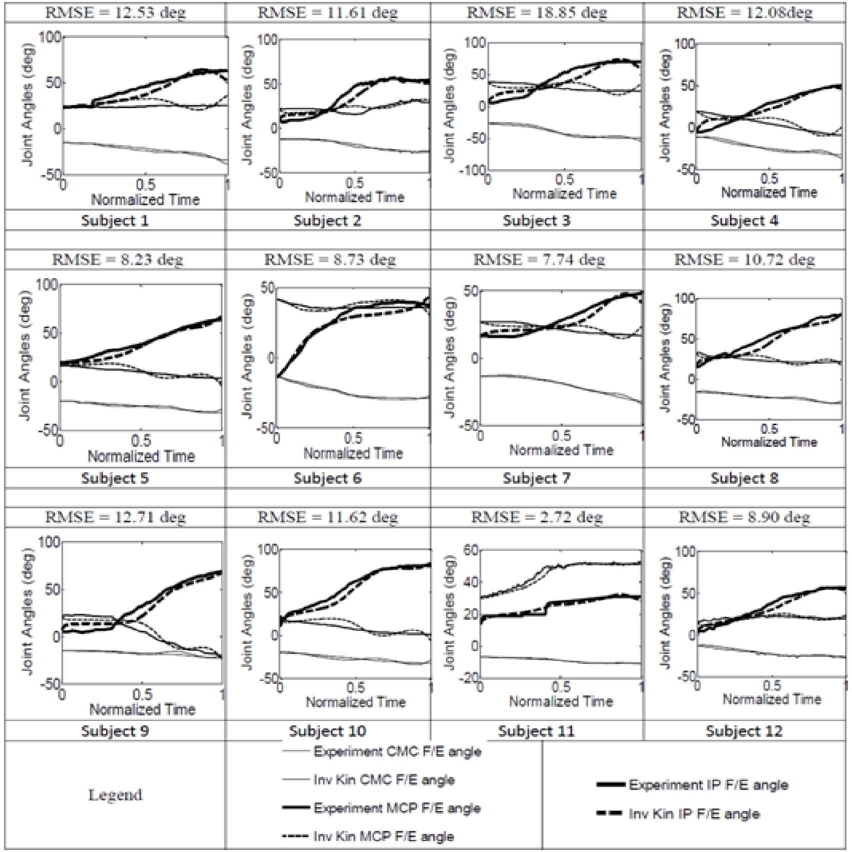
- **Comparison of the Joint angle trajectories of the index finger**
- **Best match is for Subject 5 (RMSE = 2.18 deg)**
- **Worst match is for Subject 3 (RMSE = 7.37 deg)**

Results



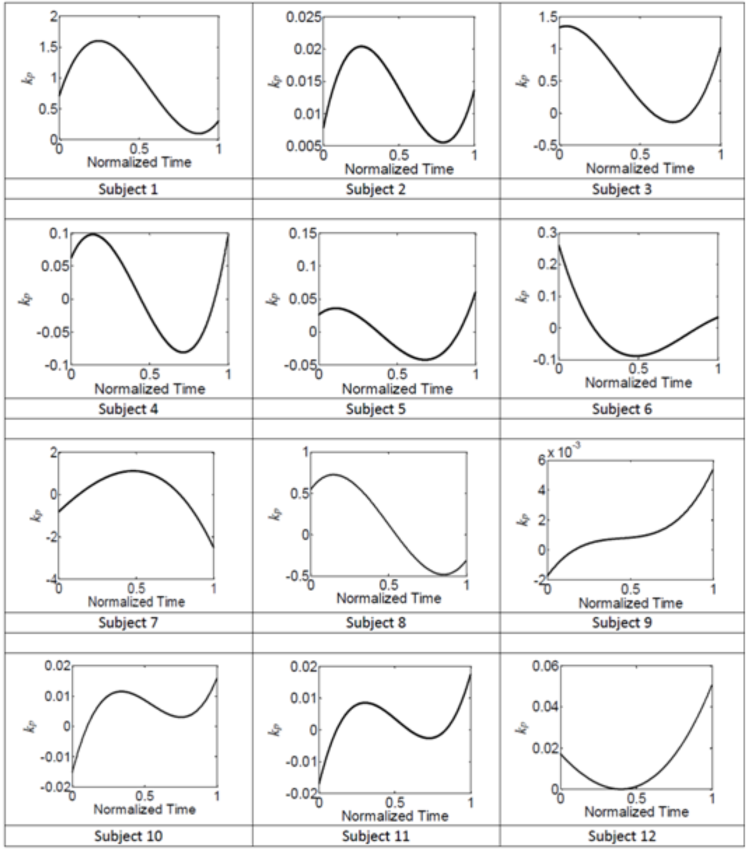
- Comparison of the Joint angle trajectories of the middle finger
- Best match is for Subject 12 (RMSE = 2.46 deg)
- Worst match is for Subject 1 (RMSE = 7.14 deg)

