IIT ROORKEE

NPTEL ONLINE CERTIFICATION COURSE

Design and Development of a Three Finger Exoskeleton

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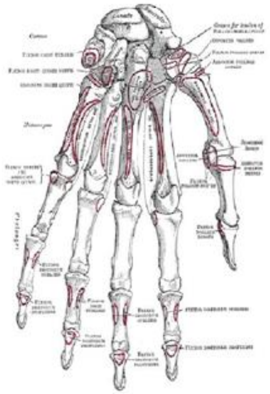
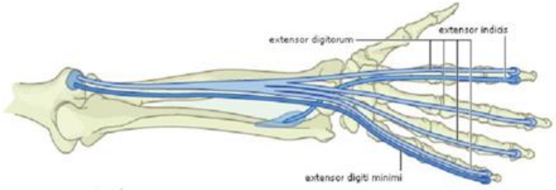
   - **Three Position Analytical Motion Synthesis of a 4-bar mechanism**
   - **Optimal 4-bar mechanism**
   - **Redundancy Resolution**
3. **Resolving Redundancy in Object Translation Task**

Introduction

Objective

- Understanding of human finger physiology.
- Optimal design of a three finger exoskeleton.

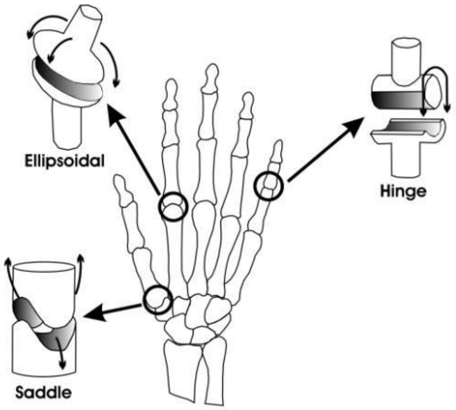




Motivation – Accomplishment

- Optimal design of a Three-finger Exoskeleton to track the human finger motion accurately – assistive and rehabilitation purposes.
- Human finger joint **cannot be modeled by a single revolute joint** – changing instantaneous center of rotation.
- Hence, **4-bar mechanism** based finger exoskeleton is designed optimally.
- The kinematic model of the designed exoskeleton is made and the exoskeleton is fabricated.
- Redundancy Resolution of the designed exoskeleton.

Methods



Human Finger Joints

Index Finger Exoskeleton – 3 DOF

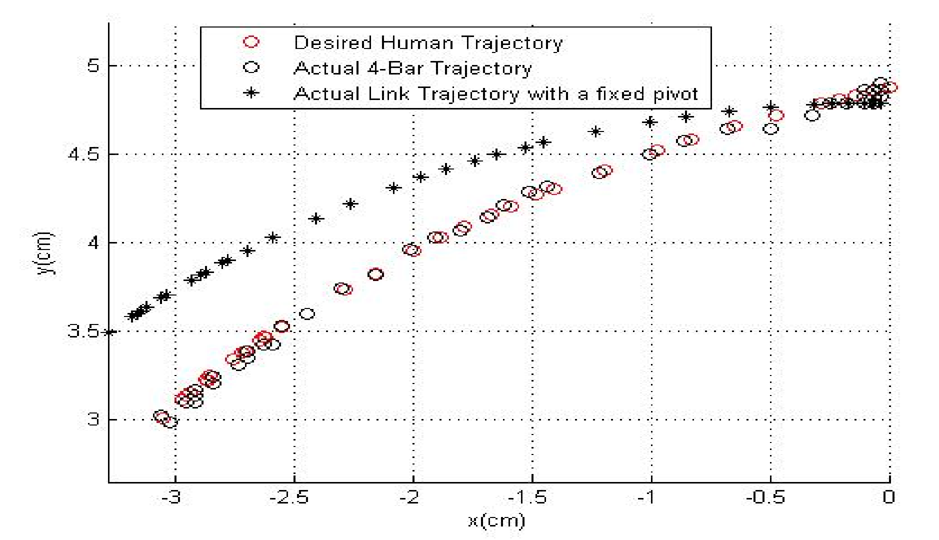
Middle Finger Exoskeleton – 3 DOF

Thumb Exoskeleton – A/A DOF

Thumb Exoskeleton – F/E DOF

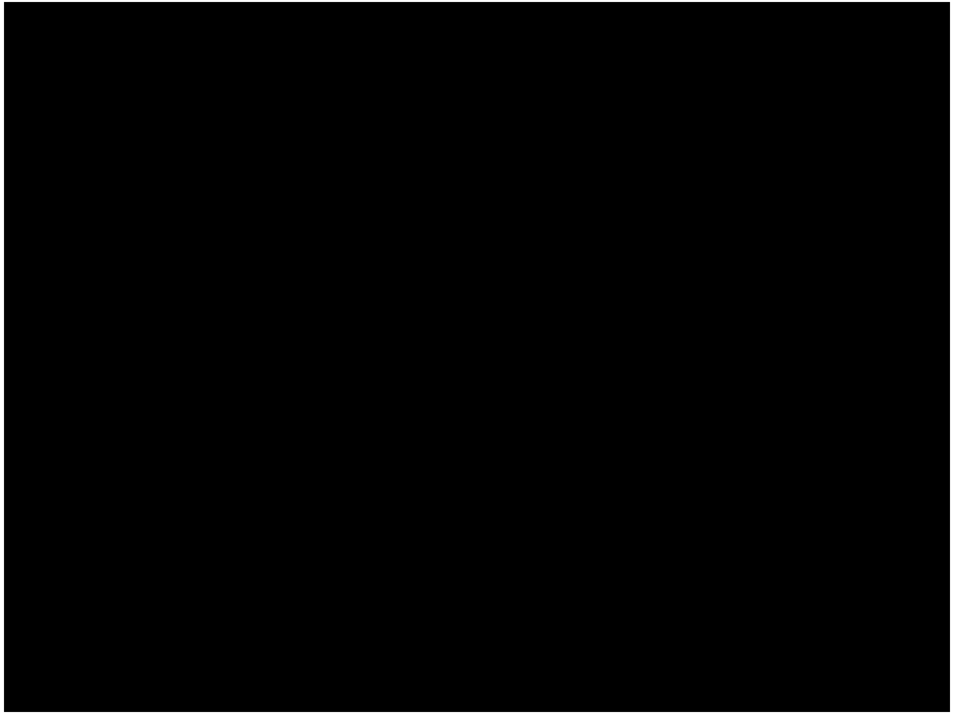
Methods (cont’d)

Comparison of the trajectories of 4-bar mechanism & revolute joint link with that of the human finger



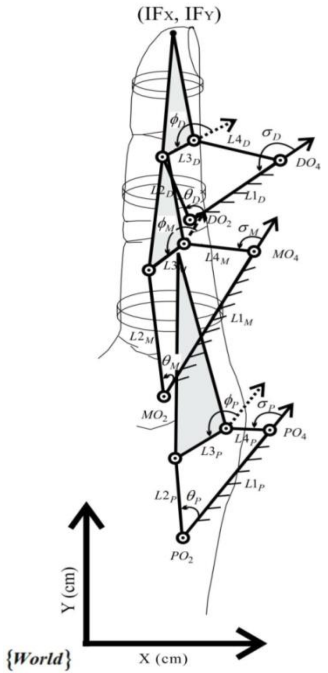
Methods (cont'd)

