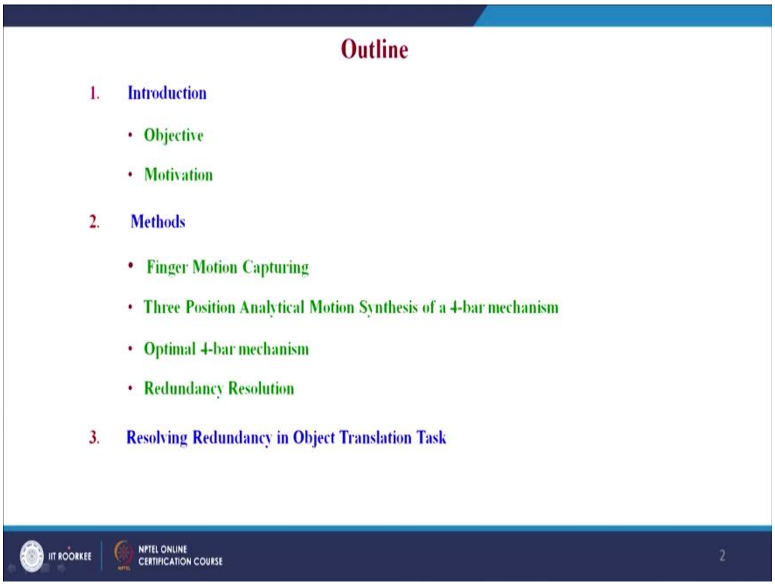
Robotics and Control: Theory and Practice

Prof. Felix Orlando
Department of Electrical Engineering
Indian Institute of Technology, Roorkee

Lecture - 27
Design and Development of a Three Finger Exoskeleton

Good afternoon, today the topic of my lecture will be on the design that is optimal Design and Development of a Three Finger Exoskeleton.

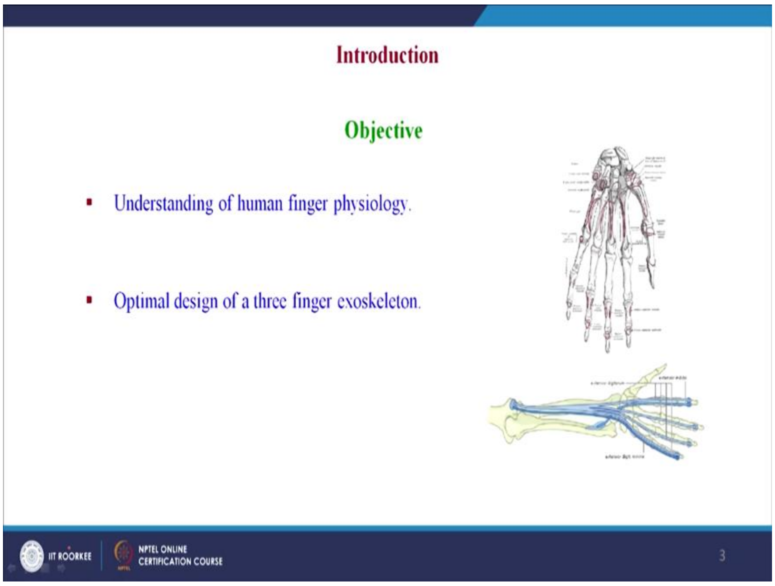
(Refer Slide Time: 00:37)



The organization of today's lecture will be as follows; first we have the introduction in that we will be seeing quickly the objective and the motivation of this work, and then the methods involved in designing the optimal and exoskeleton.

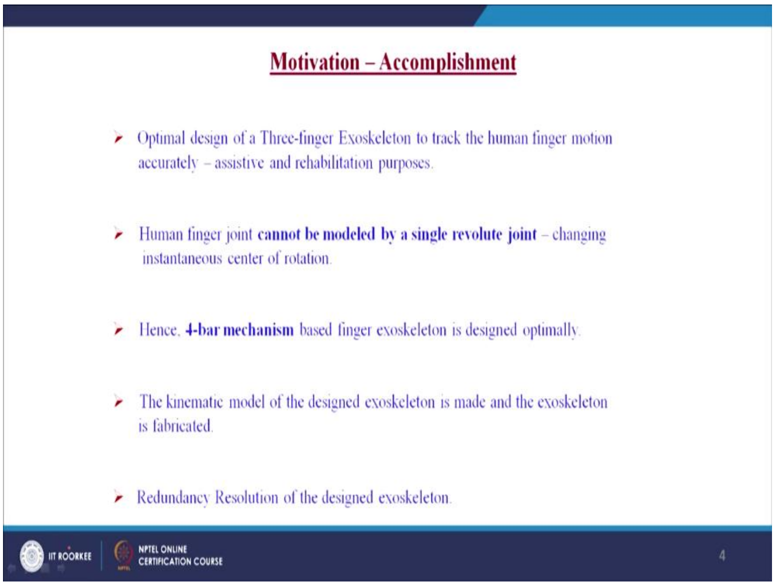
The first method is finger motion capturing of the human flexion motion and then the development of 4 bar synthesis mechanism based on three position analysis motion synthesis of a 4 bar mechanism. Then we have the optimal 4 bar mechanism synthesize, then we see redundancy resolution; and finally, resolving a redundancy resolution in object translation task.

(Refer Slide Time: 01:15)



Coming to the introduction, the objective is to understand the human finger physiology; how the joints are connected, how the links are connected by the joints by the physiological joints. So, that we design an optimal exoskeleton for the three fingers that is for; index, middle and thumb digits.

(Refer Slide Time: 01:38)

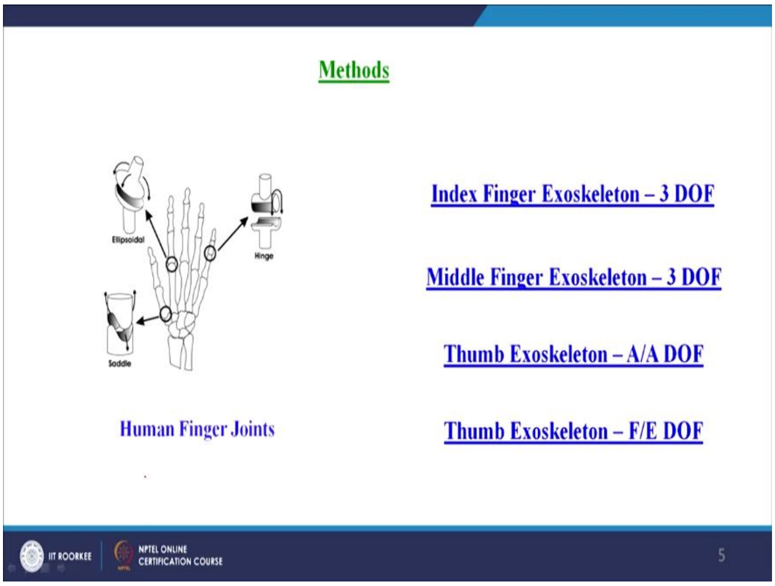


Coming to the motivation followed by the accomplishments; optimal design of a three finger exoskeleton to track the human finger motion accurately, so that it can be used for both assistive and rehabilitative purposes.

And human finger joint cannot be modeled by a single revolute joint, because of the changing instantaneous center of rotation of the human joints. And hence 4 bar mechanism based a finger exoskeleton is designed optimally in this work. The kinematic model of the design exoskeleton is proposed is made or is modeled and the exoskeleton is fabricated in the rapid prototype form; and then finally, redundancy resolution of the design exoskeleton is performed.

But in this lecture we will be seeing up to these four points that is will be seeing the optimal design and we will be seeing how the 4 bar mechanism can be generated based on three position analysis; and then the kinematic model and finally, the fabrication of the exoskeleton. The redundancy resolution will be seen in the next lecture.

