Robotics and Control: Theory and Practice
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Lecture – 24
Manipulability Analysis of Human Fingers in Cooperative Rotational Motion

Good morning; today we have the lecture on the topic Manipulability Analysis of Human digits in Cooperative Rotational Motion. The human digits involved in the study or the index finger, middle finger and the thumb.

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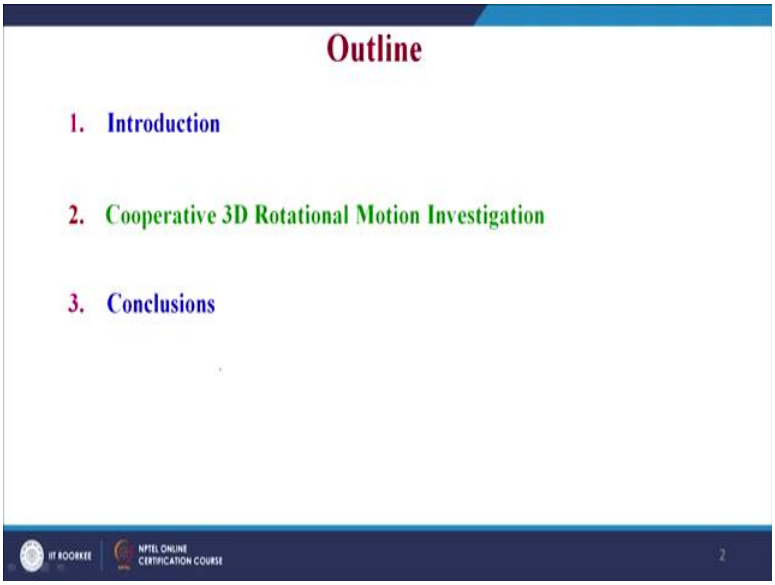

The organization of this presentation will be the introduction, then the methods involved in the cooperative 3D rotational motion investigation and then we have the results, finally, we have the conclusions.

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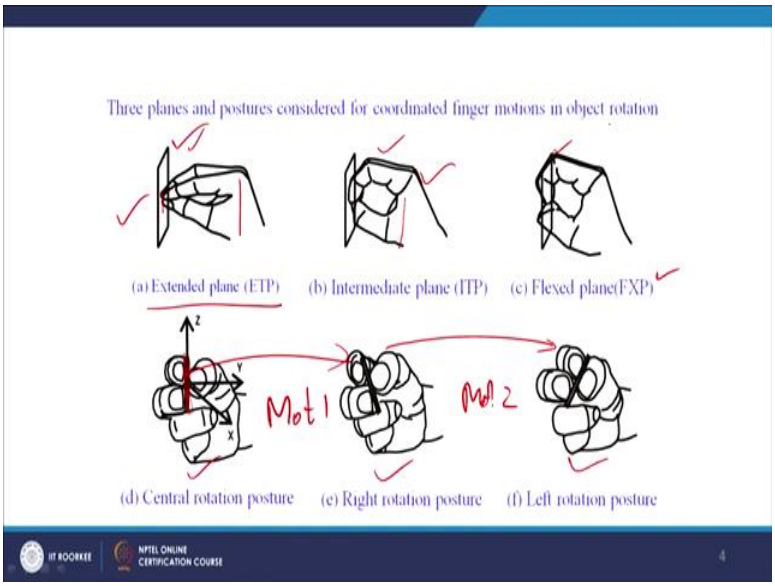

First coming to this 3D rotational motion; we have made a subject human subject to have a fine object which is basically a coin to be grabbed by these three fingers that is the index and middle fingers and the thumb as shown in the figure here.

This is the object that is grabbed by these three digits and asked the subject to move in a rotational fashion that is central rotational posture, right rotation posture and the left rotation posture such that it can be moved in these three planes. One is the extended plane that is ETP; that is the posture where the fingers joints are extended in such a way that is having greater distance from the finger tip to the palm.

Similarly, we considered the intermediate plane that is we have the moderate distance between the finger tips and the palm. Then we have considered these three rotational motions in the flexed plane given by; represented FXP term. Thus in each plane we have performed central rotation posture, right rotation posture and the left rotation posture.

Precisely in each plain we have performed two motions that is motion 1 that is from central to right rotation posture and motion 2 that is from right rotation posture to left rotation posture in each of these three planes.

