Robotics and Control: Theory and Practice
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Lecture – 22
Redundancy Resolution of Human Fingers in Cooperative Object Translation – II

Good afternoon. Today, we continue with the topic on Redundancy Resolution of the Human Fingers in Cooperative Object Translation.

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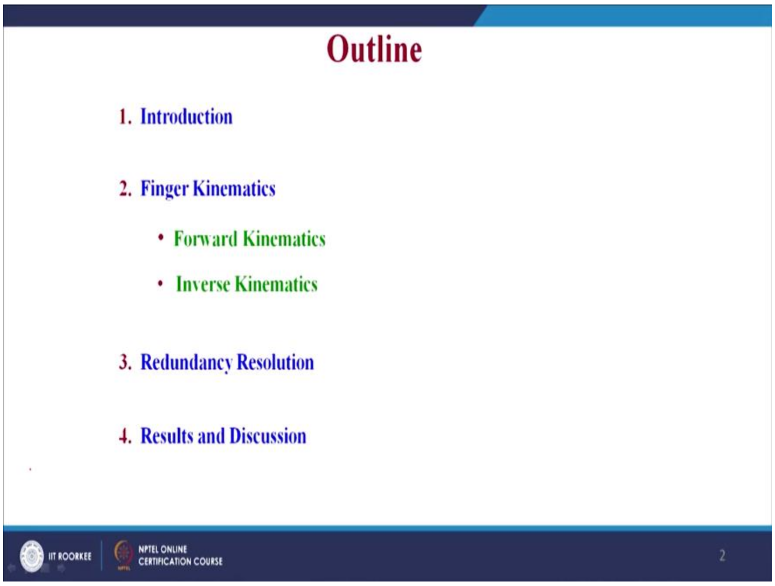

The organization of today’s lecture will be as follows first we have the introduction, and then we have the finger kinematics of the index finger, middle finger and the thumb, where we will be seeing the forward kinematics and the inverse kinematics. Then we will be seeing the major portion which is the redundancy resolution of these three digits in object translation motion. Finally, we will be seeing the results and discussion coming out with the summary.

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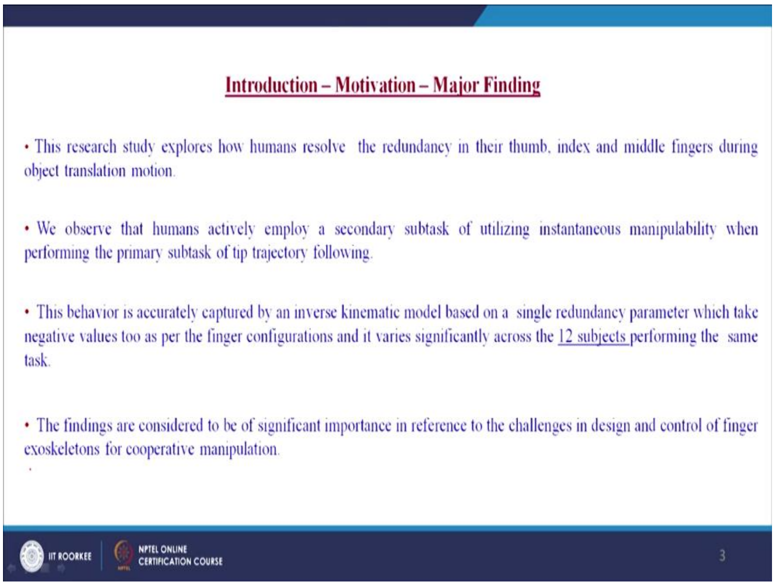

Coming to the introduction this research study explores how human explores or resolved the redundancy in their thumb, index and middle fingers while performing object translation motion. We observe that humans actively employ a secondary sub task of utilizing manipulative measure when performing a primary sub task of tracking a given decide trajectory of their fingertip.

This behavior is accurately captured by an inverse kinematic model based on a single redundancy parameter which take both negative values to and also changes in magnitude across the 12 subjects who have performed the same task of object manipulation. These findings are considered to be of significant importance towards the challenges of the design and control of hand exoskeleton especially finger exoskeletons for cooperative object manipulation.

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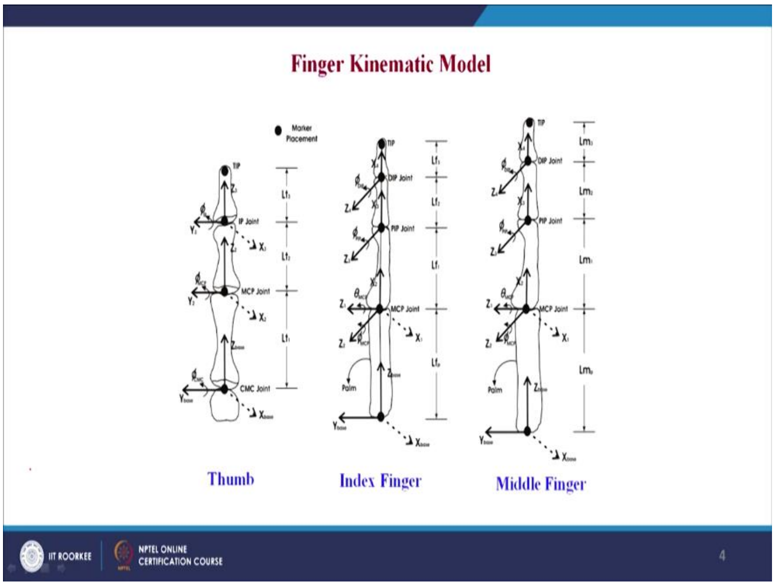

Coming to the first part which is the finger kinematic model for the these three digits thumb, index and middle fingers the thumb is modeled kinematically with the 3 degrees of freedom in order to perform the flexion extension move movement where the degrees of freedom are considered for these joints CMC flexion extension and MCP flexion extension and the IP.

This is for CMC flexion extension one degrees of freedom and one degrees of freedom in the MCP and one degrees of freedom in the IP joint. Similarly, for the index and middle fingers we have considered four degrees of freedom that is the MCP joint has two degrees of freedom.

One is the abduction adduction which is given by this theta MCP and the other one or phi MCP and phi PIP and phi DIP for the MCP PIP and DIP joints and that is where the three degrees of four degrees of freedom consider for the middle finger as well.