(Refer Slide Time: 02:42)

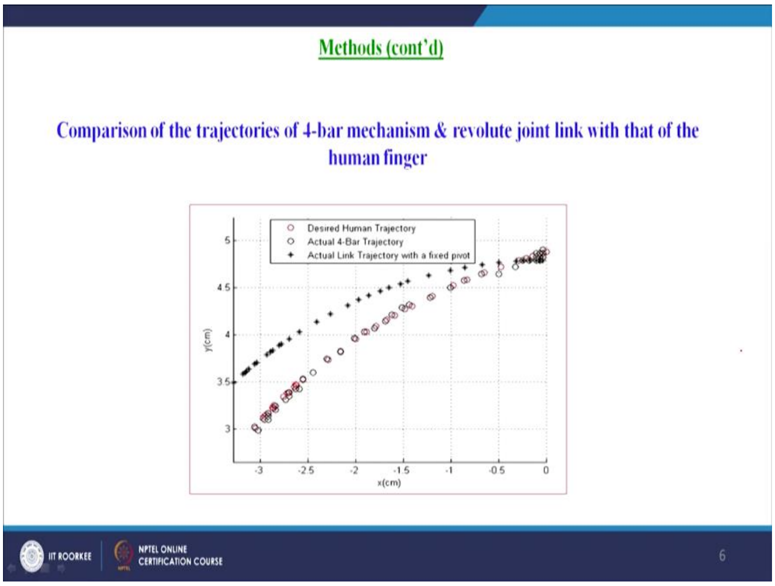


Now, coming to the methods; we see that human joints is modeled in such a way that we have in general the PAP joint of the four digits is with the hinge that is the revolute joint. And the MCP joint of the digits five digits are of ellipsoidal form which is shown here. And the thumbs joint is that is the CMC joint, carpal metacarpal phalangeal joint is made up of this shape which is the saddle shape.

And hence we have designed our exoskeleton for these three digits based on such degrees of freedom which is; finger exoskeleton having 3 degrees of freedom and the middle exoskeleton, middle finger exoskeleton also having 3 degrees of freedom mainly for the flexion extension and also the middle finger doing flexion extension.

By the thumb we have designed with four degrees of freedom; where 3 degrees of freedom for the thumb exoskeletons free flexion extension and 1 degrees of freedom for the abduction-adduction. Hence totally we have designed an exoskeleton for these three digits with 10 degrees of freedom.

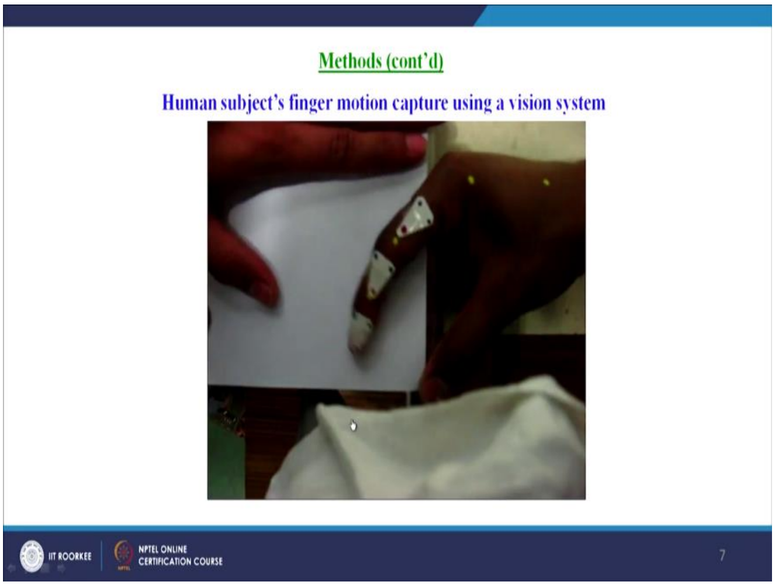
(Refer Slide Time: 03:57)



Now, comparing the human phalanx trajectory with that of the link made up of revolute joint and with that of the 4 bar mechanisms. So, you can see that the red trajectory is the one traced by the human phalanx having the instantaneously varying joint centers. And that trajectory is also traced by a link with a revolute joint that is the link with a single point joint.

Due to which what happens here is, the error is increasing because the traversing path deviates more and more as it goes till the end point; whereas, the same trajectory that is the desired human territory is traced by a 4 bar mechanism. In that case due to the instantaneously varying center of the 4 bar mechanism, we could able to trace the human desire trajectory that is what shown here in this figure.

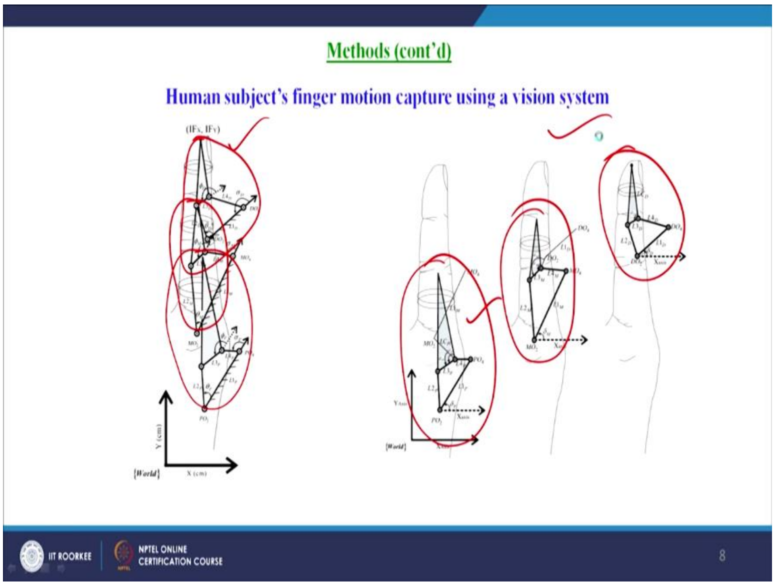
(Refer Slide Time: 04:55)



And now coming to the methods which is of tracking how the human, yes. So, as you can see that here the markers are placed on the human finger in such a way that; on the lateral surfaces of these three phalanges, three markers in the form of a triangle are placed on the finger phalanges.

So, that the subject is asked to move a flexion extension motion and then the camera which is placed on the top of the plane captures the motion; that is a planar motion which is in the plane of flexion extension of the finger. And those trajectories of those three markers; red, blue and green markers are traced in such a way that they are used to generate the 4 bar mechanism.

(Refer Slide Time: 05:45)

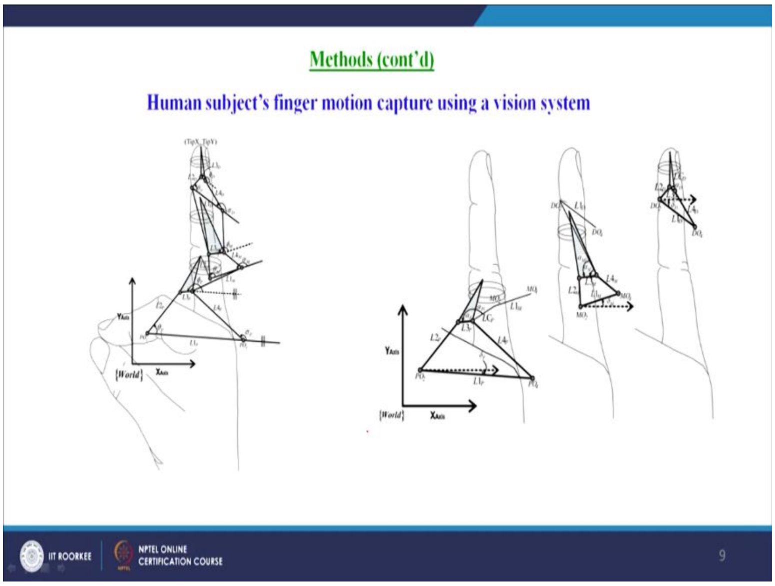


So, the desired 4 bar mechanisms for each phalanx is given by this notion that is for the index finger we have three 4 bar mechanisms that is; for the proximal phalanx, and the middle phalanx, then for the distal phalanx.