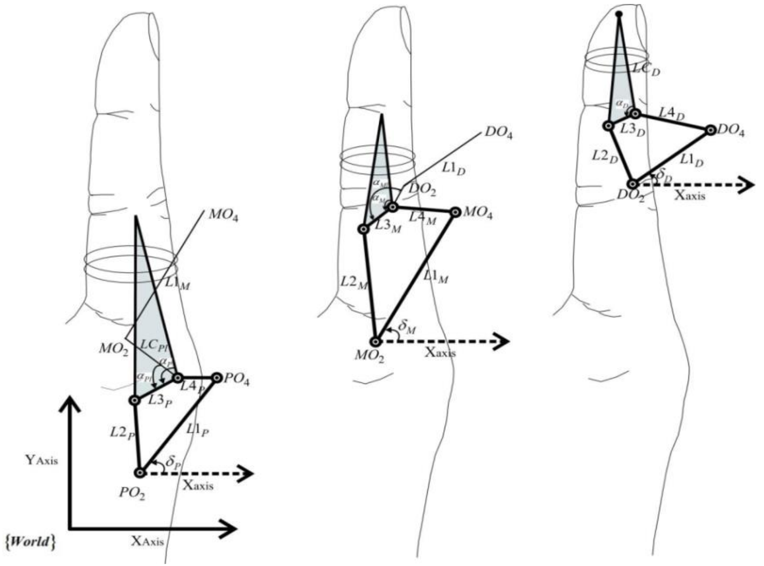
Human subject's finger motion capture using a vision system



Methods (cont'd)

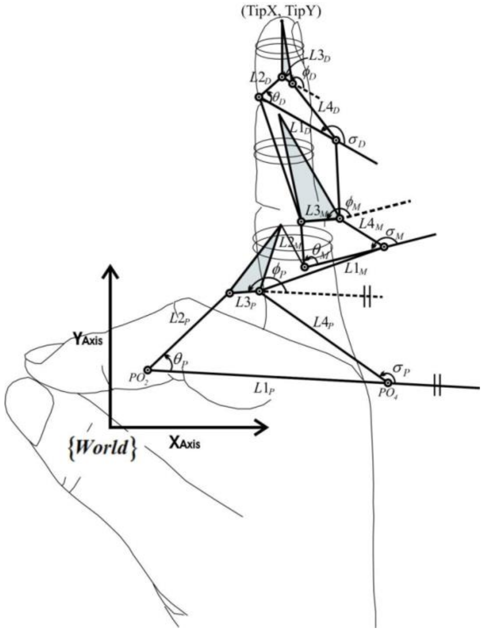
Human subject's finger motion capture using a vision system

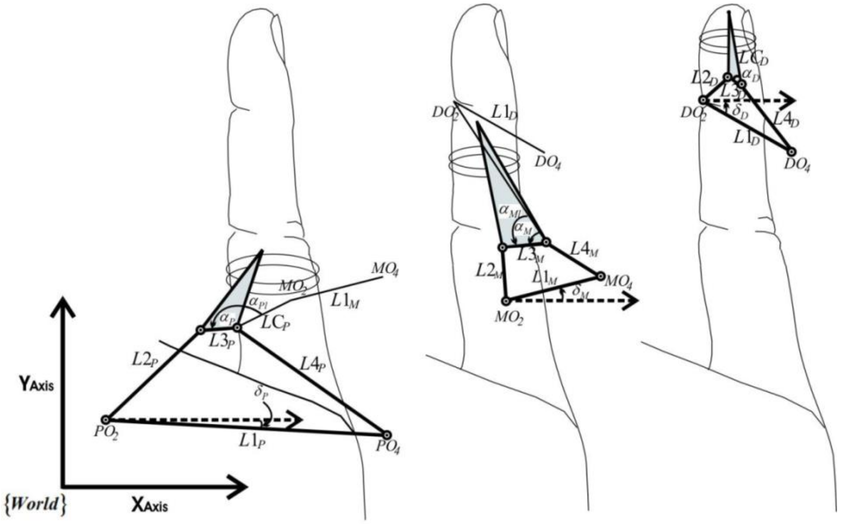




Methods (cont’d)

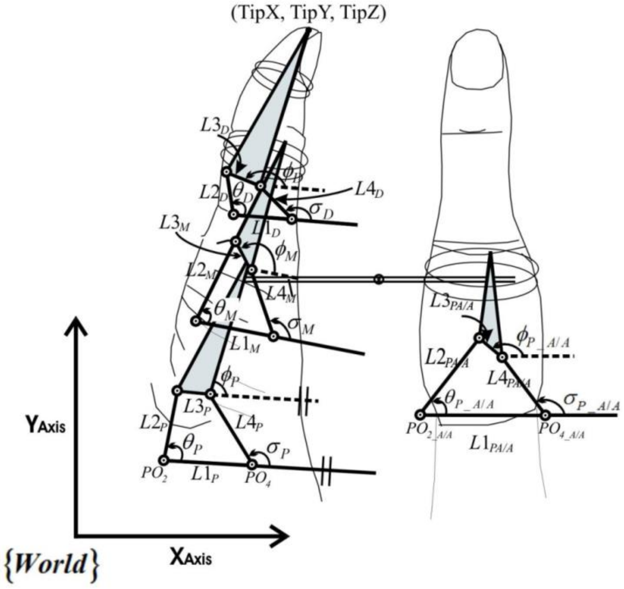
Human subject’s finger motion capture using a vision system

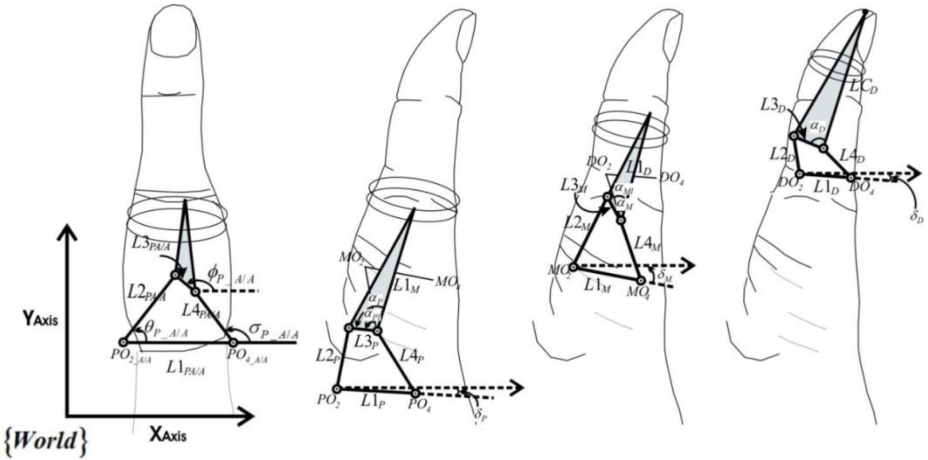




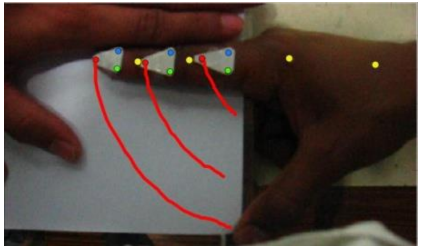
Methods (cont'd)

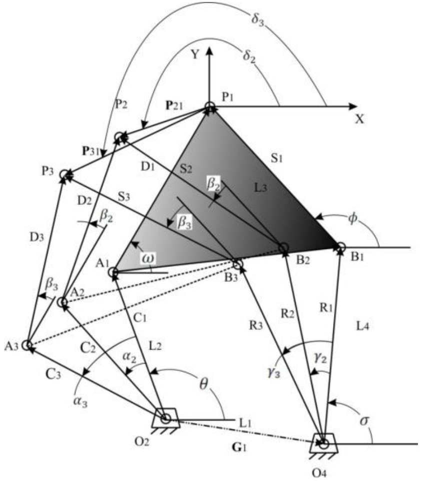
Human subject's finger motion capture using a vision system