Results



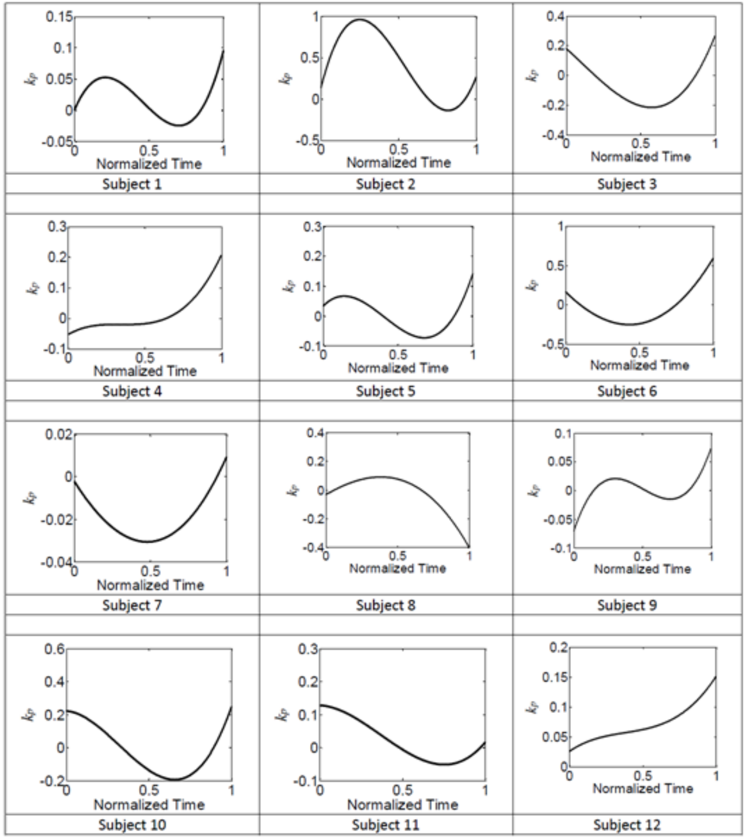
- **Comparison of the Joint angle trajectories of the thumb**
- **Best match is for Subject 11 (RMSE = 2.72 deg)**
- **Worst match is for Subject 3 (RMSE = 18.85 deg)**