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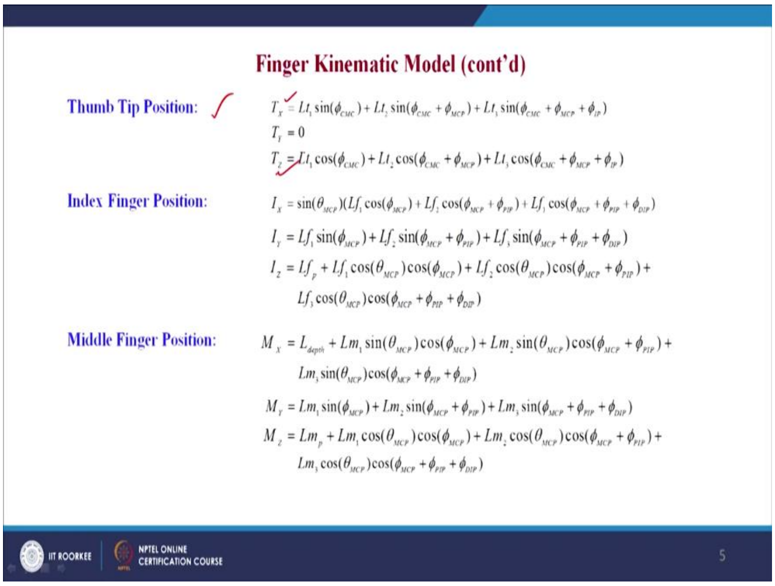

I am going to the kinematic equation forward kinematic equation of these three fingertips for the thumb it is T_x and T_z where T_y is 0 because it is going in your plane. And, similarly for the index and the middle finger we have the three x, y, z coordinate of the fingertip because of the 4 degrees of freedom including the abduction adduction. And, here are the kinematic equations which relates the joint angle to the fingertip position.

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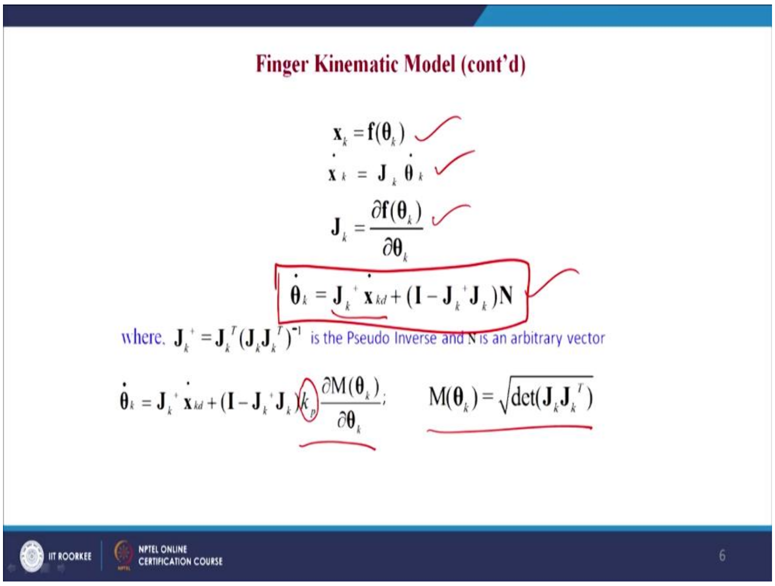

Continuation, now coming to the forward kinematic equation generalized equation for the finger is given by $x_k = f(\theta_k)$ and the differential kinematics is given by $\dot{x}_k = J_k\dot{\theta}_k$ where

J_k is the Jacobian matrix is given by the partial differentiation of the forward kinematic equation with respect to the joint coordinates θ_k.

Thus the general solution that is the joint angular velocity of the fingertip for the differential equation which is $\dot{x}_k = J_k\dot{\theta}_k$ is given by $\dot{\theta}_k$ equal to first term which is

$$J_k^+\dot{x}_k + (I - J_k^+J_k)N$$

Where, the vector N is an arbitrary vector and J_k is the right pseudo inverse and the vector N can be decomposed into $k_p\frac{\partial M(\theta_k)}{\partial \theta_k}$ where M is the manipulability measure of this relevant index or middle finger or the thumb where it is given $\sqrt{\det(J_k J_k^{+T})}$

and k_p is here positive constant.

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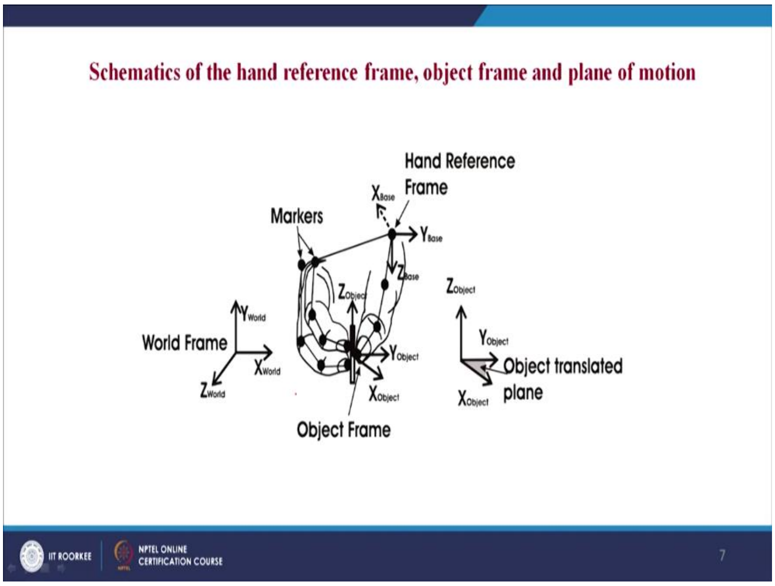

Now, coming to the schematic of the hand reference frame the body frame and the plane of motion. The plane of motion is considered with respect to the object frame which is as per the schematic it is along the x-y plane of the coordinate of the object. And, then we have put the markers on the each joints of the index finger middle finger and the thumb as shown in the figure. We have the world coordinate frame as well.

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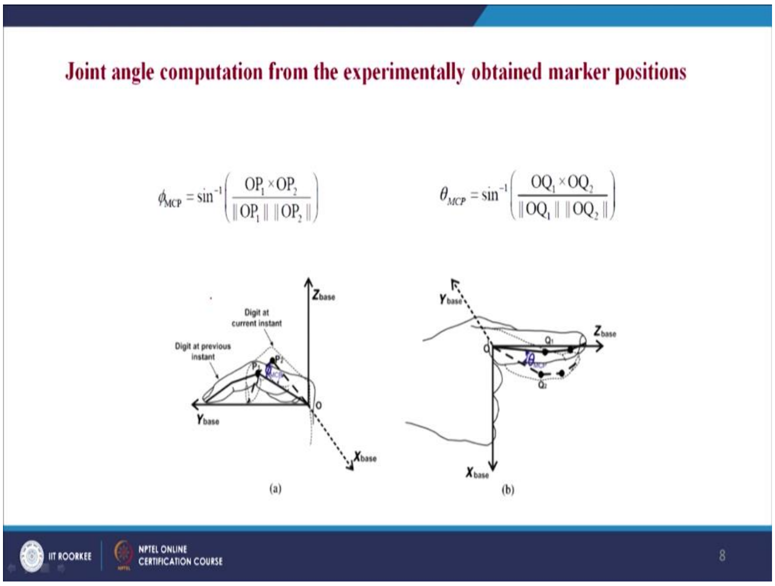

Then coming to the joint angle computation from the experimentally obtained marker points how we compute the joint angles from the marker positions which are placed on the finger joints. There are two joints to be computed in general; one is the abduction addiction angle which is theta MCP and the other one is the phi MCP which is the flexion extension angle.