Three position analytical motion synthesis of a four bar mechanism





$$V_1 = D_1 - S_1 \tag{1}$$

$$G_1 = C_1 + V_1 - R_1 \tag{2}$$

$$C_2 + D_2 - P_{21} - D_1 - C_1 = 0 \tag{3}$$

$$C_3 + D_3 - P_{31} - D_1 - C_1 = 0 \tag{4}$$

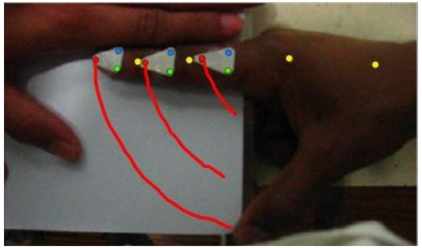
$$ce^{(i(\theta+\alpha_2))} + de^{(i(\omega+\beta_2))} - p_{21}e^{(i\delta_2)} - se^{(i\omega)} - ce^{(i\theta)} = 0 \tag{5}$$

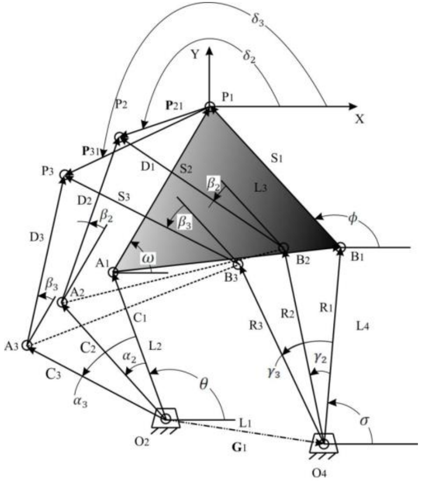
$$ce^{(i(\theta+\alpha_3))} + de^{(i(\omega+\beta_3))} - p_{31}e^{(i\delta_3)} - se^{(i\omega)} - ce^{(i\theta)} = 0 \tag{6}$$

$$ce^{i\theta}(e^{i\alpha_2} - 1) + de^{i\omega}(e^{i\beta_2} - 1) = p_{21}e^{i\delta_2} \tag{7}$$

$$ce^{i\theta}(e^{i\alpha_3} - 1) + de^{i\omega}(e^{i\beta_3} - 1) = p_{31}e^{i\delta_3} \tag{8}$$

Three position analytical motion synthesis of a four bar mechanism





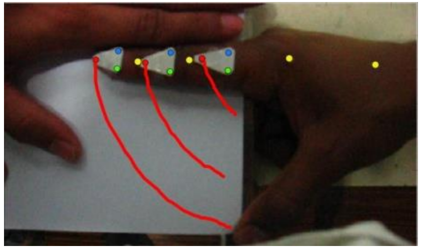
$$c\ cos\theta(cos\alpha_2 - 1) - c\ sin\theta sin\alpha_2 + d\ cos\omega(cos\beta_2 - 1) \\ -d\ sin\omega sin\beta_2 = p_{21}cos(\delta_2) \tag{9}$$

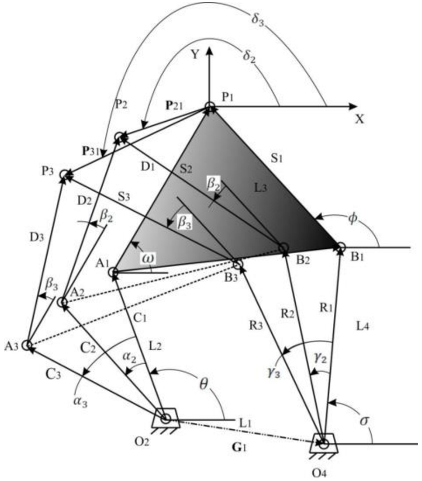
$$c\ cos\theta(cos\alpha_3 - 1) - c\ sin\theta sin\alpha_3 + d\ cos\omega(cos\beta_3 - 1) \\ -d\ sin\omega sin\beta_3 = p_{31}cos(\delta_3) \tag{10}$$

$$c\ sin\theta(cos\alpha_2 - 1) + c\ cos\theta sin\alpha_2 + d\ sin\omega(cos\beta_2 - 1) \\ +d\ cos\omega sin\beta_2 = p_{21}sin(\delta_2) \tag{11}$$

$$c\ sin\theta(cos\alpha_3 - 1) + c\ cos\theta sin\alpha_3 + d\ sin\omega(cos\beta_3 - 1) \\ +d\ cos\omega sin\beta_3 = p_{31}sin(\delta_3) \tag{12}$$

Three position analytical motion synthesis of a four bar mechanism





Twelve Variables:

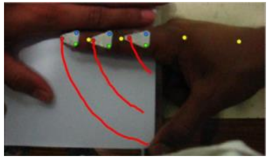
c, θ, α_2, α_3, d, ω, β_2, β_3, P_{21}, P_{31}, δ_2 and δ_3.

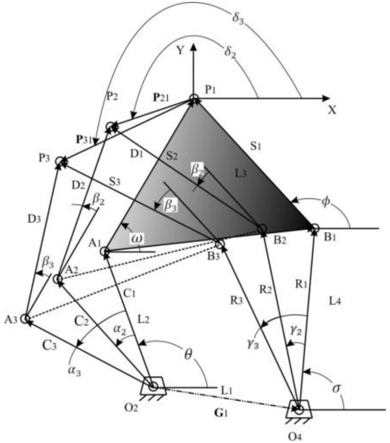
To Solve for:

the magnitudes (c, d) and angles (θ, ω)

of the vectors C and D.

Three position analytical motion synthesis of a four bar mechanism





$$\begin{bmatrix} M_L & -N_L & O_L & -Q_L \\ H_L & -I_L & J_L & -K_L \\ N_L & M_L & Q_L & O_L \\ I_L & H_L & K_L & J_L \end{bmatrix} \begin{bmatrix} C_{1x} \\ C_{1y} \\ D_{1x} \\ D_{1y} \end{bmatrix} = \begin{bmatrix} F_L \\ L_L \\ U_L \\ W_L \end{bmatrix}$$

$M_L = \sin\alpha_2 - 1,\quad N_L = \sin\alpha_2,\quad O_L = \cos\beta_2 - 1,\quad Q_L = \sin\alpha_2,\quad F_L = p_{21}\cos\delta_2,$

$H_L = \cos\alpha_3 - 1,\quad I_L = \sin\alpha_3, \mathrm{J_L} = \cos\beta_3 - 1,\quad \mathrm{K_L} = \cos\beta_3,\quad L_L = p_{31}\cos\delta_3,\quad V_L =$

$p_{21}\sin\delta_2,\ W_L = p_{31}\sin\delta_3,\quad C_{1x} = c\ \cos\theta, C_{1y} = c\ \sin\theta,\ D_{1x} = d\ \cos\omega$ and $D_{1y} =$

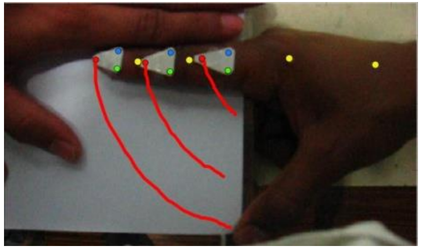
$d\ \sin\omega$

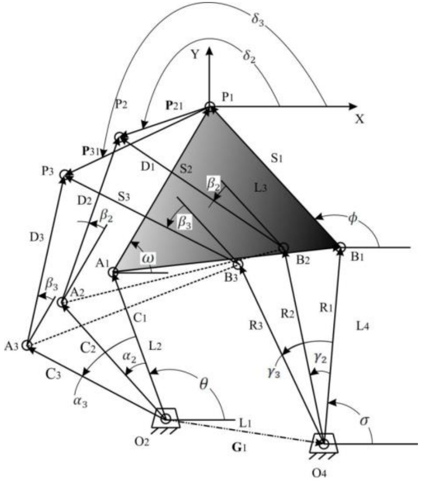
Magnitude and angles of the Left Dyad

$c = \sqrt{{C_{1x}}^2 + {C_{1y}}^2};\qquad \theta = \tan^{-1}(C_{1y}/C_{1x})\ ;$

$d = \sqrt{{D_{1x}}^2 + {D_{1y}}^2}\ ;\qquad \omega = \tan^{-1}(D_{1y}/D_{1x})\ ;$

Three position analytical motion synthesis of a four bar mechanism





$$\begin{bmatrix} M_R & -N_R & O_R & -Q_R \\ H_R & -I_R & J_R & -K_R \\ N_R & M_R & Q_R & O_R \\ I_R & H_R & K_R & J_R \end{bmatrix} \begin{bmatrix} R_{1x} \\ R_{1y} \\ S_{1x} \\ S_{1y} \end{bmatrix} = \begin{bmatrix} F_R \\ L_R \\ U_R \\ W_R \end{bmatrix}$$

where $M_R = \cos\gamma_2 - 1$, $N_R = \sin\gamma_2$, $O_R = \cos\beta_2 - 1$, $Q_R = \sin\beta_2$, $F_R = p_{21}\cos\delta_2$, $H_R = \cos\gamma_3 - 1$, $I_R = \sin\gamma_3$, $J_R = \cos\beta_3 - 1$, $K_R = \sin\beta_3$, $L_R = p_{31}\cos\delta_3$, $U_R = p_{21}\sin\delta_2$ and $W_R = p_{31}\sin\delta_3$.