Results



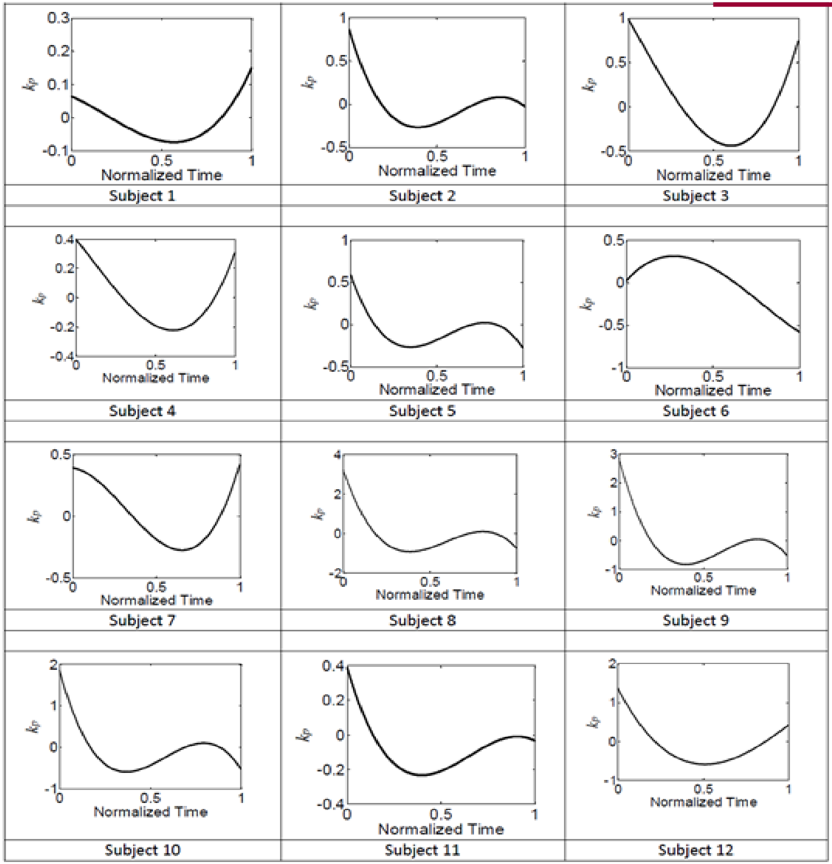
- **Optimal trajectory for *kp*(t) obtained for the kinematic model of the <u>index finger</u>**
- **A cubic polynomial for *kp*(t) permits a maximum of three roots – a single hill and a valley**
- **Out of 12 cases, 8 are with both hills and valleys present**
- **2 cases have a single valley**
- **In one case each, there is a hill and an inflexion point**

Results



- **Optimal trajectory for *kp*(t) obtained for the kinematic model of the <u>middle finger</u>**
- **4 cases with hills and valleys**
- **5 cases with only valleys**
- **2 with an inflexion point and 1 with a single hill.**

Results



- Optimal trajectory for *kp*(t) obtained for the kinematic model of the thumb
- 6 profiles with hills and valleys
- 5 with only valleys
- 1 with a single hill.

Inference

- **For a digit, no two profiles are close to identical.**

- **Even when the shapes are similar, the magnitudes are different.**

- **Except in only 4 of the 36 cases (11.11%), *kp*(t) attains negative values in all others.**