The flexion extension angle as can be seen in the body is when the digit is translating from the extension posture towards its flexion posture what is the flexion extension angle computed. How it is computed? It is computed based on the sine angle between the vector OP 1 and OP 2 where OP 1 is the vector which connects the MCP joint to the PIP joint which is nothing, but the vector representing the proximal phalanx.

And, this OP 1, OP 2 represents the initial configuration of the proximal phalanx to the intermediate configuration of the proximal phalanx and hence the angle between these two joints or these two vectors gives the fractionation angle. Similarly, for the abduction adduction angle. It is computed as the joint angle or the angle between the two vectors OQ 1 and OQ 2. OQ 1 is the vector at the initial configuration connecting the MCP joint to the proximal interphalangeal joint PIP joint.

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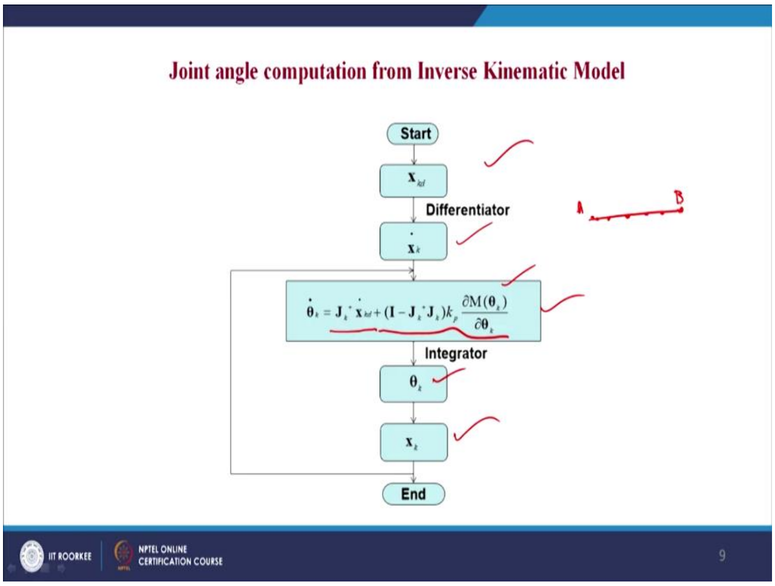

Now, coming to the generalized angle computation from the inverse kinematic model, it has been computed as per the flow chart given here that is we start with the decide given position of the fingertip and we differentiate that to have the $\dot{x}_{kd}$. Then we compute the generalize to solution based on the manipulability involvement which is given by $\dot{\theta}_k = J_k^{+}\dot{x}_{kd}$ is the first term which is the primary sub task and the secondary sub task is given by second term which is $(I - J_k^{+}J_k)$ into k_p multiplied by the $\frac{\partial M(\theta_k)}{\partial \theta_k}$ that is we are instantaneously trying to maximize the manipulative measure. Then, we integrate it to obtain the joint angle from the joint velocity. Then with the corresponding joint angle we compute the forward kinematics to obtain the fingertip position then this procedure these steps continue till we obtain the till we reach the last position of the finger trajectory fingertip trajectory. We start from here A and we ended point B till we reach the end point B it continues the algorithm continues with the instantaneous maximization of the manipulability measure.

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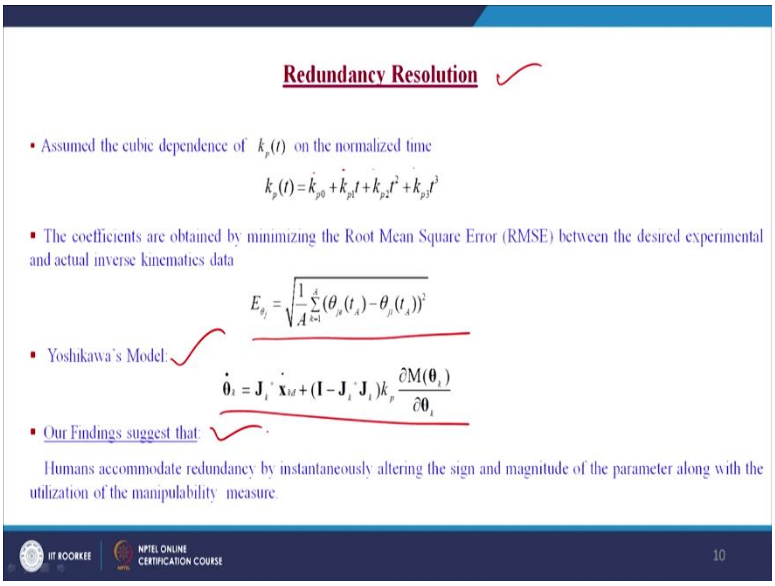

Now, coming to the major portion of this lecture which is the redundancy resolution we assumed the cubic dependence of the redundancy parameter which we have seen here k_p to be cubically dependent on the normalized time and hence it is given by the cubic polynomial equation

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

We have the four coefficients to be computed k_{p0}, k_{p1}, k_{p2} and k_{p3} to obtain the cubic value of a cubic of cubic spline of the redundant parameter. The coefficients are obtained by minimizing the root means square error between the x mentally desired joint angle and the inverse kinematically computed joint data that is given by this expression $E_{\theta j}$ that is a root mean square generalized expression between the discrepancy between the desired experimental joint angle and the computed inverse kinematic angle. And, we have the Yoshikawa model which is given in general we have seen in the last lecture it is given by this generalized expression

$$\dot{\theta}_k = J_k^+ \dot{x}_{kd} + (I - J_k^+ J_k) k_p \frac{\partial M(\theta_k)}{\partial \theta_k}$$

Our findings suggest that humans accommodate redundancy by instantaneously altering the sign and magnitude of the parameter k_p along with the utilization of the manipulability measure throughout the finger configuration in obtaining the desired trajectory.