Magnitude and angles of the Right Dyad

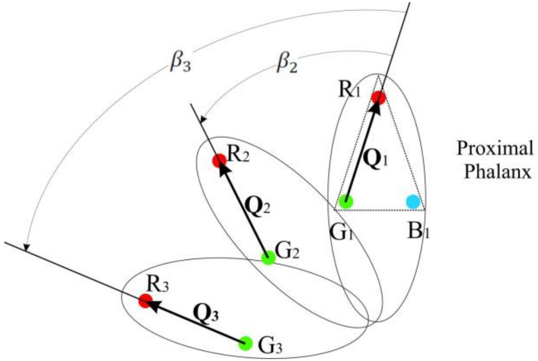
$$r = \sqrt{{R_{1x}}^2 + {R_{1y}}^2}\ ; \qquad \sigma = \tan^{-1}(R_{1y}/R_{1x})\ ;$$

$$s = \sqrt{{S_{1x}}^2 + {S_{1y}}^2}\ ; \qquad \phi = \tan^{-1}(S_{1y}/S_{1x})\ ;$$

Three position analytical motion synthesis of a four bar mechanism

Thus, for the given fixed pivot positions, O_2 and O_4 and the eight parameters $\alpha_2, \alpha_3, \beta_2, \beta_3, \mathbf{P}_{21}, \mathbf{P}_{31}, \delta_2$ and δ_3, a 4-bar linkage mechanism is determined using three-position motion synthesis.

Computation of angles in the three position analytical motion synthesis of 4-bar linkage



$$\alpha_3 = 2\tan^{-1}\left(\frac{K_2 \pm \sqrt{{K_1}^2 + {K_2}^2 - {K_3}^2}}{(K_1 + K_3)}\right)$$

$$\alpha_2 = 2\tan^{-1}\left(\frac{A_5 \sin\beta_3 + A_3 \cos\beta_3 + A_6}{A_1}\right)$$

Computation of angles in the three position analytical motion synthesis of 4-bar linkage

where,

$$K_1 = A_2A_4 + A_3A_6$$

$$K_2 = A_3A_4 + A_5A_6$$

$$K_3 = \frac{A_1{}^2 - A_2{}^2 - A_3{}^2 - A_4{}^2 - A_6{}^2}{2}$$

$$A_1 = -C_3{}^2 - C_4{}^2$$

$$A_2 = C_3C_6 - C_4C_5$$

$$A_3 = -C_4C_6 - C_3C_5$$

$$A_4 = C_2C_3 + C_1C_4$$

$$A_5 = C_4C_5 - C_3C_6$$

$$A_6 = C_1C_3 - C_2C_4$$

$$C_1 = Z_3\cos(\beta_2 + \eta_3) - Z_2\cos(\beta_3 + \eta_2)$$

$$C_2 = Z_3\sin(\beta_2 + \eta_3) - Z_2\sin(\beta_3 + \eta_2)$$

$$C_3 = Z_1\cos(\beta_3 + \eta_1) - Z_3\cos(\eta_3)$$

$$C_4 = -Z_1\sin(\beta_3 + \eta_1) + Z_3\sin(\eta_3)$$

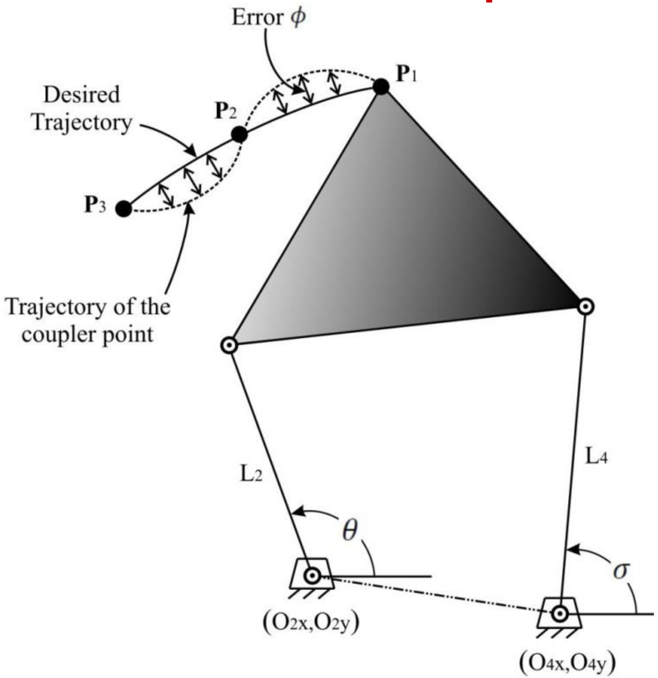
$$C_5 = Z_1\cos(\beta_2 + \eta_1) - Z_2\cos(\eta_2)$$

$$C_6 = -Z_1\sin(\beta_2 + \eta_1) + Z_2\sin(\eta_2)$$

Optimal Design of a Three Finger Hand Exoskeleton (cont'd)

Methods (cont'd)

Optimal four-bar mechanism



General Optimization Strategy:

A total of ten design variables such as

$$P_{1x}, P_{1y}, O_{2x}, O_{2y}, O_{4x}, O_{4y}, L_2, L_4, \theta \text{ and } \sigma$$

An alternative Optimization Strategy:

Four design variables such as

$$O_{2x}, O_{2y}, O_{4x} \text{ and } O_{4y}$$

Optimal four-bar mechanism

Objective Function

$$\phi = \sum_{i=1}^{n} d_i^2$$

where, $d_i = H(i) - F(i)$;

$H(i) = i^{th}$ path point of the Human data;

$F(i) = i^{th}$ path point of the 4-bar Coupler.

The procedural steps to get the optimal 4-bar are:

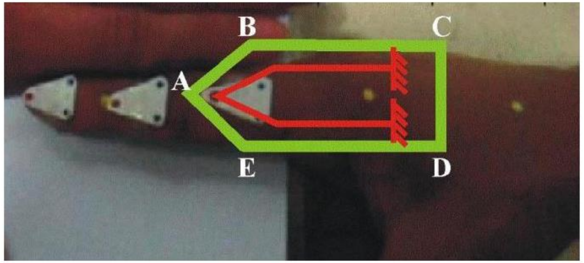
(i) Perform three-position motion generation by analytical synthesis using fixed pivot points (design variables) suggested by the optimization algorithm.

(ii) Evaluate the objective

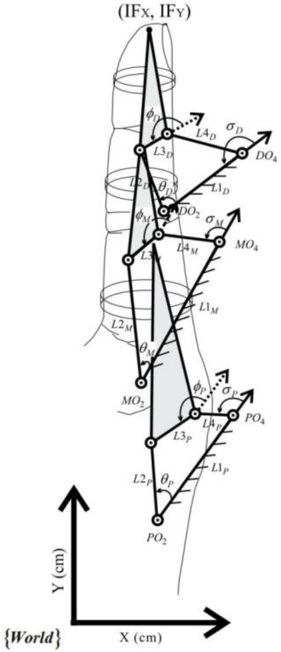
(iii) Constraint violation check.