So, these three 4 bars are serially attached, so that they can be meant to move the index finger in the flexion extension motion without taking the finger phalanges in a diversed way. So, that precisely we can see that for the; this is the figure for showing the 4 bar mechanism for the proximal phalanx alone.

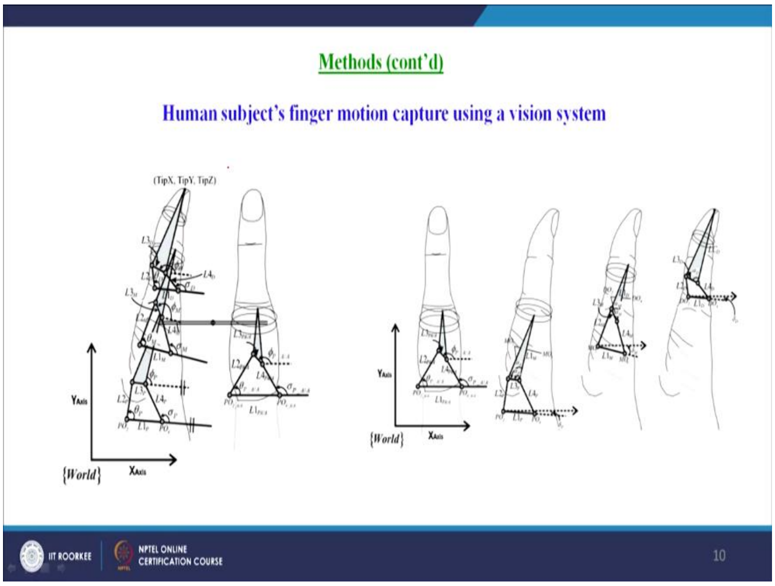
And this is the figure which shows the 4 bar mechanism for the middle phalanx alone and this is the 4 bar mechanism for the distal phalanx alone. And these three phalanges are serially connected to form the index finger exoskeleton. This is the concept and this is a quite good idea we have to develop or to design from the previous video which I have shown here with this video.

(Refer Slide Time: 06:52)



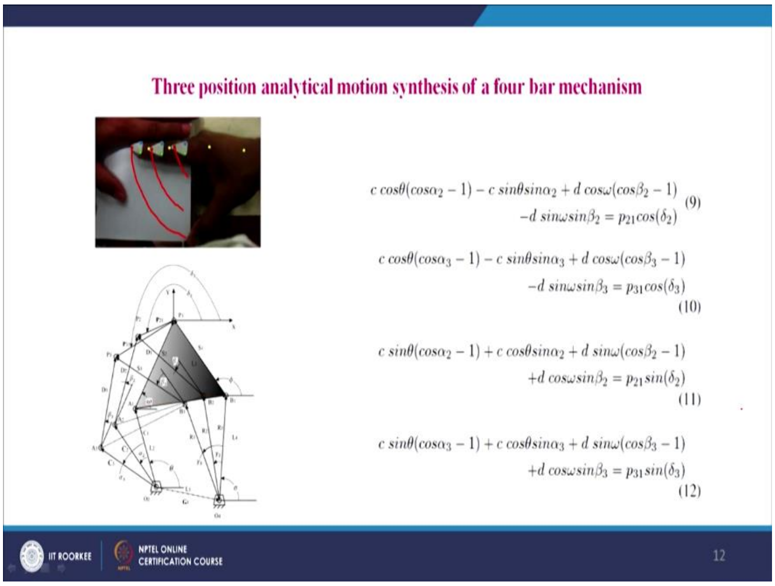
So, now similarly for the middle finger also we place the markers in the lateral surface as shown here and obtain the threes, these three 4 bar mechanism attach serially.

(Refer Slide Time: 07:02)



And likewise for the thumb we have four 4 bar mechanisms; one meant for the abduction adduction motion or degrees of freedom and three more for the flexion extension of the thumb.

(Refer Slide Time: 07:15)



Now, coming to the major part of the methods which is the three-point analytical motion synthesis of a 4 bar mechanism. So, as can be seen here due to that motion, that is the flexion extension motion of the index finger we have three decide trajectories; one by the proximal phalanx and the other one by the middle phalanx, and then the third one by the distal phalanx of the index finger.

So, having these trajectories we are going to generate the 4 bar mechanism based on three position analytical motion synthesis method. So, in that we take three different points P_1 from the start of the trajectory; for example, we consider first the proximal phalanx alone. So, we take this 4 bar, this markers trajectory such that it is meant for the proximal phalanx alone.

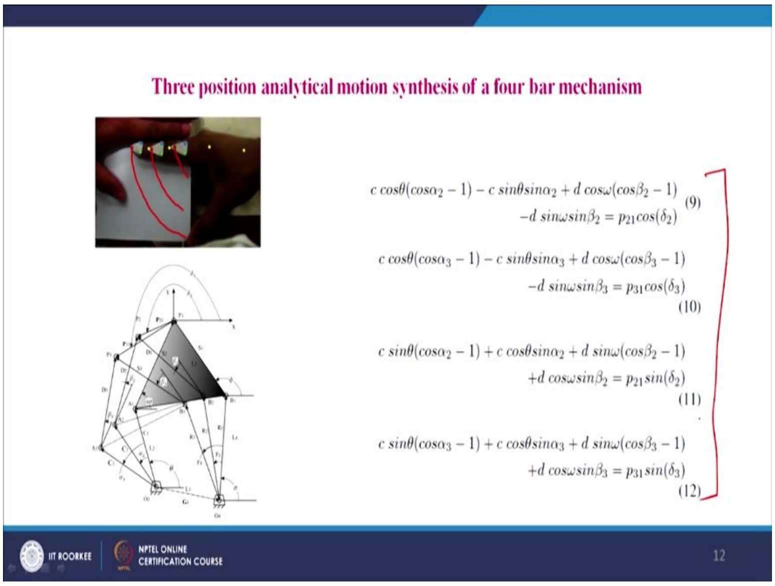
So, for the proximal phalanx from these trajectories from this trajectory, we take the start point and the middle point and then the end point. These three points are taken for the three position analytical motion synthesis of a 4 bar mechanism; that is P_1, P_2 and P_3. So, now, we take this diagram schematic as shown here, where G_1 where L_1, L_2 and this is the coupler L_3 and then L_4 are the link lengths of the 4 bar mechanism; where L_1 is the ground link, and L_2 is the crank link, the L_4 is a rocker link and L_3 is the coupler. And now we take these positions that is P_1, P_2 and P_3 these are the start, intermediate and the end points from the trajectory traced by the proximal phalanx red marker.

Then as shown in this schematic we see that V_1, vector V_1 this is vector V_1 that is pointing from point A_1 to B_1; that is vector V_1 is given by D_1 minus S_1 as can be seen here that is equation 1. Similarly vector G_1 is C_1 plus V_1 minus R_1 that is the second equation as can be seen from this schematic. Likewise we have C_2 that is C_2 plus D_2 minus P_{21}; $P_{21}$is the vector connecting between the points P_{12}, P_2 minus P_{21} minus D_1 minus C_1 is equal to 0. Likewise C_3 plus D_3 minus P_{31} and minus D_1 minus C_1 equal to 0; so the four equations how we have obtained I have described here from the schematic.