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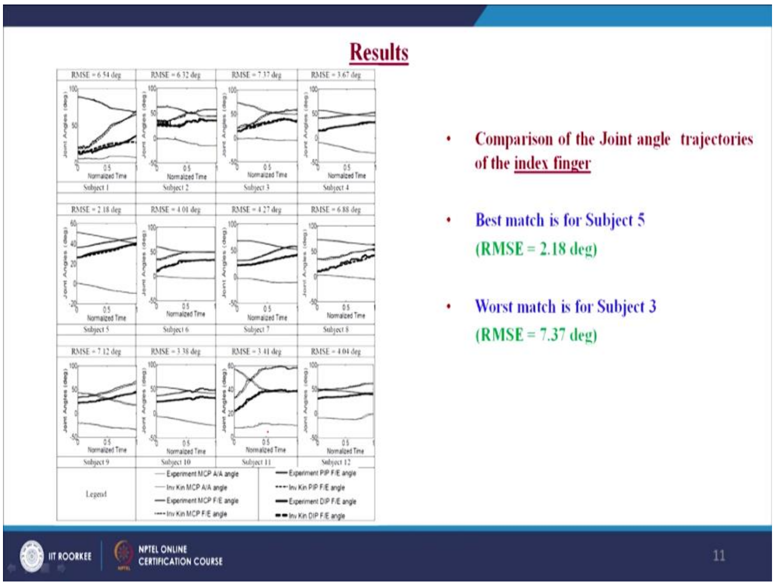

Coming to the results now first we compare the joint angle at trajectories of the index finger for all the 12 human subjects who performed in the same object translation task where we have the row wise subject 1, subject 2, subject 3, subject 4 accordingly 12 subjects we have with all the four joint angle variations. MCP abduction addiction angle, MCP flexion extension angle, PIP flexion extension angle and the DIP distal interphalangeal joint angle ok, these four joint angles are compared with the inverse kinematic angles.

So, the best match is for subject 5 who has the root mean square error 2.18 degree and the worst match is for subject 3 who has the root means square error value which is 7.37 degrees. Similarly, the comparison of the joint trajectories joint angle trajectories for the middle finger for the 12 subjects is given here in this figure and the best match is up to is observed for the subject 12 who has the root means square error to be 2.46 degrees and the worst match is for subject 1 who has the root mean square error value coming out to be 7.14 degrees.

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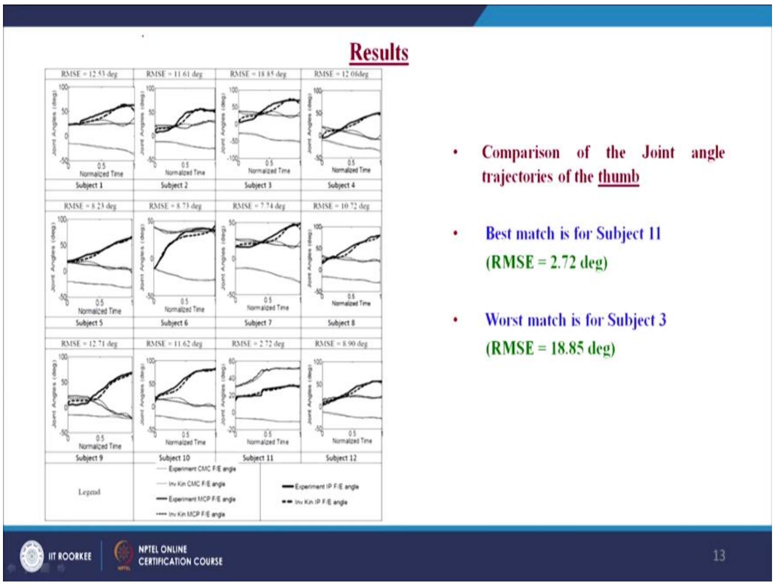

Finally, for the thumb the joint angle trajectories are compared between the inverse kinematic angle and the exponential data. The best match is obtained for subject to 11 who has the root mean square error 2.72 degrees and the worst match is for subject 3 who has the highest value of 18.85-degree root mean square error.

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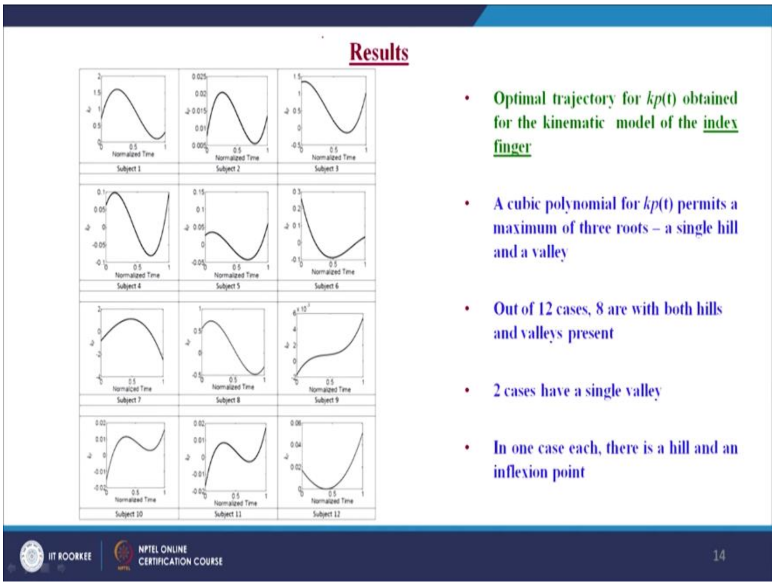

Now, coming to the comparison of the optimal trajectory of $k_p(t)$ obtained for the kinematic model of the index finger first. In general this profiles of these k_p trajectories have a single hill and a single valley in general.

So, out of these 12 cases for the 12 subjects for the index finger, 8 are with both hills and valleys present and 2 cases have a single valley and in one case each there is a hill and an inflection point.

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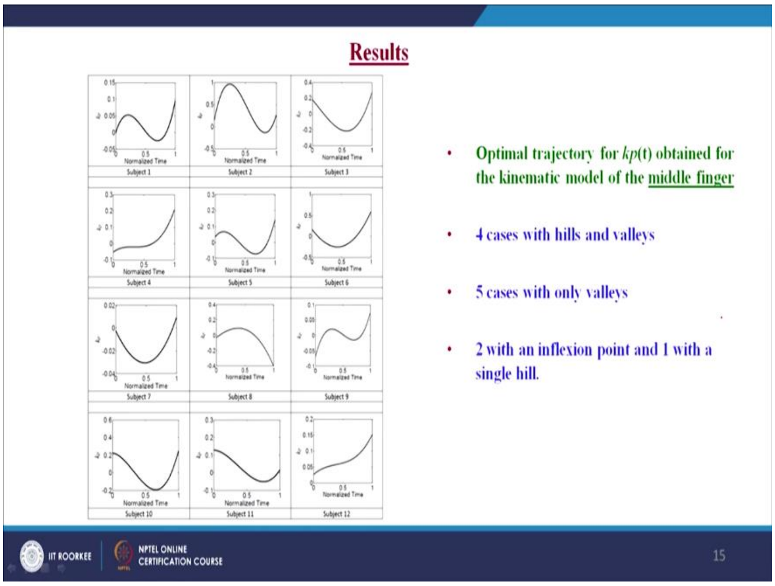

Now, coming to the same optimal trajectory profile of the k_p of t the redundancy parameter for the middle finger for the 12 subjects that we have observed that 4 cases or with hills and valleys and 5 cases or with only hills only valleys, a 2 with an inflection point and 1 with a single hill.