(iv) Replace the previous design by a new one (obtained through stochastic mutation of the fixed pivot point positions).

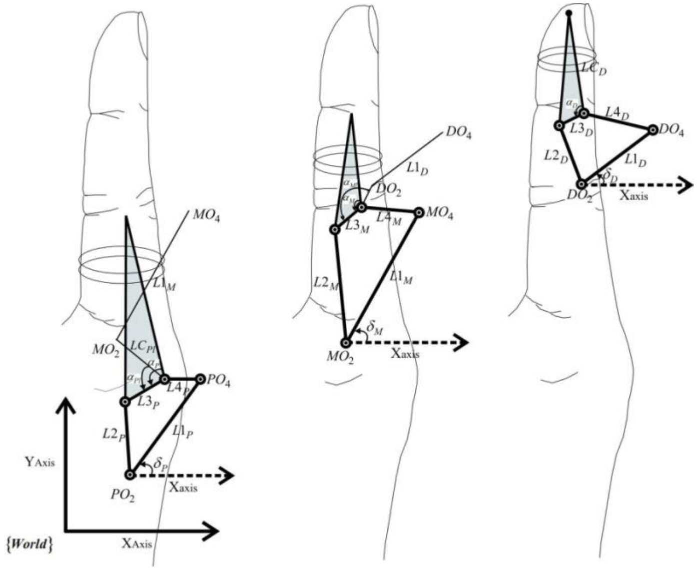
Constraint



Kinematic Model of the Index Finger Exoskeleton



(a) Serially connected 4-bars



(b) Proximal 4-bar (c) Middle 4-bar (d) Distal 4-bar

Kinematic Model of the Index Finger Exoskeleton (cont'd)

$$X_{IF} = \cos(\delta_M)\times(L1_M + L4_M\times\cos(\sigma_M) + LC_{Ml}\times\cos(\phi_M - \alpha_{Ml})) - \sin(\delta_M)\times(L4_M\times\sin(\sigma_M)$$

$$+LC_{Ml}\times\sin(\phi_M - \alpha_{Ml})) + \cos(\delta_P)\times(L1_P + L4_P\times\cos(\sigma_P) + LC_{Pl}\times\cos(\phi_P - \alpha_{Pl}))$$

$$-\sin(\delta_P)\times(L4_P\times\sin(\sigma_P) + LC_{Pl}\times\sin(\phi_P - \alpha_{Pl})) + \cos(\delta_D)\times(L1_D + L4_D\times\cos(\sigma_D)$$

$$+LC_D\times\cos(\phi_D - \alpha_D)) - \sin(\delta_D)\times(L4_D\times\sin(\sigma_D) + LC_D\times\sin(\phi_D - \alpha_D))$$

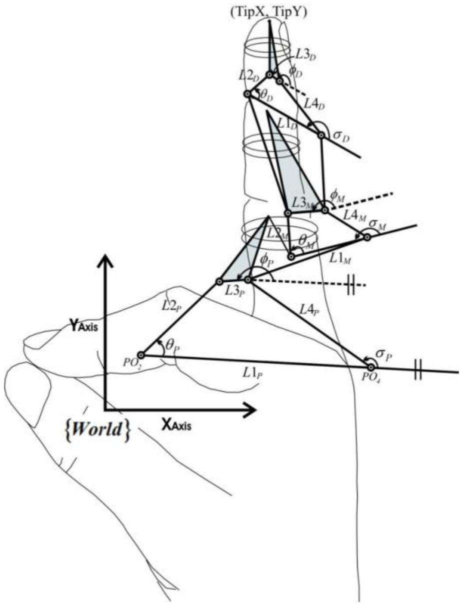
$$Y_{IF} = \sin(\delta_M)\times(L1_M + L4_M\times\cos(\sigma_M) + LC_{Ml}\times\cos(\phi_M - \alpha_{Ml})) + \cos(\delta_M)\times(L4_M\times\sin(\sigma_M)$$

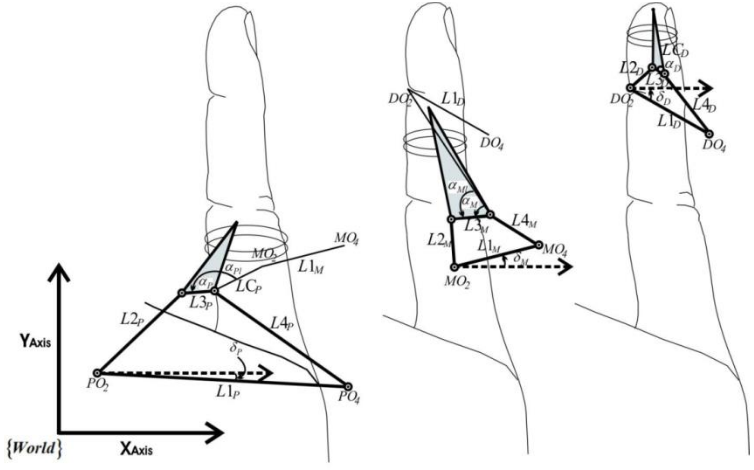
$$+LC_{Ml}\times\sin(\phi_M - \alpha_{Ml})) + \sin(\delta_P)\times(L1_P + L4_P\times\cos(\sigma_P) + LC_{Pl}\times\cos(\phi_P - \alpha_{Pl}))$$

$$+\cos(\delta_P)\times(L4_P\times\sin(\sigma_P) + LC_{Pl}\times\sin(\phi_P - \alpha_{Pl})) + \sin(\delta_D)\times(L1_D + L4_D\times\cos(\sigma_D)$$

$$+LC_D\times\cos(\phi_D - \alpha_D)) + \cos(\delta_D)\times(L4_D\times\sin(\sigma_D) + LC_D\times\sin(\phi_D - \alpha_D))$$

Kinematic Model of the Middle Finger Exoskeleton





(b) Proximal 4-bar (c) Middle 4-bar (d) Distal 4-bar

(a) Serially connected 4-bars

Kinematic Model of the Index Finger Exoskeleton (cont'd)

$$X_{MF} = \cos(\delta_M)\times(L1_M + L4_M\times\cos(\sigma_M) + LC_{Ml}\times\cos(\phi_M - \alpha_{Ml})) - \sin(\delta_M)\times(L4_M\times\sin(\sigma_M)$$

$$+LC_{Ml}\times\sin(\phi_M - \alpha_{Ml})) + \cos(\delta_P)\times(L1_P + L4_P\times\cos(\sigma_P) + LC_{Pl}\times\cos(\phi_P - \alpha_{Pl}))$$

$$-\sin(\delta_P)\times(L4_P\times\sin(\sigma_P) + LC_{Pl}\times\sin(\phi_P - \alpha_{Pl})) + \cos(\delta_D)\times(L1_D + L4_D\times\cos(\sigma_D)$$

$$+LC_D\times\cos(\phi_D - \alpha_D)) - \sin(\delta_D)\times(L4_D\times\sin(\sigma_D) + LC_D\times\sin(\phi_D - \alpha_D))$$