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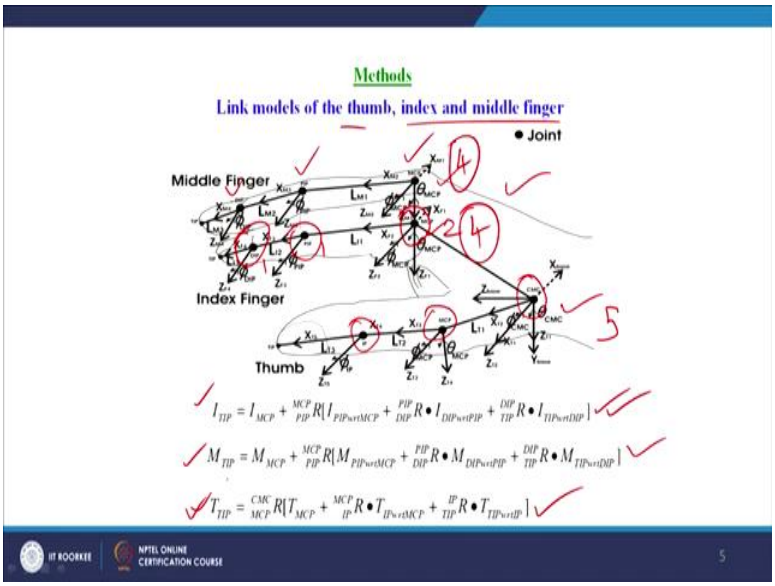

And we have investigated how these three finger digits have affected the behavior of the manipulability measure or we can say that how these three fingers behave in the cooperative rotational moisture based on the manipulability analysis.

The kinematic model of these three links or these three fingers that is thumb and index and middle fingers or given by these three equations that is I TIP equation for the index finger and the M TIP equation for the middle finger and thumb T TIP equation for the thumb; digit that is, we have modeled in such a way that the thumb is having total 5 degrees of freedom and the index finger and the middle finger are having each 4 degrees of freedom.

So, what are these 5 degrees of freedom of the thumb? The CMC joint is modeled to have 2 degrees of freedom that is flexion extension; given by phi CMC and the abduction adduction given by theta CMC. Similarly, the MCP joint of the thumb is given by 2 degrees of freedom; which is both having flexion extension given by phi MCP and the abduction adduction given by theta MCP.

Then the IP join interphalangeal joint of the thumb is given by 1 degrees of freedom which is a flexion extension which is the generalized coordinate given by or represented by phi IP. Similarly, the index finger is having 4; is modeled with 4 degrees of freedom that is MCP joint having 2 degrees of freedom that is abduction and adduction and flexion extension movements. Then the PIP joint having 1 degrees of freedom that is flexion

extension; similarly, the dip has 1 degrees of freedom that is flexion extension. And hence it has 2 here; 1 and 1; totally 4 degrees of freedom.

Similarly, the middle finger just follows the total degrees of freedom of the index finger; does it has also has 4 degrees of freedom. Whereas, the overall kinematic model of this 3 digits coming out to be 5 for the thumb, 4 for the middle index finger and 4 for the middle finger. Does the kinematic equation relating the joint angles to the tip is given by this equation I TIP; for the index finger forward kinematic equation and the M TIP that is the middle finger forward kinematic equation and the T TIP that is a thumb tip forward kinematic equation which has relationship between the joint angle and the fingertips.

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Now, this study has been investigated with the human subjects; with the total of 30 subjects; most of the subjects are put here or shown here with the pictorial representation. So, these subjects are performed under the motion capture system focusing on their hand part alone; by the motion analysis capturing systems with a cameras placed around them so that their finger motions are focused.

Because by having the markers placed on their finger joints and having a fine object grabbed by these three digits; we have investigated how the human digits behave during the cooperative rotational motion having rotation of a fine object; based on manipulability analysis.

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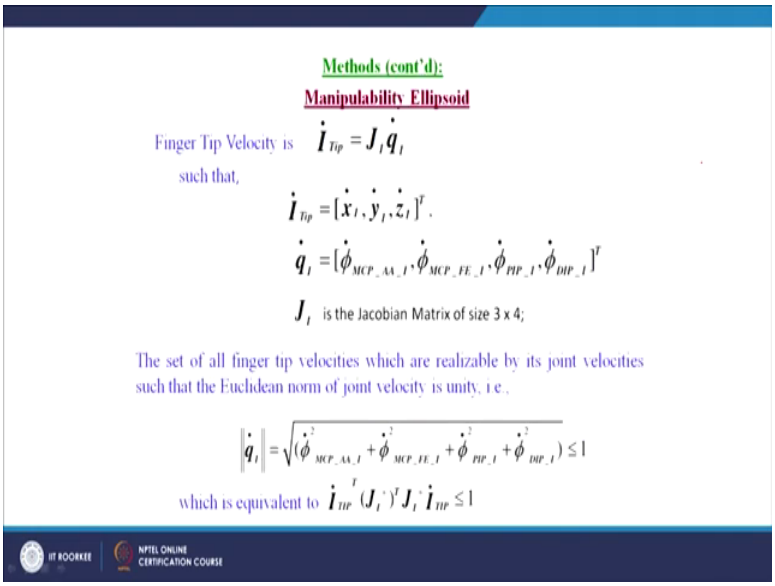

Precisely, there are a total of 15 auto reflective markers which are the passive markers are placed on each finger joint as shown here; that is the thumb has three joints and placed on the tip as well and similarly the index finger and the thumb index finger and the middle finger.