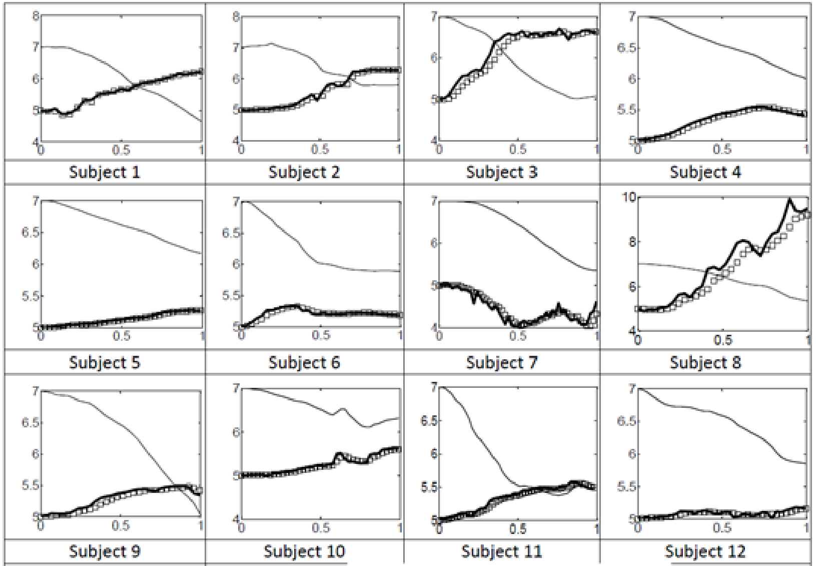
Results

Variation of RMSE in joint angles for all three digits

	Index Finger		*Middle Finger*		3 *dof* thumb model	
Subject	Optimized *kp*	*kp* = 0	Optimized *kp*	*kp* = 0	Optimized *kp*	*kp* = 0
1	6.54	10.86	7.14	8.15	12.53	27.97
2	6.32	7.40	5.00	6.44	11.61	40.34
3	7.37	8.76	6.62	10.16	18.85	71.18
4	3.67	8.92	2.59	5.71	12.08	76.29
5	2.18	3.63	2.87	5.58	8.23	35.83
6	4.01	14.23	4.62	10.12	8.73	63.65
7	4.27	4.70	2.62	3.77	7.74	25.27
8	6.88	16.21	5.94	8.00	10.72	60.53
9	7.12	7.20	4.18	4.97	12.71	71.76
10	3.38	3.72	3.38	13.38	11.62	77.98
11	3.41	3.58	5.06	5.20	3.50	5.41
12	4.04	4.13	2.46	3.40	8.90	44.69

- **Optimized *kp* minimizes the RMSE significantly compared to *kp* = 0**
- ***Maximum discrepancy*: Index Finger (subject 6) : 10.22 deg**
  Middle Finger (subject 10) : 10.00 deg
  Thumb (subject 10) : 66.36 deg

Results



Legend	Experimental Manipulability Inverse Kinematics Manipulability Distance Travelled
X label	Normalized Time
Y label	$1\dfrac{M^H}{M_0^H} - 4,\ 1\dfrac{M}{M_0} - 4,\ 1\dfrac{D}{D_0} + 3$

Variation of the manipulability measure for the <u>index finger</u>

- ***<u>General Trend</u>*: The individual manipulability measures increase**

- **Manipulability measure increases:**

  Subjects 3, 9,11

- **Manipulability measure increases then decreases:**

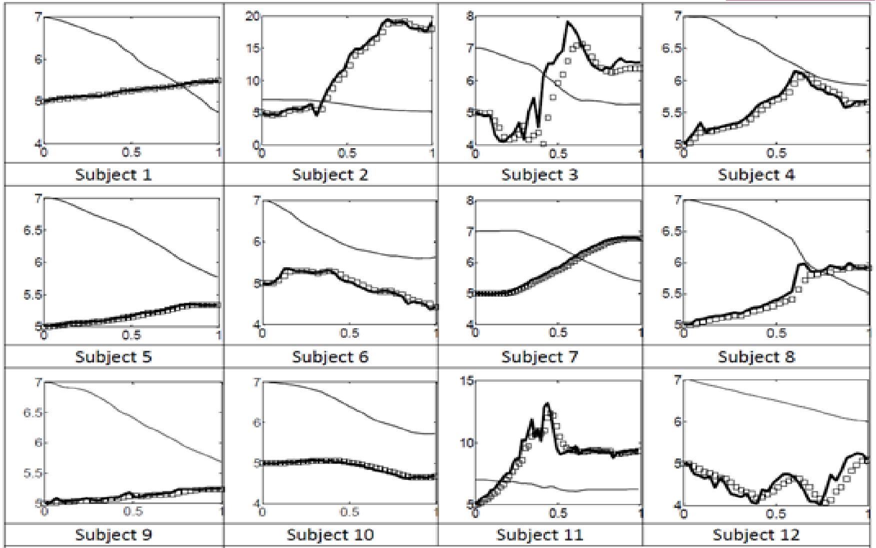
  Subjects 4, 6

- **Marginal increase in Manipulability measure:**

  Subjects 5, 10

- ***Subject 12* remains almost unaltered**

Results



Legend	Experimental Manipulability Inverse Kinematics Manipulability Distance Travelled
X label	Normalized Time
Y label	$1\frac{M^H}{M_0^H} - 4, 1\frac{M}{M_0} - 4, 1\frac{D}{D_0} + 3$