Then from this having the complex notations we can have the vectors represented by this notations which is given by the complex notations given by c e power i theta plus alpha 2 plus d e power i into omega plus beta 2 minus p 2 1 e power i delta 2 minus s e power i omega minus c e power i theta equal to 0. Similarly, the equation 6 also obtained based on the complex notations of these two equations 3 and 4; where c d or the vector magnitudes or the magnitudes of the vector c and d respectively.

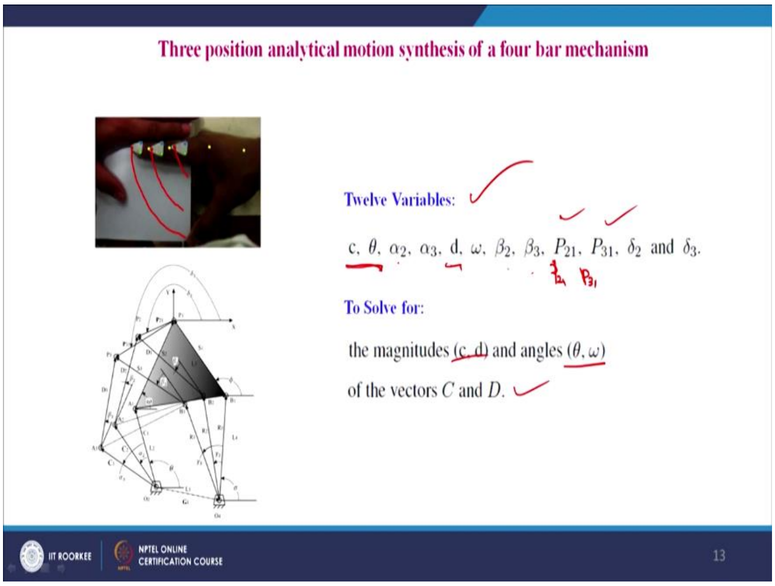
Now, coming to this equation 7 and 8, by simplifying this equation that is, by taking this two p 2 1 and p 3 1 part in the right hand side; we have the equations 7 and 8 obtained from equations 5 and 6.

(Refer Slide Time: 11:08)



So, in continuation then we have four equations in equations 9 to 12 from the by having this representation of that is e power polar form e power I; e power plus or minus i theta equal to cos theta plus or minus i sine theta. So, with that representation we could have these four equations 9 to 12 coming up from these two equations; previously 7 and 8.

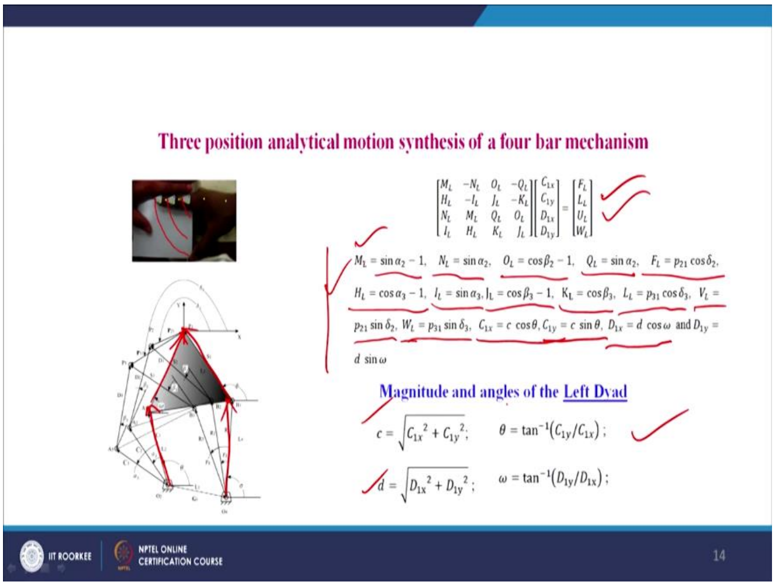
(Refer Slide Time: 11:42)



Then for these four equations that is 9 to 12, we have 12 variables that is c, θ, α_2, α_3, d, w, β_2, β_3, P_{21}, P_{31}, $\delta_2$and δ_3. Basically it must be small p_{21} and small p_{31}, ok.

So, these are the 12 variables with those four equations and these are solved for the magnitudes θ; that is magnitude c and d and angles θ and w. So, these four equations can be solved for these four variables that is c, d, θ and w for the vector C and D; provided we give other eight parameters at priori.

(Refer Slide Time: 12:40)



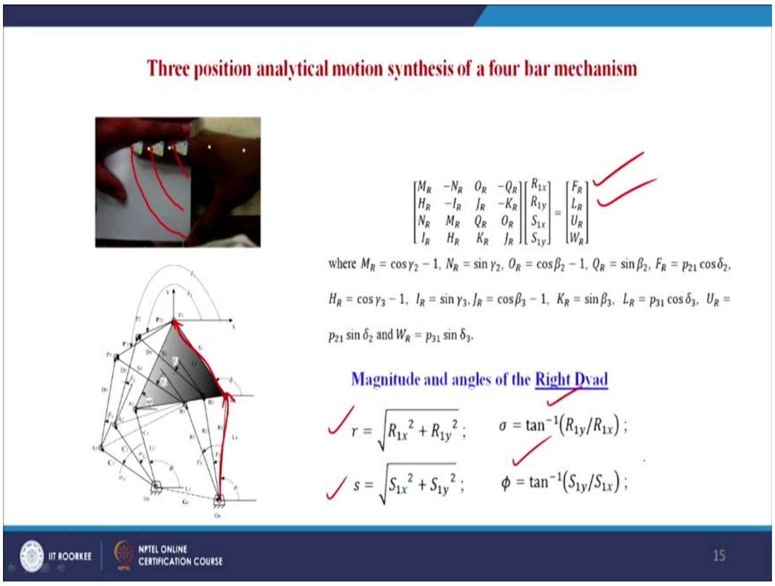
And now in continuation; so we represent from the four equations, if we represent or if we assume $M_l = sin\alpha_1 - 1$ and $N_l = sin\alpha_2 - 1$ and $O_2 = cos\beta_2 - 1$, $O_l = sin\alpha_2 - 1$, $F_l = p_{21}cos\delta_2$.

Similarly $H_l = cos\alpha_3 - 1$, $I_l = sin\alpha_3$, $J_l = cos\beta_3 - 1$ and $K_l = cos\beta_3$, $L_l = p_{31}cos\delta_3$, then $V_l = p_{21}cos\delta_2$. Then $w_l = p_{31}sin\delta_3$, $C_{1x} = c\ cos\theta$; then $C_{1y} = c\ sin\theta$, then D_{1x}, D_{1y} are given by $d\ cosw$ and $d\ sinw$ respectfully.

Then we will have a standard matrix form which is given by this equation; that is matrix multiplied by a vector equal to this vector. This standard matrix form will be obtained provided we assume this M L equal to this for the previous 9 to 12 four equations. Then we will have the magnitude by solving this matrix form, we will have the magnitude c and d and the angles θ and w of the left dyad; this is the left dyad that is this vector pair is the left dyad. This vector pair is a dyad, a vector pair is a dyad and the 4 bar has left dyad and the right dyad.

Now, we have solved the magnitude for the left dyad that is c and d for this vector C 1 and D 1. Similarly, theta and omega for t that is theta between the ground link on the crank link and omega that is the between the x axis and the vector D 1 of the left dyad of the 4 bar mechanism or obtained by solving this standard matrix form which is obtained by assuming these values for the previous equations 9 to 12.