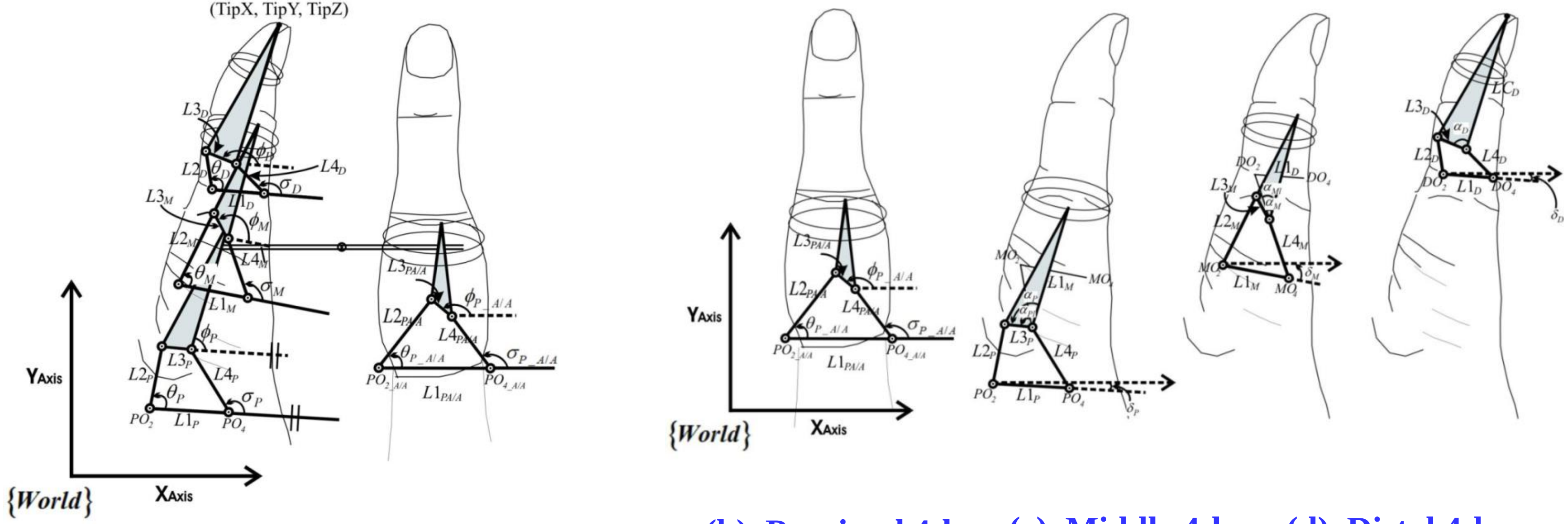
$$Y_{MF} = \sin(\delta_M)\times(L1_M + L4_M\times\cos(\sigma_M) + LC_{Ml}\times\cos(\phi_M - \alpha_{Ml})) + \cos(\delta_M)\times(L4_M\times\sin(\sigma_M)$$

$$+LC_{Ml}\times\sin(\phi_M - \alpha_{Ml})) + \sin(\delta_P)\times(L1_P + L4_P\times\cos(\sigma_P) + LC_{Pl}\times\cos(\phi_P - \alpha_{Pl}))$$

$$+\cos(\delta_P)\times(L4_P\times\sin(\sigma_P) + LC_{Pl}\times\sin(\phi_P - \alpha_{Pl})) + \sin(\delta_D)\times(L1_D + L4_D\times\cos(\sigma_D)$$

$$+LC_D\times\cos(\phi_D - \alpha_D)) + \cos(\delta_D)\times(L4_D\times\sin(\sigma_D) + LC_D\times\sin(\phi_D - \alpha_D))$$

Kinematic Model of the Thumb Finger Exoskeleton



(b) Proximal 4-bar (c) Middle 4-bar (d) Distal 4-bar

(a) Serially connected 4-bars

Kinematic Model of the Index Finger Exoskeleton (cont'd)

$$X_{Th} = -\sin(\phi_{P\_A/A})\times(\cos(\delta_M)\times(L1_M + L4_M\times\cos(\sigma_M) + LC_{Ml}\times\cos(\phi_M-\alpha_{Ml})) - \sin(\delta_M)\times(L4_M\times\sin(\sigma_M)$$

$$+LC_{Ml}\times\sin(\phi_M-\alpha_{Ml})) + \cos(\delta_P)\times(L1_P + L4_P\times\cos(\sigma_P) + LC_{Pl}\times\cos(\phi_P-\alpha_{Pl}))$$

$$-\sin(\delta_P)\times(L4_P\times\sin(\sigma_P) + LC_{Pl}\times\sin(\phi_P-\alpha_{Pl})) + \cos(\delta_D)\times(L1_D + L4_D\times\cos(\sigma_D)$$

$$+LC_D\times\cos(\phi_D-\alpha_D)) - \sin(\delta_D)\times(L4_D\times\sin(\sigma_D) + LC_D\times\sin(\phi_D-\alpha_D)))$$

$$Y_{Th} = \cos(\phi_{P\_A/A})\times(\sin(\delta_M)\times(L1_M + L4_M\times\cos(\sigma_M) + LC_{Ml}\times\cos(\phi_M-\alpha_{Ml})) + \cos(\delta_M)\times(L4_M\times\sin(\sigma_M)$$

$$+LC_{Ml}\times\sin(\phi_M-\alpha_{Ml})) + \sin(\delta_P)\times(L1_P + L4_P\times\cos(\sigma_P) + LC_{Pl}\times\cos(\phi_P-\alpha_{Pl}))$$

$$+\cos(\delta_P)\times(L4_P\times\sin(\sigma_P) + LC_{Pl}\times\sin(\phi_P-\alpha_{Pl})) + \sin(\delta_D)\times(L1_D + L4_D\times\cos(\sigma_D)$$

$$+LC_D\times\cos(\phi_D-\alpha_D)) + \cos(\delta_D)\times(L4_D\times\sin(\sigma_D) + LC_D\times\sin(\phi_D-\alpha_D)))$$

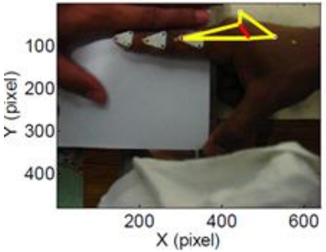
$$Z_{Th} = \cos(\delta_M)\times(L1_M + L4_M\times\cos(\sigma_M) + LC_{Ml}\times\cos(\phi_M-\alpha_{Ml})) - \sin(\delta_M)\times(L4_M\times\sin(\sigma_M)$$

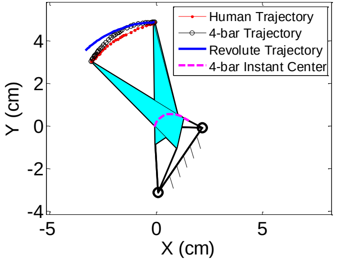
$$+LC_{Ml}\times\sin(\phi_M-\alpha_{Ml})) + \cos(\delta_P)\times(L1_P + L4_P\times\cos(\sigma_P) + LC_{Pl}\times\cos(\phi_P-\alpha_{Pl}))$$

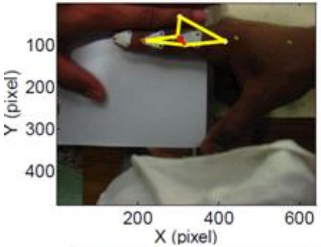
$$-\sin(\delta_P)\times(L4_P\times\sin(\sigma_P) + LC_{Pl}\times\sin(\phi_P-\alpha_{Pl})) + \cos(\delta_D)\times(L1_D + L4_D\times\cos(\sigma_D)$$

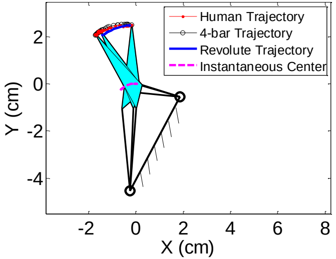
$$+LC_D\times\cos(\phi_D-\alpha_D)) - \sin(\delta_D)\times(L4_D\times\sin(\sigma_D) + LC_D\times\sin(\phi_D-\alpha_D))$$