Variation of the manipulability measure for the <u>middle finger</u>

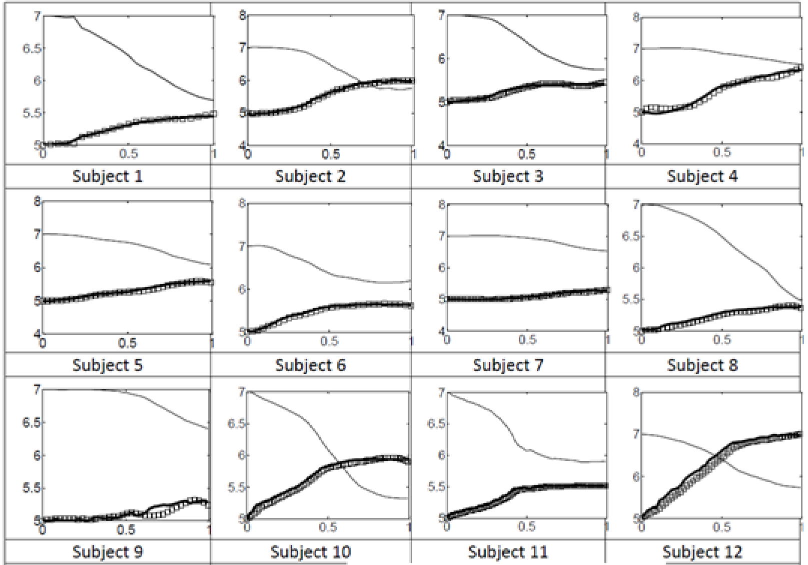
- ***<u>General Trend</u>*: The individual Manipulability measures increase**
- **Manipulability measure increases:**

  Subjects 7, 8
- **Manipulability measure increases then decreases:**

  Subjects 2, 4, 6, 11
- **Marginal increase in Manipulability measure:**

  Subjects 1, 5

Results



Legend	Experimental Manipulability Inverse Kinematics Manipulability Distance Travelled
X label	Normalized Time
Y label	$1\frac{M^H}{M_0^H} - 4,1\frac{M}{M_0} - 4,1\frac{D}{D_0} + 3$

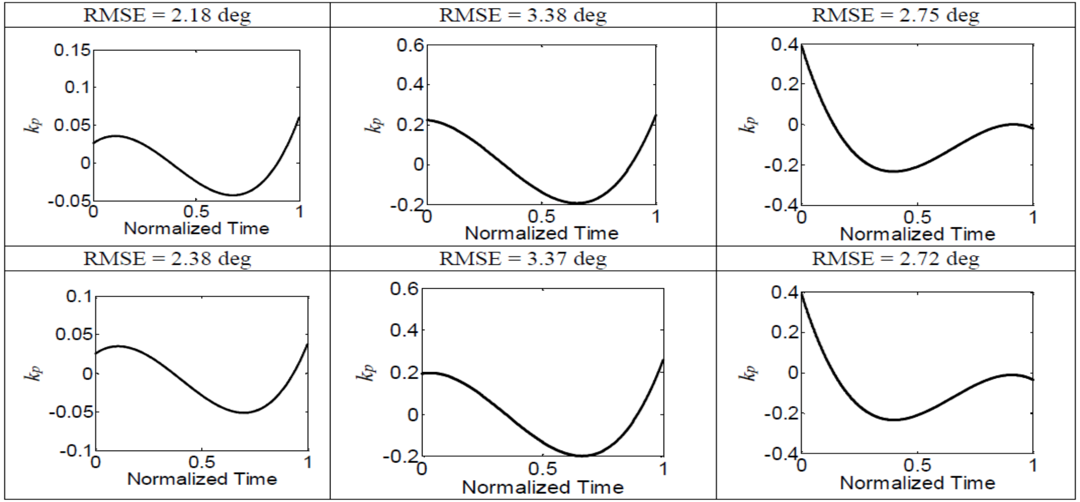
Variation of the manipulability measure for the thumb

- ***General Trend***: **The individual manipulability measures increase**
- **Manipulability measure increases:** ***Subjects 4, 10, 12***
- **Marginal increase in Manipulability measure:** ***Subjects 1, 3, 7, 8, 9***
- **Out of 36 cases, 33 (91%) – increase in manipulability measure**