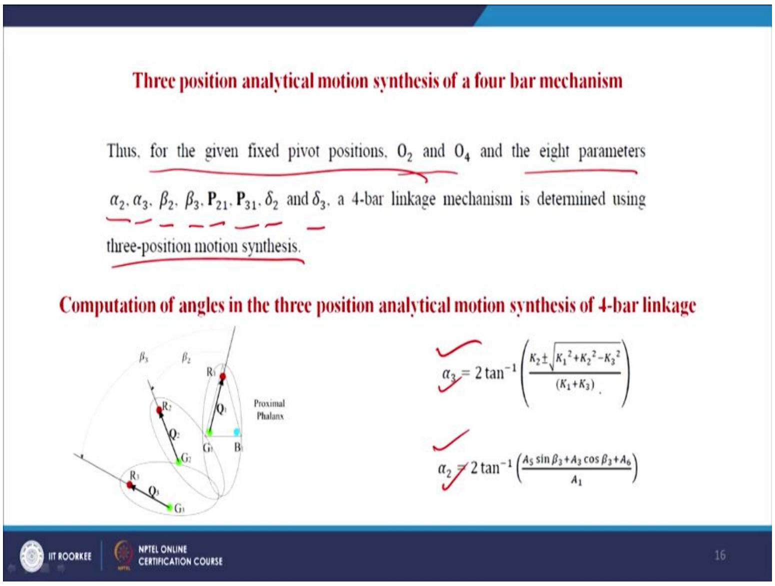
(Refer Slide Time: 14:59)



Then similarly we can also do the same procedure in order to get the standard matrix form for the right dyad that is obtained by the vector pair R_1 and S_1. So, we can also obtain the standard form of the matrix which is given by this equation that is matrix having the members M_R, N_R, O_R, Q_R, H_R, I_R, J_R, K_R, N_R, M_R, Q_R or J_R, H_R, K_R and I_R.

So, we have by solving this equations, this standard matrix equation we could solve for the magnitude r and s and the angles δ that is σ and φ for this right dyad; which is given by this expressions $r = \sqrt{R_{1x}^2 + R_{1y}^2}$. And similarly $s = \sqrt{S_{1x}^2 + S_{1y}^2}$; and σ and φ are given by this expressions which is $tan^{-1}\left({R_{1y}}/{R_{1x}}\right)$ and $\varphi = tan^{-1}\left({S_{1y}}/{S_{1x}}\right)$.

(Refer Slide Time: 16:08)

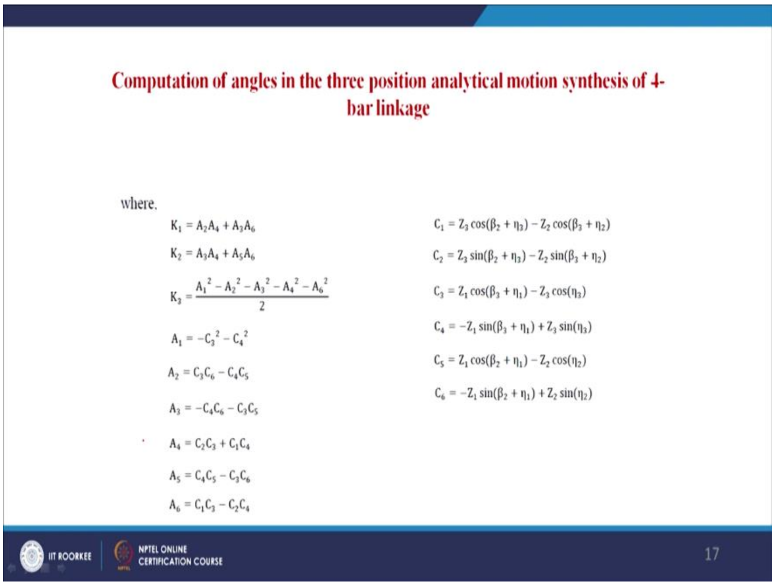


Now, having solved this, we should also see how we could give the variables that is the α_3 and α_2. How that can be obtained? Because that is a value which we could able to obtain by the marker positions; that is why we have taken the marker in the form of a triangle with three marker points red, green and blue.

So, thus having solved that right dyad magnitude and the angles and the left dyad magnitude and the angles for the given fixed pivot points; that is O_2 and O_4 and the eight parameters that is α_2, α_3, β_2, β_3, P_{21}vector, P_{31} vector and the angles δ_2 and δ_3, a 4 bar linkage mechanism can be determined using the three position motion synthesis methodology.

Now, coming to the computation of the angles α_2 and α_3. As can be seen here we could get that α_3 and α_2 are given by $2\ tan^{-1}$ of the expression which is given in terms of K_2, K_1 and K3; likewise A_2, A_1, A_3 and A_6 in terms of β_2 and β_3.

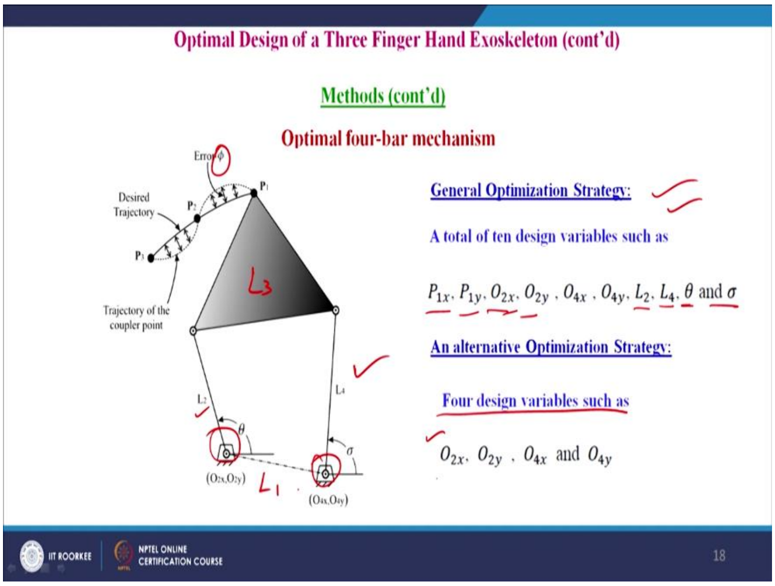
(Refer Slide Time: 17:25)



Where these variables or the parameters are the expressions for K_1 till K_3; and A_1 till A_6 and C_1 till C_6 are given here which I can read it very fast. So, $K_1 = A_2A_4 + A_3A_6$; $K_2 = A_3A_4 + A_5A_6$. Similarly, $K_3 = \frac{A_1^2 - A_2^2 - A_3^2 - A_4^2 - A_6^2}{2}$.

Where $A_1 = -C_3^2 - C_4^2$; and $A_2 = C_3C_6 - C_4C_5$; and $A_5 = C_4C_6 - C_3C_5$; similarly we go up to A_6, then we have C_1 in terms of β_2 and η_3 similarly it goes up to C_6. Thus having these eight parameters that is α_2, α_3, β_2, β_3, δ_2, δ_3 and P_{21} and P_{31} which is the vectors connecting from the point P_1 to P_2 and P_3 to P_1; we could able to have the 4 bar mechanism provided the pivot points are obtained from this user.

(Refer Slide Time: 18:42)



And now going to the optimal 4 bar mechanism. So, where comes the optimization? So, now we are going to the optimization after the three position synthesis of the 4 bar mechanism. Now we see that where is optimization coming into picture. So, having placed the marker and the finger phalanx; so we want the 4 bar mechanism in a way that, that is the optimal 4 bar mechanism.