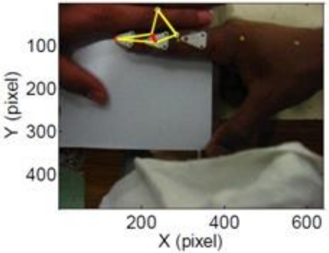
Optimal Index Finger Exoskeleton











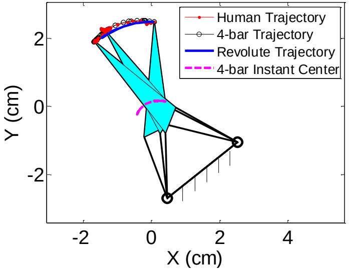
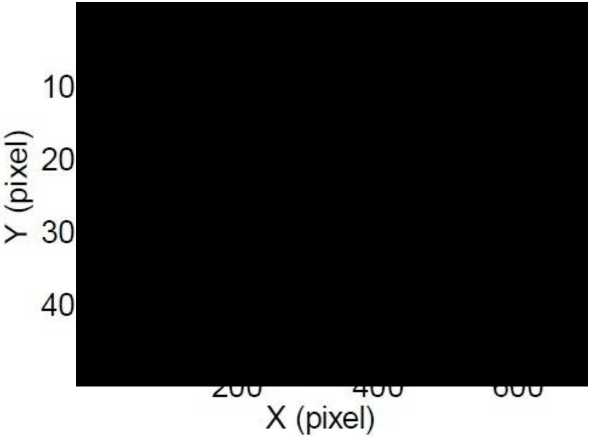


Table 1. Optimal Link length parameters for the Index Finger Exoskeleton

	L1i (cm)	L2i (cm)	L3i (cm)	L4i (cm)
Proximal 4-bar	3.65	2.25	1.44	1.00
Middle 4-bar	4.50	3.50	1.01	1.69
Distal 4-bar	2.64	1.92	0.80	2.09

L1i: L1P, L1M, L1D; L2i: L2P, L2M, L2D; L3i: L3P, L3M, L3D; L4i: L4P, L4M, L4D;



Optimal Middle Finger Exoskeleton

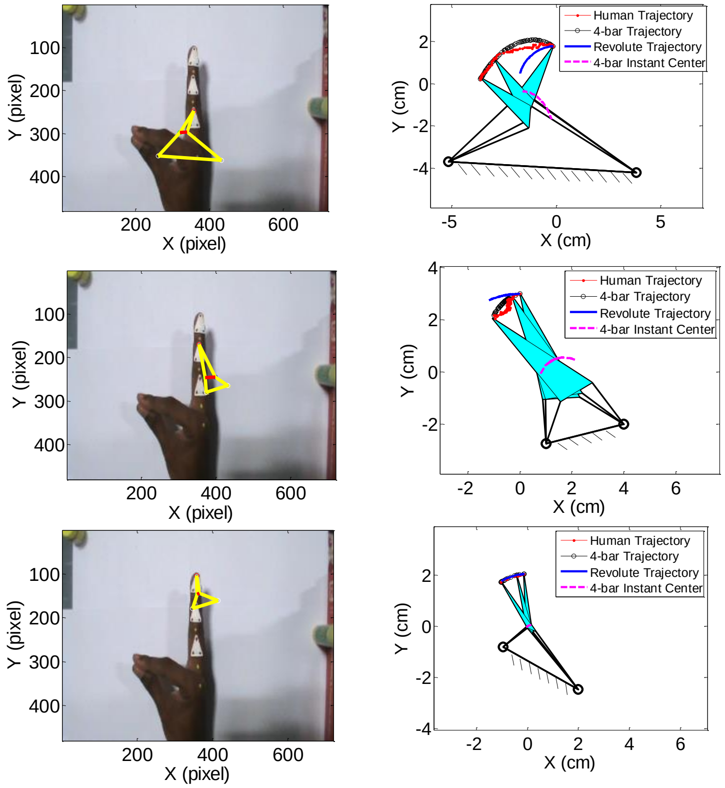
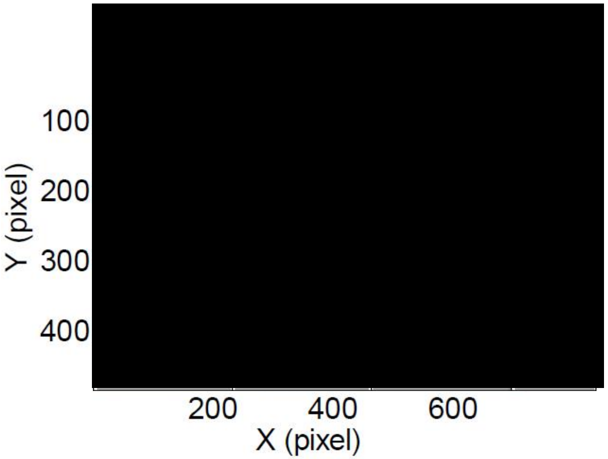


Table 2. Optimal Link length parameters for the Middle Finger Exoskeleton

	L1i (cm)	L2i (cm)	L3i (cm)	L4i (cm)
Proximal 4-bar	9.01	4.16	1.08	5.99
Middle 4-bar	3.09	1.71	1.42	2.00
Distal 4-bar	3.38	1.20	0.35	2.81

L1i: L1P, L1M, L1D; L2i: L2P, L2M, L2D; L3i: L3P, L3M, L3D; L4i: L4P, L4M, L4D;



Results(cont'd)

Optimal Thumb Exoskeleton

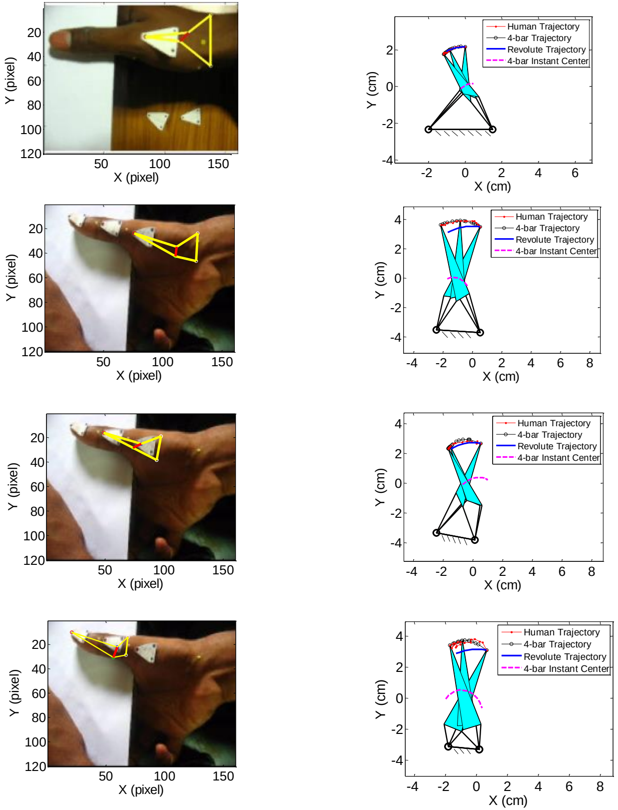
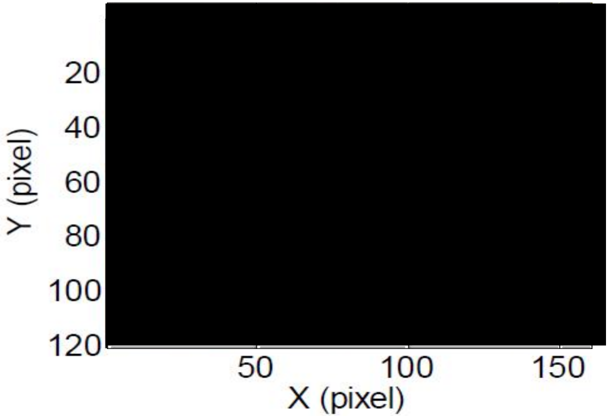