<u>Repeatability and Global Optimality of *kp*(t)</u>

- To determine the uniqueness of *kp*(t), optimization was performed again for three cases – one for each finger

- Cubic dependence of *kp*(t), filtered experimental data and computational effort (100, 000 RMSE evaluations) are retained

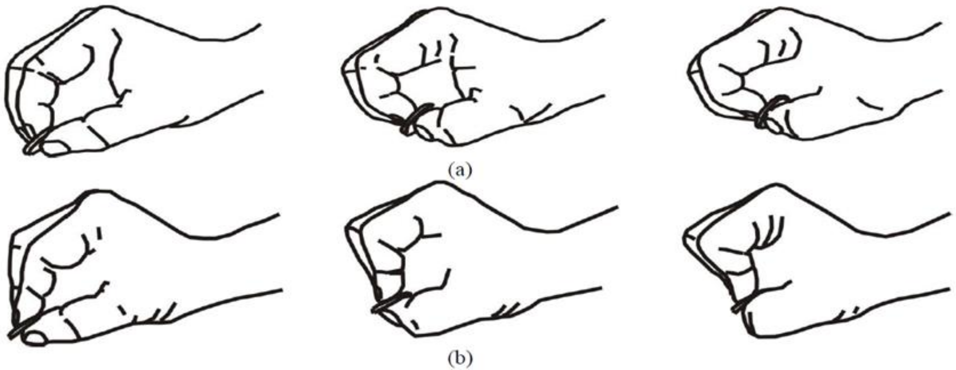


Two possibilities exist when translating a small object

- If the MCP and PIP joints are fixed, the depicted two cases represent two different solutions for the respective DIP joints, similar to the parallelogram solutions offered by a 2 DOF planar manipulator

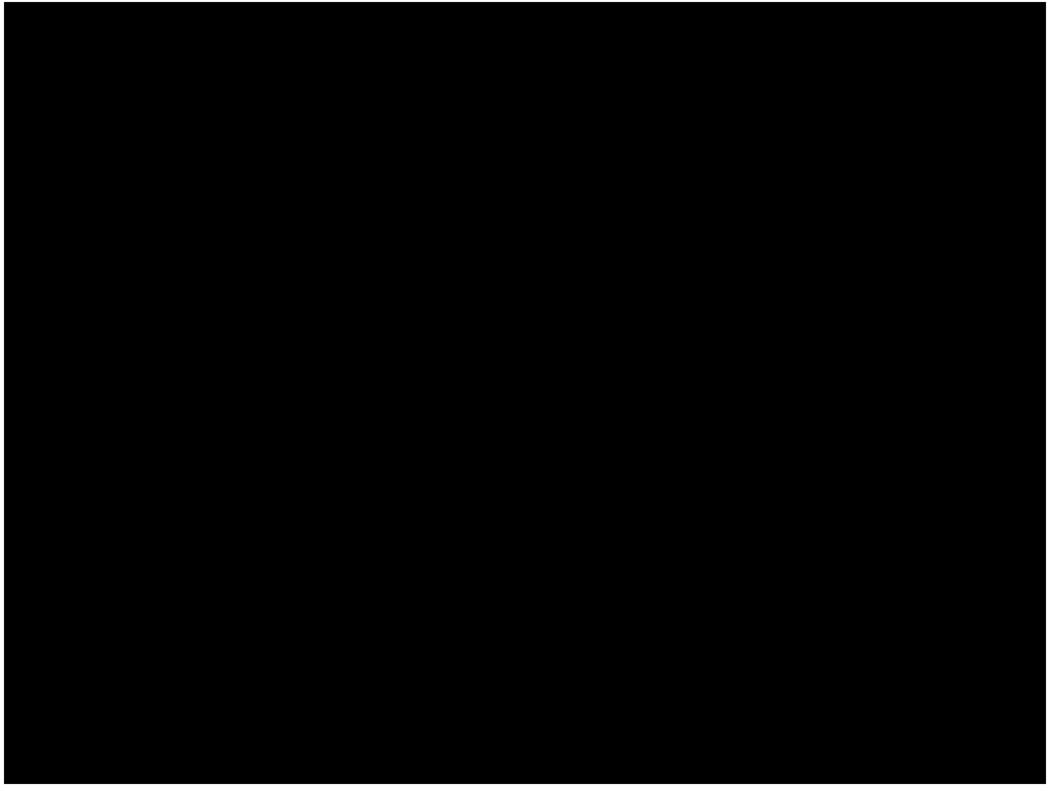
- Some humans may subconsciously prefer one way of translating an object over the other