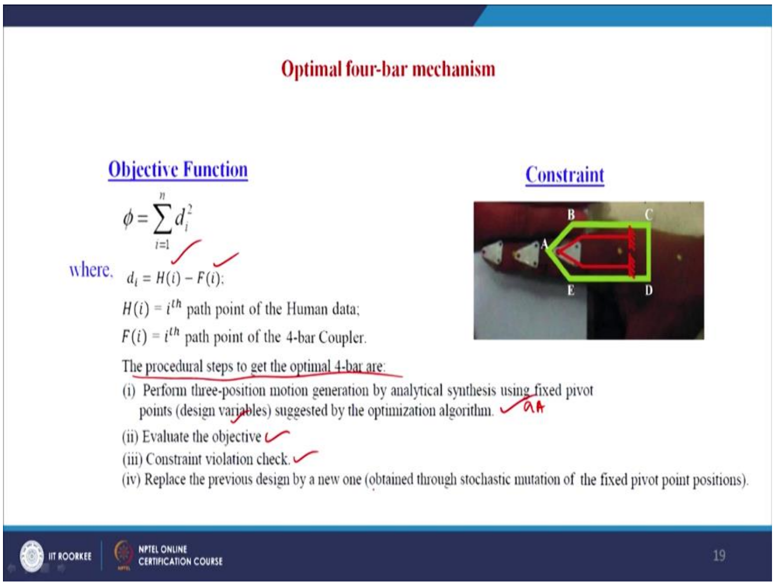
So, that the discrepancy between the desired a human trajectory that is the darker line here and the dotted line that is the trajectory traced by the 4 bar mechanism must be minimized. That is the discrepancy between the desired human trajectory and the actual 4 bar coupler trajectory must be minimized; that is the error here, which is given by the symbol phi.

And you can see that the 4 bar mechanism is the one which has the ground link; say $L_1$and the input link which is the actuated link, that is the crank link L_2. Then this is the coupler which is L_3 and then we have the rocker which just follows the based on the input it rocks that is the L_4, that is the output link you can say. And the input angle is theta and the output angle is sigma here; and the dotted line is a digit desired trajectory and the thick line is the desired trajectory and the dotted line is the trajectory of the coupler point.

Now, coming to the general optimization strategy. So, here we have ten design variables such that P_{1x}, P_{1y}; similarly O_{2x}, O_{2y} that is the pivot points, one pivot point in the left and one pivot point in the right. So, we have 4 here, 2 plus 2 4 plus this point P_{1x}, P_{1y}; then we have the link lengths L_2 to L_4 that is θ and σ.

So, these ten design variables can be obtained from the general optimization strategy; but the alternative smart optimization trajectory strategy is that, we could have the four design variables to be obtained from the optimization methodology in such a way that by giving the input or the parameters are priori the other six parameters. Thus it can be having only the O_2 and O_4 points, that a pivot points will be the design variables of the optimization output.

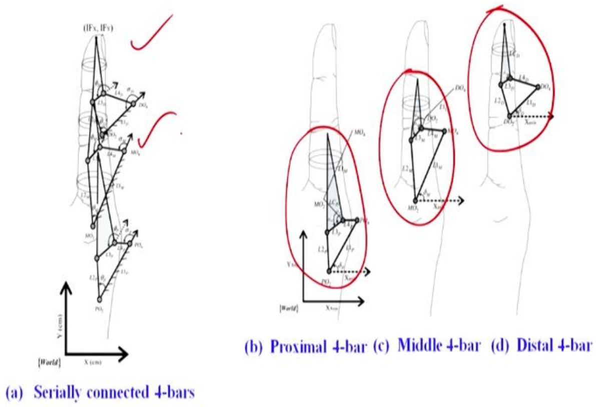
(Refer Slide Time: 21:19)



Now, coming to the objective function, we have framed the objective function such that the discrepancy between the human path and the coupler path. Thus $\Phi = \sum_{i=1}^{n} d_i^2$ where d_i is the discrepancy of the human point at that instant and the coupler point at that instant i. And the procedures steps to get the optimal 4 bar are, perform the three position generated motion generation by analytical synthesis using fixed pivot points that is the design variables suggested by the optimization algorithm. We have used the genetic algorithm, optimization technique from the mat lab toolbox. Then evaluate the objective function, then check whether the constraint is not violated and then replace the previous design by a new one; that is how it continues and goes for the convergence.

(Refer Slide Time: 22:13)

Kinematic Model of the Index Finger Exoskeleton



And now coming to the kinematic model of the index finger exoskeleton having designed the three finger exoskeleton; first we see the kinematic model of the index finger exoskeleton.

So, we have design in such a way that the first 4 bar is for the proximal phalanx and the second 4 bar is for the middle phalanx and the third 4 bar is for the distal phalanx. And these three are connected or attached serially as shown here in this figure on the left.

(Refer Slide Time: 22:43)

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

$$X_{IF} = \cos(\delta_M)\times(L1_M + L4_M\times\cos(\sigma_M) + LC_{Ml}\times\cos(\phi_M - \alpha_{Ml})) - \sin(\delta_M)\times(L4_M\times\sin(\sigma_M)$$
$$+LC_{Ml}\times\sin(\phi_M - \alpha_{Ml})) + \cos(\delta_P)\times(L1_P + L4_P\times\cos(\sigma_P) + LC_{Pl}\times\cos(\phi_P - \alpha_{Pl}))$$
$$-\sin(\delta_P)\times(L4_P\times\sin(\sigma_P) + LC_{Pl}\times\sin(\phi_P - \alpha_{Pl})) + \cos(\delta_D)\times(L1_D + L4_D\times\cos(\sigma_D)$$
$$+LC_D\times\cos(\phi_D - \alpha_D)) - \sin(\delta_D)\times(L4_D\times\sin(\sigma_D) + LC_D\times\sin(\phi_D - \alpha_D))$$

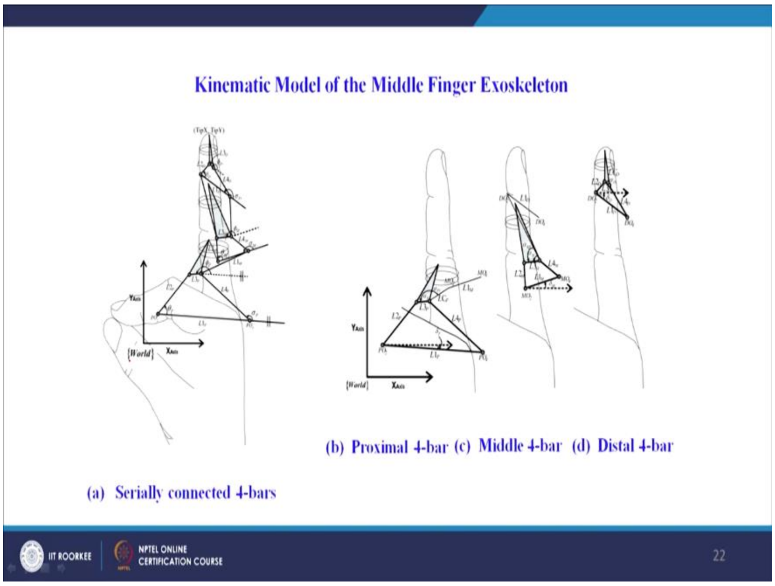
$$Y_{IF} = \sin(\delta_M)\times(L1_M + L4_M\times\cos(\sigma_M) + LC_{Ml}\times\cos(\phi_M - \alpha_{Ml})) + \cos(\delta_M)\times(L4_M\times\sin(\sigma_M)$$
$$+LC_{Ml}\times\sin(\phi_M - \alpha_{Ml})) + \sin(\delta_P)\times(L1_P + L4_P\times\cos(\sigma_P) + LC_{Pl}\times\cos(\phi_P - \alpha_{Pl}))$$
$$+\cos(\delta_P)\times(L4_P\times\sin(\sigma_P) + LC_{Pl}\times\sin(\phi_P - \alpha_{Pl})) + \sin(\delta_D)\times(L1_D + L4_D\times\cos(\sigma_D)$$
$$+LC_D\times\cos(\phi_D - \alpha_D)) + \cos(\delta_D)\times(L4_D\times\sin(\sigma_D) + LC_D\times\sin(\phi_D - \alpha_D))$$

Likewise we go for the index fingers kinematic model which is a power kinematic equation where the X_F; that is the planar tip X_F and X_Y is given by these expressions in terms of the link lengths and the angle parameters which is having δ, σ and α.