And then we also have placed 3 markers on the dorsal side of the hand so that we could have them throughout the motion having them in the straight line so that, they cannot be moving such that the fingers of that the motions performed by all the 30 subjects could be in the uniform fashion. And each marker size is of size 6 millimeter diameter and this markers positions are captured by the motion analysis corporation; 3D motion capture system and this is a passive marker. What the difference between passive and active marker? Passive marker is a one when light is projected on it; it gets reflected, reflecting that and hence we could see the position of that marker.

Whereas the active marker is the one where it is the one example is the LED; it has its own power, it does not need the external source.

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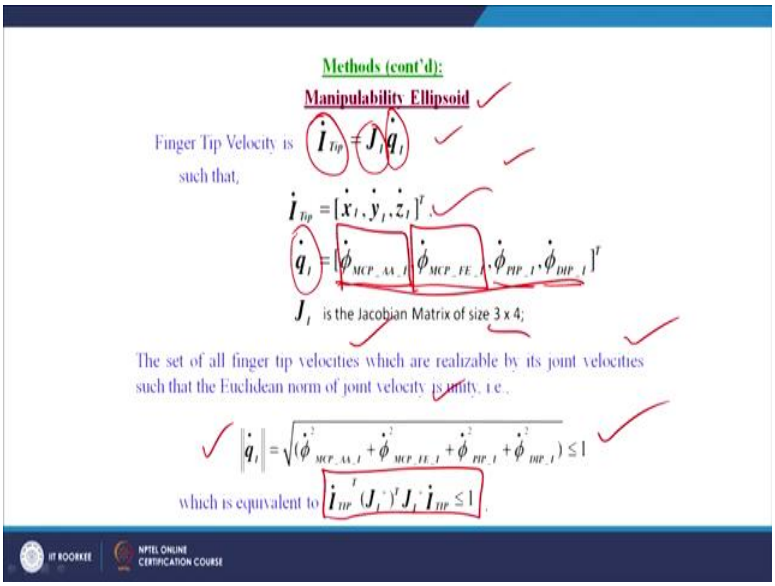

And now coming to the manipulability ellipsoid; so first of all we consider the fingertip velocity that is a Cartesian velocity is given by the expression $\dot{I}_{Tip} = J_1 \dot{q}_i$; where $\dot{q}_i$ is the joint angular velocity and $\dot{I}_{Tip}$ is the Cartesian velocity of their finger; where J is the Jacobian matrix which is the one; which maps the joint angular space to the Cartesian space.

And the $\dot{I}_{Tip}$ is given by the expression $\dot{x}_i$, $\dot{y}_i$ and $\dot{z}_i$ because the tip for example, for the index finger and middle finger and the thumb all are having the motion in the Cartesian space in 3D form. And the $\dot{q}_i$ is given by is composed of these four parameters for the index and middle finger that is joint angular velocity of the abduction, adduction angle and joint velocity of including the MCPs joints flexion extension and PIP joints flexion extension velocity and dip joint flexion extension velocity. Thus it has 4 degrees of freedom and hence the size of the Jacobian matrix will be 3 cross 4 which maps the joint angular velocity to the (Refer Time: 08:50) velocity or the tip velocity.

Now, coming to the definition of the manipulability ellipsoid as given by the author Tsuneo Yoshikawa; from him the definition has been taken as such, that is the set of all fingertip velocities which are realizable by the joint velocity such that the equality and norm of the joint velocity is unity; that is given by this expression $\dot{q}_i$ nor is equal to $\sqrt{\dot{\emptyset}^2}$

MCP abduction plus $\dot{\emptyset}^2$ MCP flexion extension plus $\dot{\emptyset}^2$ PIP plus $\dot{\emptyset}^2$ dip which is less than equal to 1 which is equivalent to the expression; this is the manipulability ellipsoid expression which is given by $\dot{I}^T{}_{Tip}$ multiplied by J_I^{+T}; multiplied by J_I^{+T} multiplied by J_I^+ into $\dot{I}_{Tip}$ which is less than equal to 1.