- Further investigation is needed to determine the more preferred posture

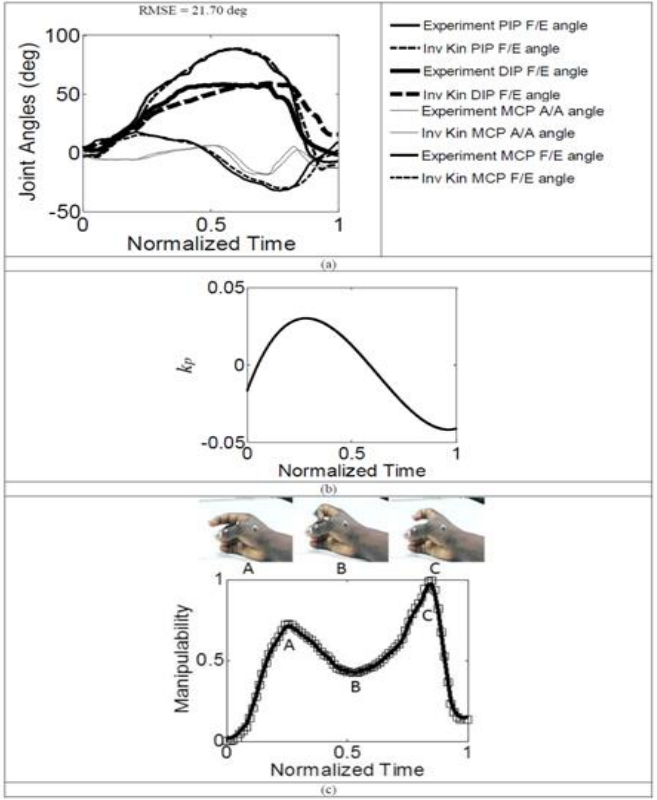


Two possibilities exist when translating a small object

Free Finger Motion



Manipulability and finger configuration



Free Finger Motion Example

- Match between the joint angles of the experimental & the kinematic model of index finger; RMSE value.
- kp(t); Assumes varying values to adjust the instantaneous redundancy contribution of the finger.
- The maxima & minima of the manipulability depends on instantaneous finger configuration – confirming Yoshikawa's observation.
- Here as well, the humans vary redundancy parameter – both sign & magnitude

Assumptions and Limitations

- The findings and observations are based on 3D motion capture system's experimental data $\rightarrow$ marker placement & data filtering errors

- The task motion was performed in two seconds. In normal life, manipulations are performed much faster.

- Only kinematics is considered in this study

- Tip-pinch grasp was used in the kinematic model determination, though in reality, finger pads also participate

- Intersecting and orthogonal joint axes of rotation of the digit models; 3 DOF of thumb

- To determine kp(t) accurately, choosing its approximate polynomial dependence on instantaneous finger configuration is essential.

Summary

- Studied the motion data from 12 subjects who performed cooperative translation of an object by flexing their three digits

- Using Yoshikawa's model (1990), we confirm that humans employ the manipulability based redundancy as a secondary task to accomplish the primary kinematic task

- However, to accurately capture the human joint trajectories, given the tip path and the initial configuration, the redundancy parameter needs to vary with the intermediate configurations

- We observe that this adjusting term exhibits varying behavior across humans, both in magnitude and sign, and not much commonality exists between the redundancy parameters of respective fingers of different subjects

- This work aims to provide a partial but crucial knowledge base in finger motion that would assist in the design & development of finger exoskeletons in future.

Thank You!