Based on them that is for the proximal phalanx delta, sigma and alpha and the middle phalanx δ, σ and α; and for the distal phalanx δ, σ and α for all these collectively the tip can be obtained that is X_F and Y_F. That is starting from this point we could able to reach here and then go here; then from there you reach here, then from there you can go here, then reach here, then reach here, then reach the tip. That is from the closed loop equation method we could be able to reach from the start point O_2 till the tip position by this power kinematic equation.

Thus given the input θ; θ_D, θ_M and θ_P; that is θ_P is the input angle for the proximal phalanx, and θ_M is the input angle for the middle phalanx, and θ_D is the input angle for the distal phalanx, distal 4 bar. Having these 4 bar input angles, we could be able to get the tip position that is X_{IF} and Y_{IF} equation. So, apart from the θ_P, θ_D and θ_M; other parameters are the constant values.

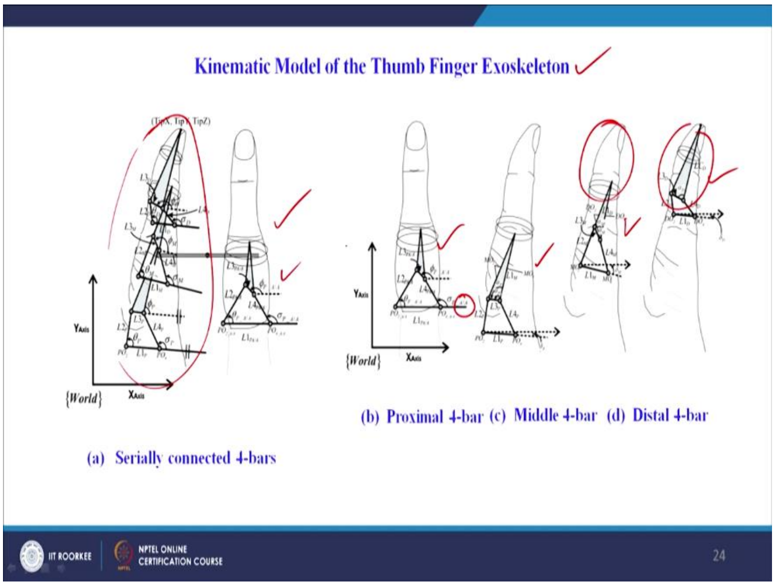
(Refer Slide Time: 24:37)



Now, similarly for the middle finger, the optimal middle finger exoskeleton is obtained by these three 4 bar mechanisms; similarly as in the case of index finger we have the 4 mechanism optimal designed first for the proximal phalanx, then for the middle phalanx, and then for the distal phalanx. And they are connected serially such that the optimal optimally designed serial 4 bar mechanism based index finger is shown here, for the middle finger is exoskeleton is shown here in the left side.

And then likewise for the index finger exoskeleton the tip power kinematic equation for the middle finger exoskeleton tip is given here; which is also the function of sigma, delta, phi, alpha of the three 4 bar mechanisms that is proximal, middle and the distal of the middle finger.

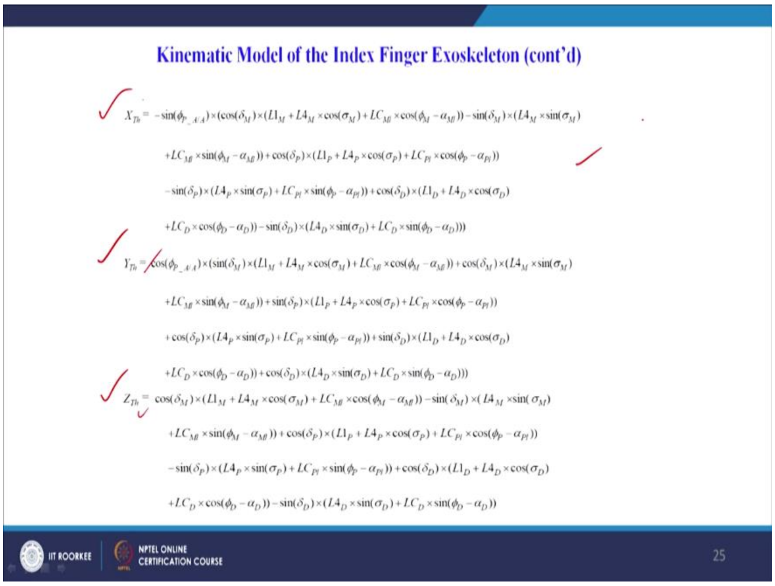
(Refer Slide Time: 25:34)



Finally we come for the kinematic model of the thumb exoskeleton. As can be shown here the first 4 bar mechanism is considered for the abduction-adduction motion; that is given by the subscript A by A that is abduction-adduction. And then we developed the second 4 bar mechanism for the flexion extension of the same phalanx; then the middle phalanx 4 bar mechanism for the middle phalanx, and then for the distal phalanx.

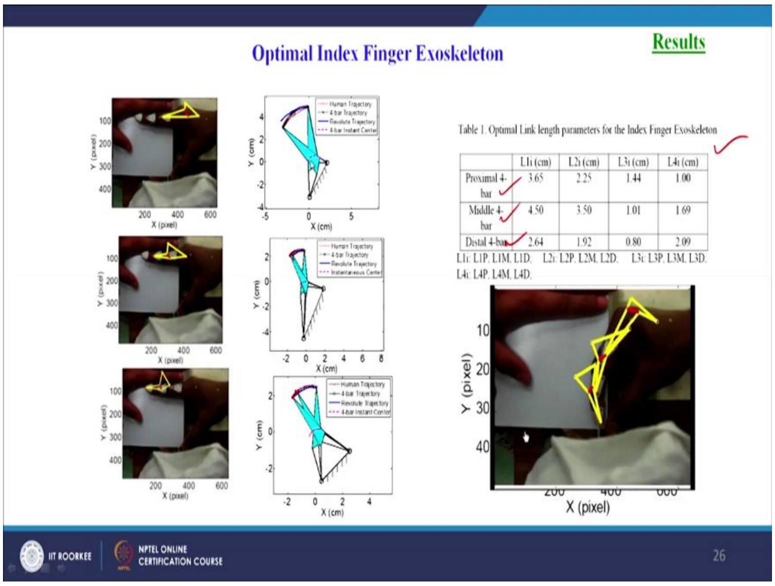
We have computed and we have designed it and hence the attachment is like this; that is this 4 bar mechanism is in one plane and the serially connected three 4 bar mechanism meant for flexion extension motion is in the plane which is perpendicular to this abduction-adduction 4 bar mechanism plane.

(Refer Slide Time: 26:28)



And then due to which the 4 bar thumb exoskeleton having four 4 bar mechanisms meant for both abduction and flexion extension moments; it has the tip motion coming in the 3 D position. Thus it is given by X_{Th}, Y_{Th} and Z_{Th} given by this expression which is also based on the angles that is δ, σ and Φ of these four mechanisms, that is 4 bar mechanisms. And the inputs for that is the joint variables that is generalized to coordinate for this thumb exoskeleton is; θ_P, θ_P adduction and θ_M, θ_D these four joint variables are the generalized coordinates for this thumb exoskeleton.