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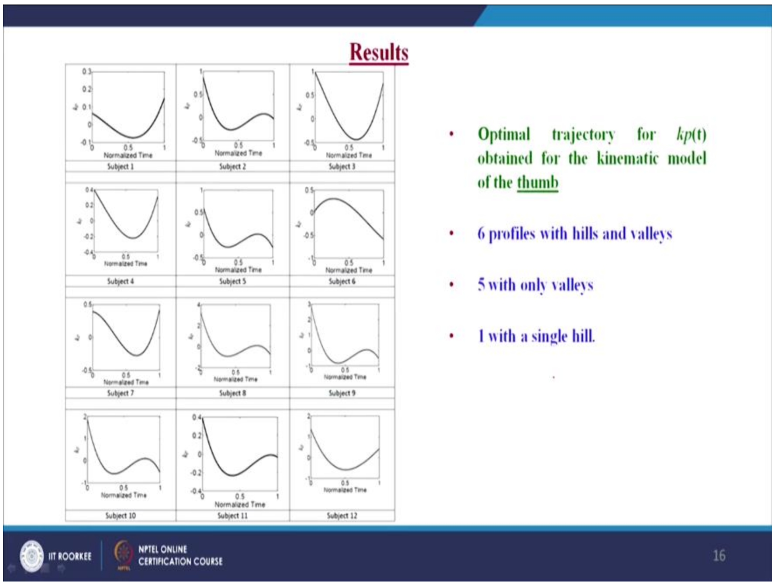

Finally, the optimal trajectories trajectory profiles for the $k_p(t)$ is obtained for the kinematic model of the thumb where we observe that from these profiles we observe that 6 profiles or with hills and valleys, 5 with only valleys and 1 with a single hill.

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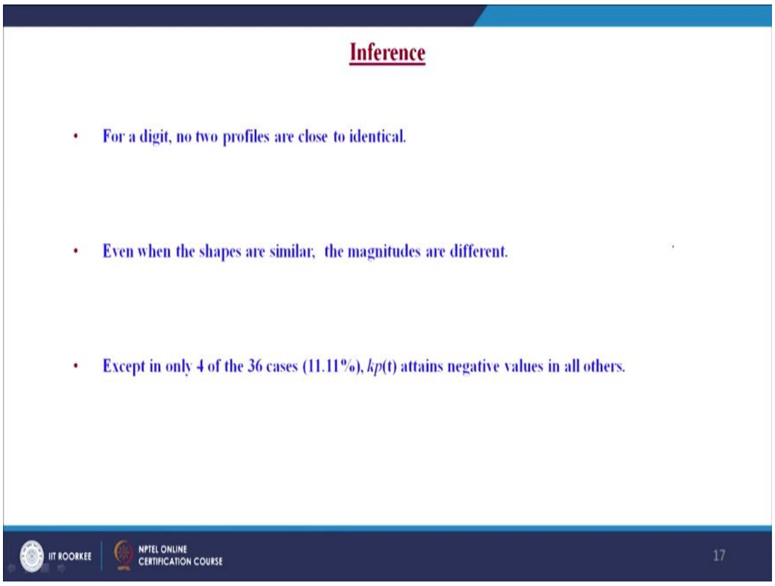

Now, the inference from these optimal trajectories of the residency parameter is that for a digit no two profiles are close to identical. Even when the shapes are identical they are different magnitude significantly. Except in 1 in only 4 of the 36 cases; why 36 cases? 12 for each finger, 12 subjects performing the 3 figures and hence 36 cases. Among this only 11.11 percentage the attains the k_p values positive the remaining all other all having the negative values of the k_p.

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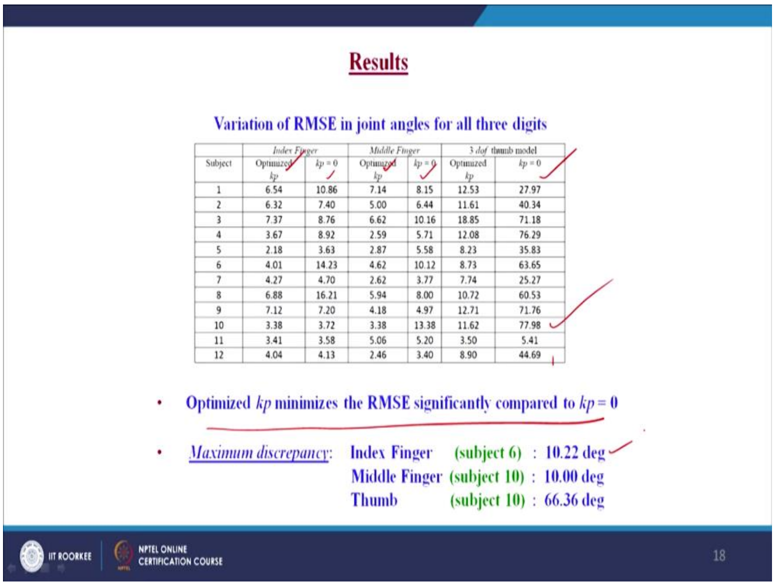

	Index Finger		Middle Finger		3 dof thumb model	
Subject	Optimized kp	kp = 0	Optimized kp	kp = 0	Optimized kp	kp = 0
1	6.54	10.86	7.14	8.15	12.53	27.97
2	6.32	7.40	5.00	6.44	11.61	40.34
3	7.37	8.76	6.62	10.16	18.85	71.18
4	3.67	8.92	2.59	5.71	12.08	76.29
5	2.18	3.63	2.87	5.58	8.23	35.83
6	4.01	14.23	4.62	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

Now, coming to the variation of root mean square error in joint angles for all the three digits, we compare the root mean square of all the three digits in the joint angles when considering redundancy and with no redundancy; that means, I mean no redundancy we put the value of k_p to be 0. And, hence we observe that optimized k_p minimizes the root mean square error significantly compared to the value with k_p equal to 0 that is clearly observed in the columns 1 and 2 of table.

And, similarly for middle finger k_p is optimized and k_{p0} we can see that they are seemingly greater compared to the optimized values and for the tumbles we observe that there are significantly higher values. So, the max maximum discrepancy is obtained for the index finger subject 6 is having 10.22 degrees and for the middle finger subject 10 is having 10 degrees and for the thumb subject 10 is again having 66.36 degrees.