Table 3. Optimal Link length parameters for the Thumb Exoskeleton

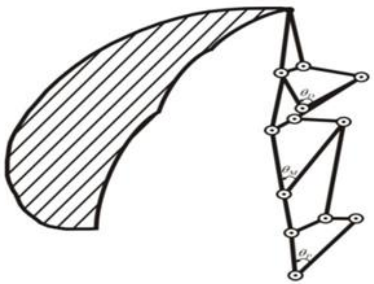
	L1i (cm)	L2i (cm)	L3i (cm)	L4i (cm)
Proximal A/A 4-bar	3.50	2.71	0.85	1.92
Proximal 4-bar	3.00	2.36	1.04	2.78
Middle 4-bar	2.64	3.00	1.05	2.36
Distal 4-bar	2.01	1.45	1.20	1.64

L1i: L1PA/A, L1P, L1M, L1D; L2i: L2PA/A, L2P, L2M, L2D;
L3i: L3PA/A, L3P, L3M, L3D; L4i: L4PA/A, L4P, L4M, L4D;

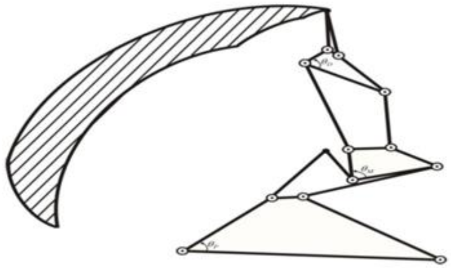


Work Volume of the Three Finger Exoskeleton

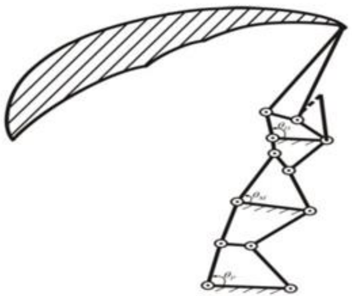
Index Finger Exoskeleton



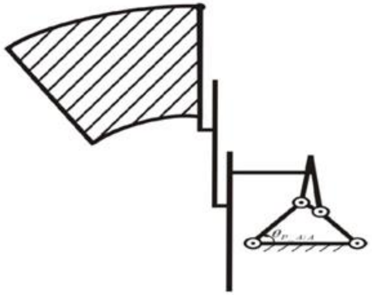
Middle Finger Exoskeleton



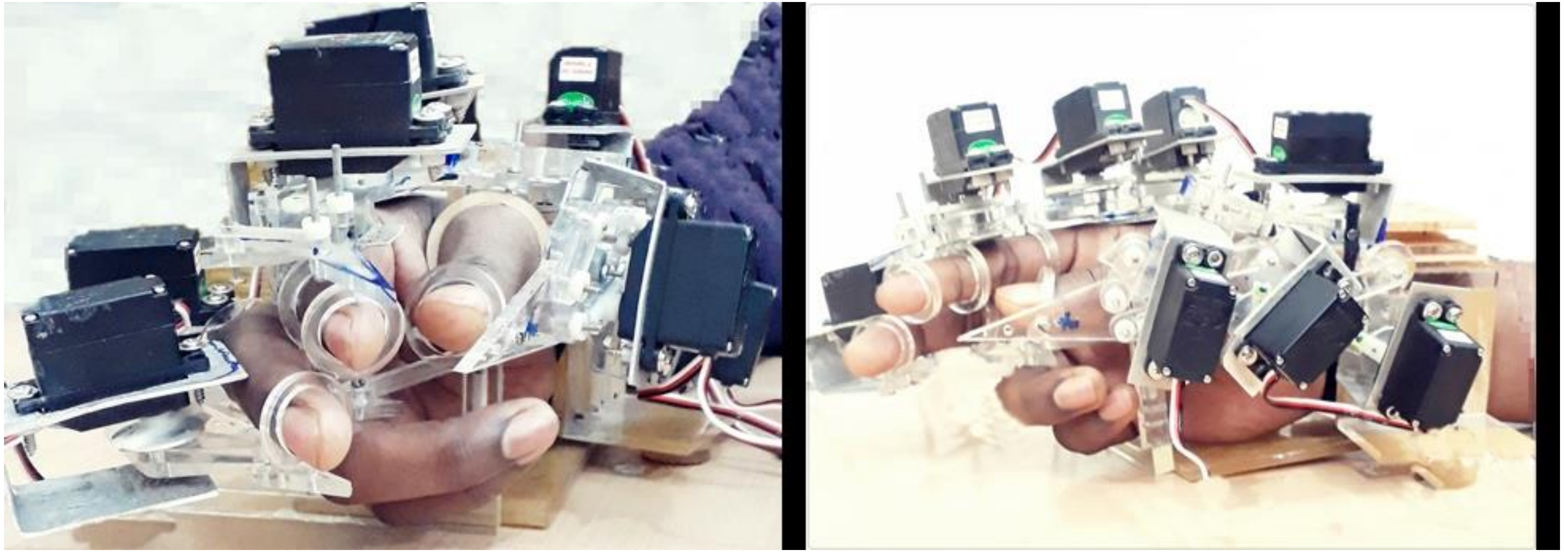
Thumb Exoskeleton Side -View



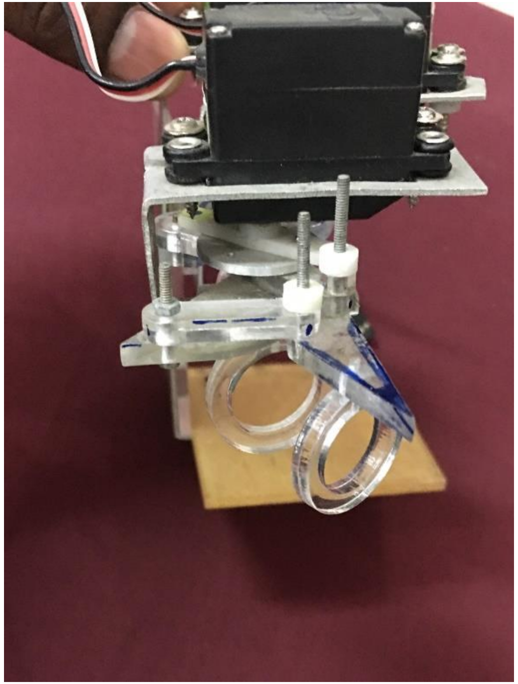
Thumb Exoskeleton Top -View

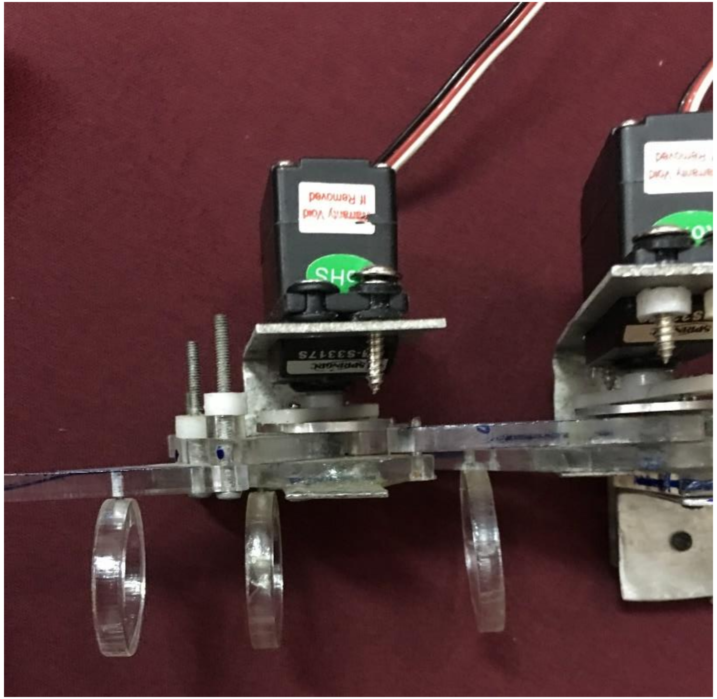


Rapid Prototype of the Three Finger Exoskeleton



Actuator Attachment





Thank You!