(Refer Slide Time: 27:20)

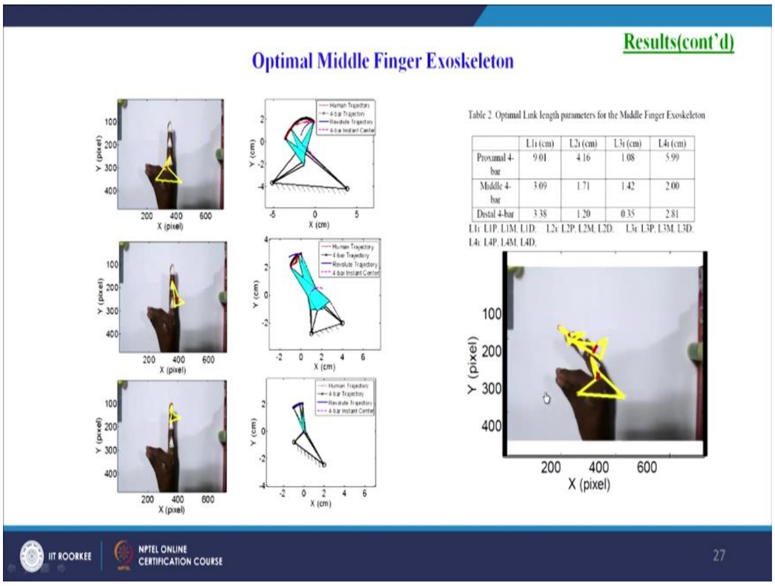


And now coming to the optimal parameters; that is the final optimal parameters of this index finger, middle finger and the thumb exoskeletons. So, as can be see shown in the table here, we have the optimal link length parameters of each 4 bar mechanisms that is proximal, middle and distal mechanisms and everything lengths are given in the centimeters.

And now we can see that, as you can see that simulation of the 4 bar, serially connected 4 bar mechanisms for the index finger exoskeleton in tracing the desired trajectory. And you can see here, this is the trajectory of the instantaneous joint center of the 4 bar mechanism.

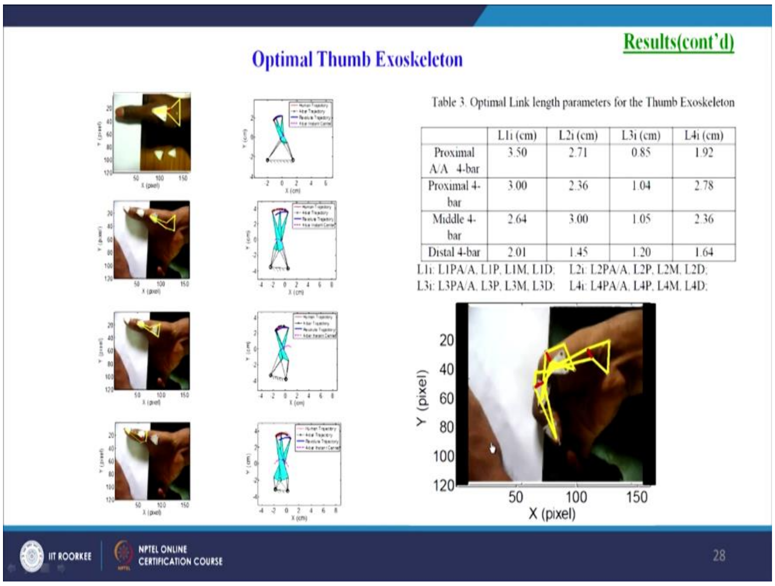
And you can see that here, you can have the trajectory compared with that of the link having the revolute link revolute joint and with the 4 bar mechanism with that of the human trajectory. Similarly, we can see for that of the 4 bar mechanism of the middle phalanx and for the distal phalanx.

(Refer Slide Time: 28:25)



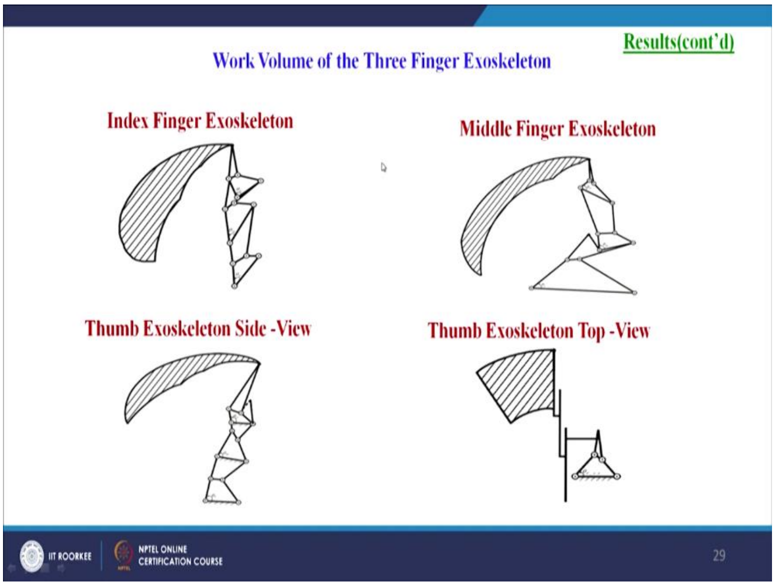
Likewise, for the middle finger exoskeleton, we have the trajectories varying here and instantaneous trajectory of the 4 bar mechanism is also shown here. Then we have this video coming out for the middle finger exoskeleton and these are the optimal parameters of the middle finger exoskeleton.

(Refer Slide Time: 28:48)



Then we have finally, the thumb exoskeleton that is for the flexion extension and also for the abduction adduction motion. And thus it has four degrees of freedom and all these parameters are given here; that is the link length parameters for all the 4 bar mechanisms. Totally for number of 4 bar mechanisms, we have the trajectory comparison for each 4 bar mechanisms with that of the serial link.

(Refer Slide Time: 29:20)



And then we could also take the work volume of the 4 bar mechanisms for each exoskeleton; that is the index finger exoskeleton, middle finger exoskeleton and the thumb exoskeleton, 3 D view both in the side view and the top view.

(Refer Slide Time: 29:33)

Then finally, we have the rapid prototype of the developed or the optimal designed three finger exoskeleton. As you can see that this is made up of acrylic material; the prototype is made up of acrylic material.

And we have the clamp also having the motor attached to these each 4 bar mechanism to have the motor attached to it; and this is the complete prototype of this three finger exoskeleton designed optimally for this three fingers that is the index finger thumb and the middle finger.

(Refer Slide Time: 30:05)

Then you can see here how the motor is attached let me closely show that. Here the motor shaft is attached to the that is a 4 bars input link. Because the input link is acting as a crank link which is going to give the angle to the mechanism; and the other 3, other 2 links will that is a coupler link and the rocker link will behave in such a way that a coupler can trace the decide human trajectory.

So, as you can see that, the motor shaft is attached to the link of the crank and then this is the rocker link and we have the coupler here. Then this 4 bar mechanism that is this is the distal 4 bar mechanism it is placed on the just above the coupler that is this is the coupler of the previous 4 bar mechanism. That is the if this is the distal 4 bar mechanism, then this 4 bar mechanism is placed on the coupler of the middle 4 bar mechanisms.

And as you can see that the clamp is clearly shown here, it is the clamp it is a metal element which is clamping the motor in such a way that; it is attaching the top and bottom surface of the full 4 bar mechanism, so that the planes that is this is the plane having the link and this is the plane having the coupler. With this we could wind up this lecture, which is the optimal design and development of the three 4 bar based index finger middle finger and thumb exoskeleton.

Thank you.