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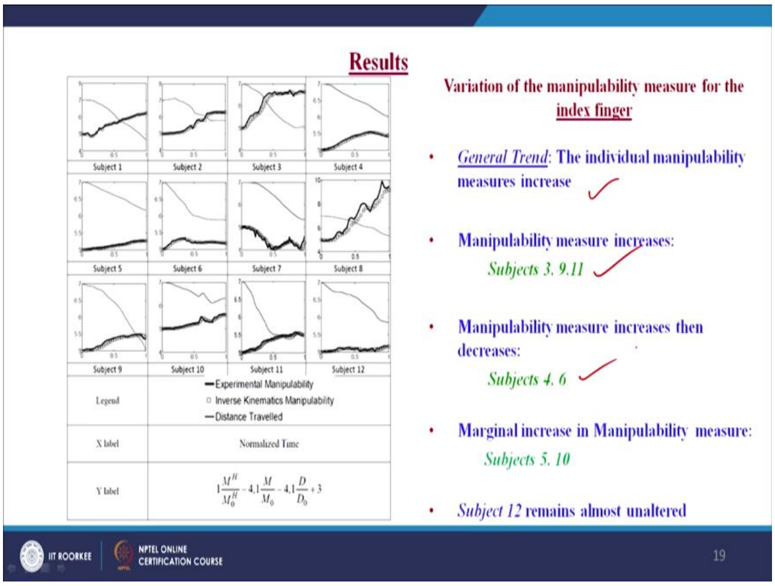

Now, coming to the variation of the manipulability measure for the index finger among the 12 subjects. The general trend is that individual manipulability measure generally increases. The manipulability measure increases for subjects 3, 9 and 11 significantly and the manipulation increases then decreases or for subjects 4 and 6 marginal increase in manipulability measure is observed in subjects of 5 and 10 and subject 12 remains almost unaltered in manipulability measure.

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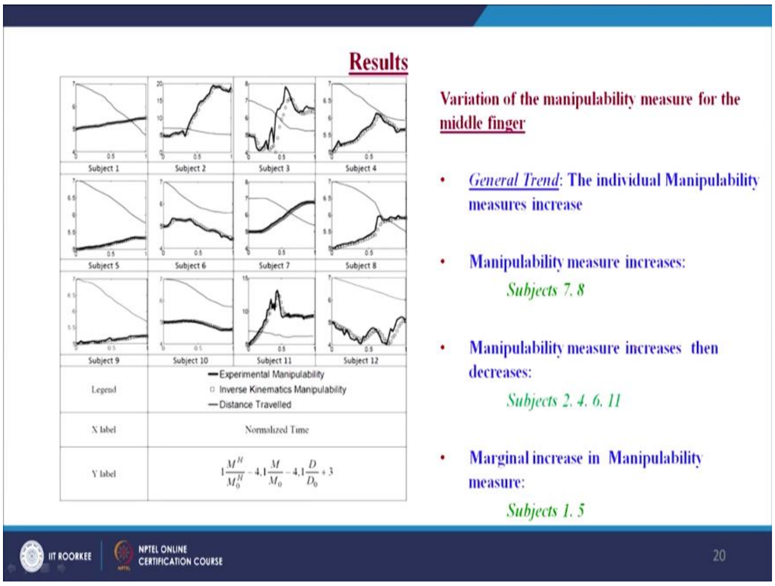

And now the variation of the manipulability measure for the middle finger is shown here, where the general trend is obviously, the manipulability measure increases as in the case of the index finger. So, manipulability measure only increases or for subjects 7 and 8 and the manipulability measure increases then decreases for subjects 2, 4, 6 and 11 and then marginal increase in manipulability measure is for subjects 1 and 5.

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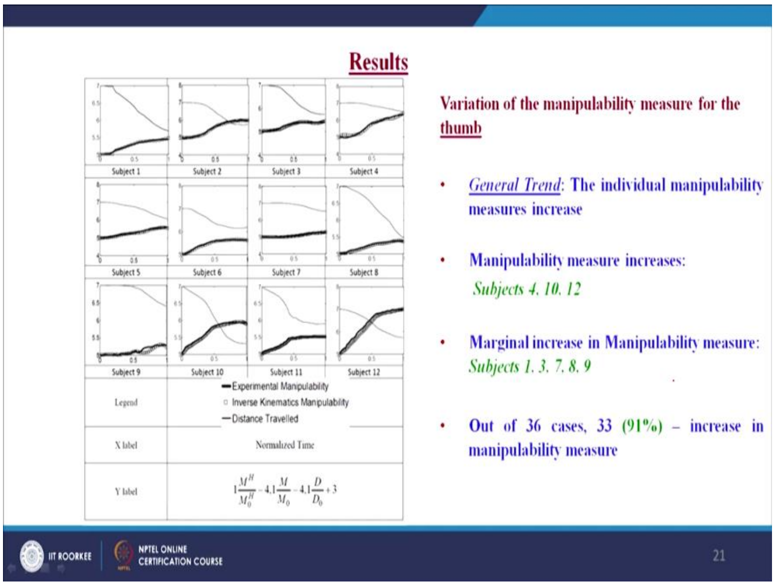

Then finally, the manipulability measure variation for the thumb. The general trend is increasing the manipulability measure. Subjects 4, 10 and 12 have only the increase in manipulability measure and marginally increase in manipulability measure or for subjects 1, 3, 7, 8 and 9 out of 36 cases coming to the inference out of 36 cases 33 cases that is 91 percentage have increased in the manipulability measure.

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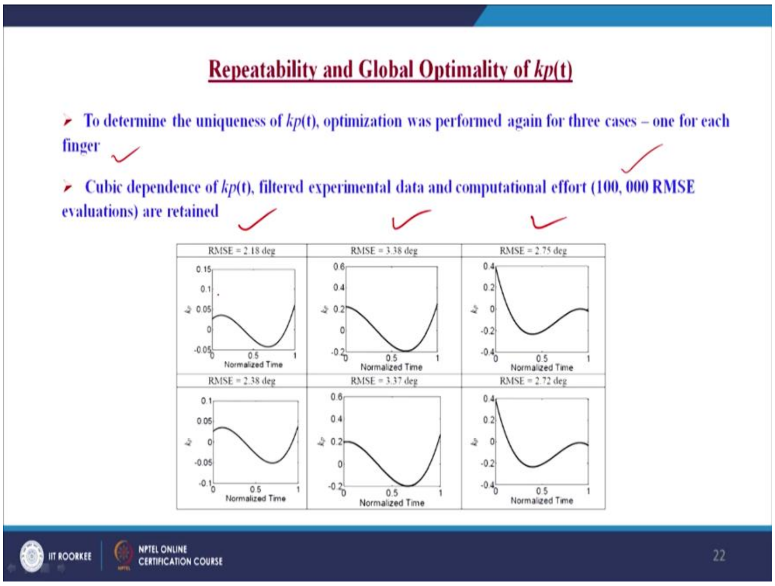

Now, coming to the repeatability and global optimization of $k_p(t)$. To determine the uniqueness of $k_p(t)$ optimization was performed again for three cases one for each digit that is one for each finger. Cubic dependence of the $k_p(t)$, then total number of evaluations that is 100000 evaluations and the filtered experimental data and the computational effort with the 100000 RMSE evaluations are retained same for this repeatability analysis.

And each column here in the table shows that we are we have done two times for each digit that is for index finger column 1, middle finger column 2 and column 3 shows the profile of k_p for thumb. And, we can observe that we have the same profile obtained in the repeatability case which tested first time again, and the second time also we have performed with the same evaluations, with the same conditions retained we have observed almost the same profile where the root mean square error value remains almost closely same that is 2.18 and 2.38.

Similarly, for the middle finger it is obtained with the root mean square at a discrepancy being 0.01 degrees and for the thumb it is 0.03-degree discrepancy when these two repeatability cases.

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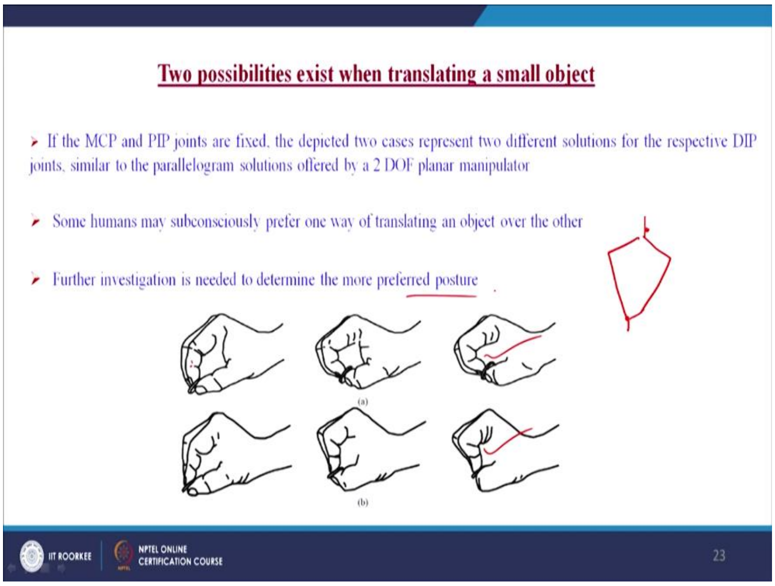

Now, there are two possibilities exist when translating a small object that is which is similar to the parallelogram solutions offered by a 2 degrees of freedom planar manipulated. That is, given a point we have this type of solution. So, hence some humans make subconsciously prefer one way of translating an object over the other because of when we translate it there could be different ways, one way is translating with this joint that is DIP joint coming into picture with JIP joint coming into picture being the straight line and the DIP joint having flexed.

So, these are the two cases which is identical to the parallelogram solution of the 2 degrees of freedom manipulator. So, further investigation is needed to determine the preferred most preferred posture by using these subjects.

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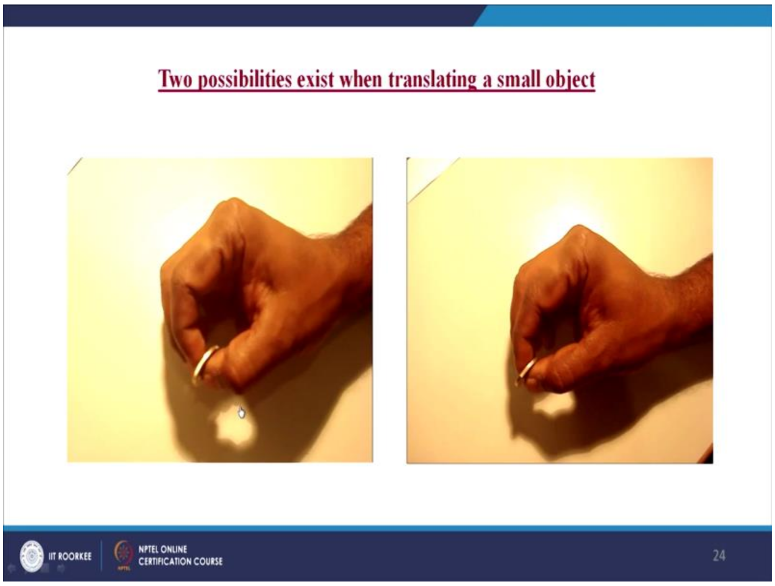

We can see the object getting translated with the first way and this the second way where the object is translated without bending the DIP joint that is this last joint where you can see that it is bent with all the joints coming to be flexed whereas, this joint is not flexed while translating the object. So, these are the two ways humans can translate an object with their three fingers.

Now, coming to the free finger motion we want to test whether this observation or the inference is same, is true only for the task oriented motion or free motion.

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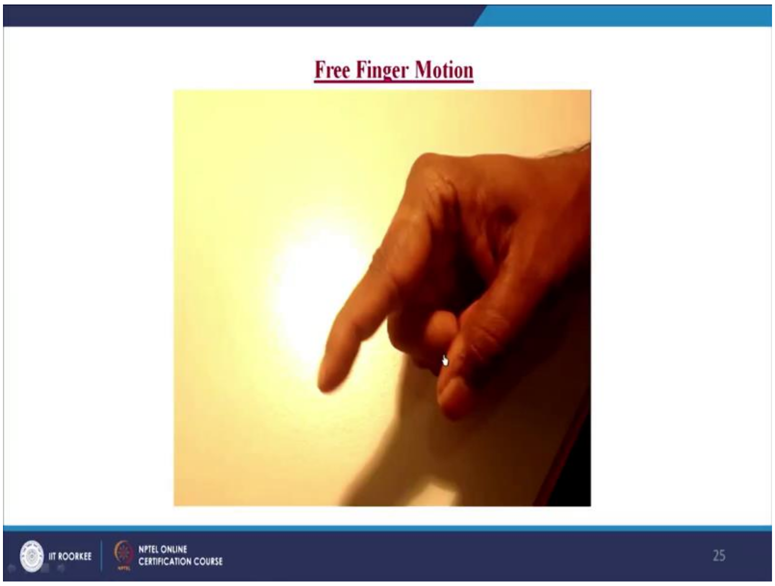

So, we have tested our algorithm for free motion as well as shown in the figure as shown in this video. We flux the finger with this free motion without expecting any task to be performed.

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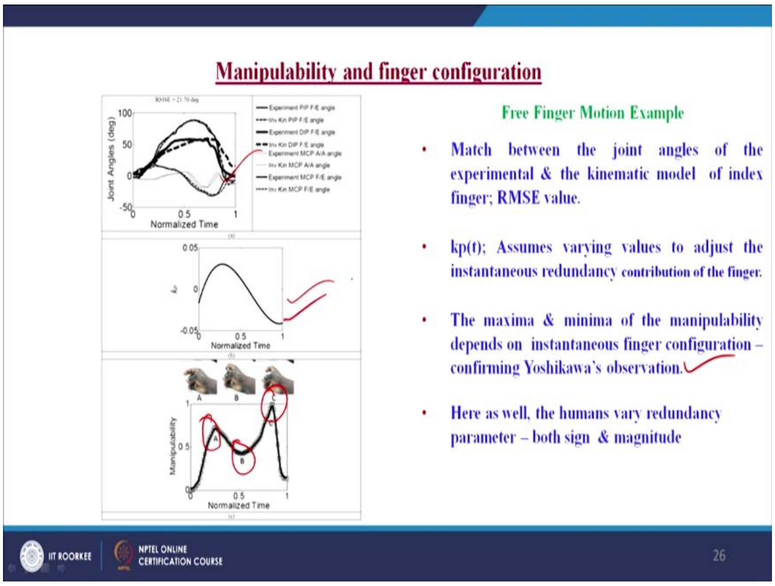

So, for this we have performed this analysis again for this index finger and we have plotted the profile which is almost closely matching with the experimental data with the root means square error of 21.70 degrees and the k_p also shows that it varies with the sign and magnitude throughout the finger configuration in obtaining the desired trajectory.

And, finally, the manipulative measure shows that it varies and it takes the value changing with the finger configuration as we can see that there is a peak in the configuration pertaining to posture A and for posture B it is having the valley here and we have in posture C we have again hill.

So, the maximum and minimum of the manipulability depends on the instantaneous finger configuration as it is confirming the results or the observation from Yoshikawa. Here as well the humans very redundancy parameter both in sign and magnitude let us see final observation.

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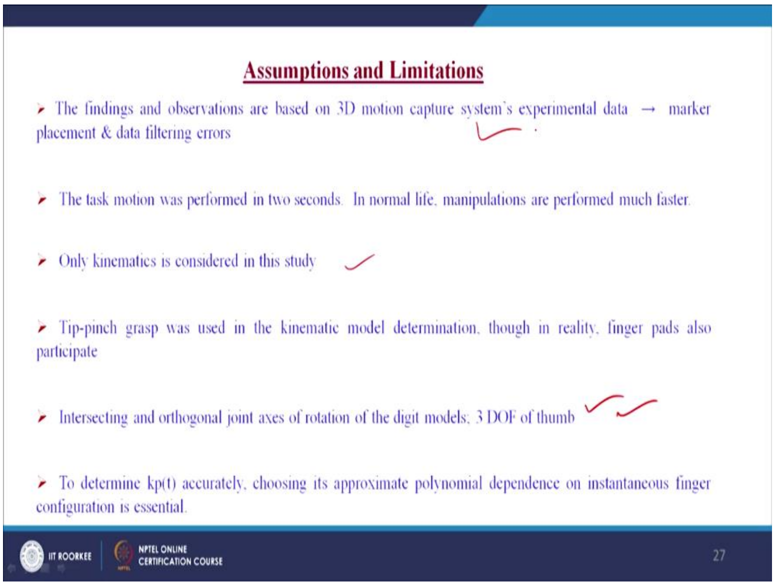

And, now coming to the assumptions and limitations we have performed we have considered only kinematics in this study, and the task motion was performed in 2 seconds. Generally, humans perform these type of activities of daily living very fast lesser than 2 seconds.

So, we have considered in our kinematic model the tip pinch grasp such that only point contact is considered though in reality finger pads also coming into picture. And, we have considered for the modeling of the finger joints in the kinematic model we have considered the orthogonal joint axis and the integral intersecting joint axis, but in reality by the biological modeling of the system we do not have the orthogonal joint axis, especially we have considered only the 3 degrees of freedom of the thumb, but it is basically it has 5 degrees of freedom.

And, the finding and observations are based on a 3D motion capture system experimental data and that data will be depending on the positioning or placement of the markers on the finger joints and also the data filtering errors. So, to determine the $k_p(t)$ that is the redundancy parameter variation with time accurately choosing it is approximate polynomial must also be necessary that is it we have considered the cubic polynomial may be it will be quintet also so, that observation, that exploration must also be done.

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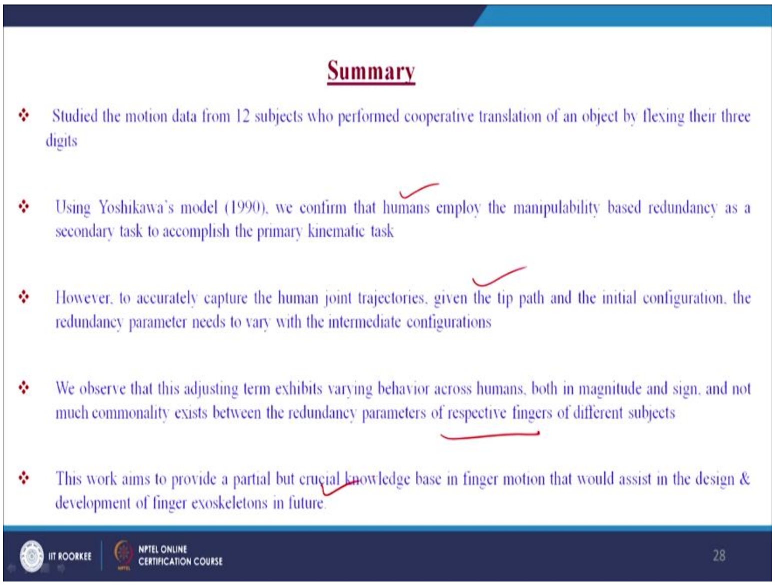

Now, coming to the summary the study we have studied the motion data of 12 subjects, human subjects performing the object translation task by flexing their fingers towards their palm. Using the Yoshikawa's model that is given in 1990, we confirm that the humans actively employ the manipulability base tendency as a secondary sub task while performing this primary sub task of tracking the given decide finger trajectory.

However, we observed that the redundancy parameter varies in both sign and magnitude in order to map with the joint coordinates of the human. We observed that this adjusting term can also have the variation towards a finger configuration, towards it you know to complete the full trajectory.

And, this work we believe that it aims to provide a partial, but crucial knowledge base in finger motion that would assist in the design and development of finger exoskeleton for cooperative motion translations in the future in the near future. So, we come to the conclusion that is summary of this study, experimental study. We studied the motion data of 12 subjects who perform the co operative translation of fine objects by flexing their digits towards their palm.

Using Yoshikawa's model we confirm that the humans employ the manipulability based redundancy as a secondary sub task in performing the primary sub task of tracking the decided trajectory for the fingertip. However, we from our inverse kinematic model we accurately captured the human joint trajectories given the tip path and the initial configuration the redundancy parameter needs to vary in the sign and magnitude with the intermediate configurations.

We observed that by adjusting this term exhibits varying behavior across the 12 subjects because these 12 subjects do not have the same profile. Even though if they have the same profile that kp profile varies in magnitude as well and, there exists lesser commonality between these subjects of the redundancy parameters.

And, this work aims at providing a partial, but crucial knowledge base for the challenges towards the design and control of finger exoskeletons for performing cooperative motions.

Thank you.