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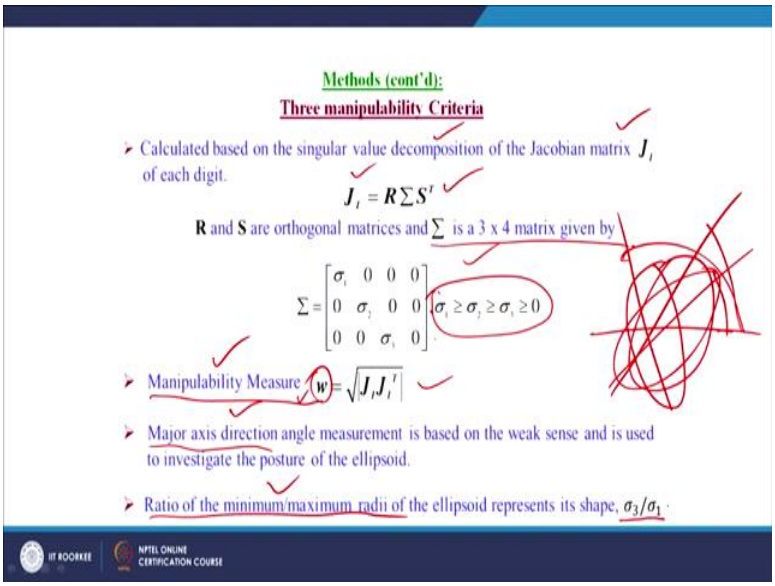

Now, coming to the tree manipulability criteria which are considered in our study; the three manipulability criteria precisely are manipulability measure and major axis direction angle; what is that I am going to tell you and the ratio of the max minimum to maximum radii of the ellipsoid.

So, first of all how these three criteria are calculated? Yes, these are calculated based on the singular value decomposition of the Jacobian matrix; J_I of each digit. In our case, in our study we have considered thumb index and middle finger. Thus taken example for index finger it is $J_I = R\sum S^T$; that is the singular value decomposition of the Jacobian matrix; J is given by $R\sum S^T$, where R and S are the orthogonal matrices.

And $\sum$ is a 3×4 matrix for this finger index and is given by $\sum$ equal to $\begin{bmatrix} \sigma_1 \\ 0 \\ 0 \end{bmatrix}$; the second column is $\begin{bmatrix} 0 \\ \sigma_2 \\ 0 \end{bmatrix}$ and third column is $\begin{bmatrix} 0 \\ 0 \\ \sigma_3 \end{bmatrix}$. If it is having 4 degrees of freedom; if it is of

size 4×5, then it will be $\begin{bmatrix} 0 \\ 0 \\ 0 \\ \sigma_4 \end{bmatrix}$. as well and the last column will be $\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$. And then this where σ_1 to σ_3 are given basically by the radius of the principal axis of the ellipsoid and in this case it is given by the condition which is σ_1 greater than equal to σ_2, greater than equal to σ_3, which is greater than equal to 0.

And now coming; having the singular value decomposition of the Jacobian matrix and all the singular values of the Jacobian matrix, we could able to compute the three criteria. The first one being the manipulability measure which is given by $\sqrt{|JJ^T|}$. Because it is redundant system that is that system has 4 degrees of freedom where the Cartesian plane is Cartesian space is having 3 degrees of freedom in this case.

And hence 4 to 3 mapping and hence 1 degrees of freedom is redundant here; does it is a redundant system and hence we have the manipulability measure given by the expression $w = \sqrt{|JJ^T|}$. If it is a nonredundant system, the manipulability measure w is given by determinant of J.

So, now coming to the second criterion that is the angle; that is a major axis direction angle measurement based on the weak sense and is used to investigate the posture of the ellipsoid. Yes, this first one is the manipulability measure and the second one is the major axis direction angle which gives the information about the posture of the ellipsoid; that means, if this is the x axis and this is ellipsoid for example, and it can give how the posture how it is configured with respect to the x axis in this way, this way or this way.

And now we can see that that is the major axis direction angle you can see; that it is varies from here from the axis here or here or could be here. So, the form or the posture of the exoskeleton; posture of the ellipsoid is given by this criterion which is major axis direction angle. But what is given by this manipulability measure?

Yes, that gives the volume of the ellipsoid and the third criterion that is the ratio of the minimum to the maximum radii of the ellipsoid represents its shape. Yes, the third criterion which is the ratio of the maximum; ratio of the minimum to the maximum radii is given by in this case it is $\frac{\sigma_3}{\sigma_1}$. It gives the shape of the ellipsoid does we could have; from this three criterion we could have the shape of the ellipsoid, form of the ellipsoid and the

volume of the ellipsoid; manipulability ellipsoid I mean to analyze the behavior of these three fingers in the cooperative rotational motion of his fine object which is the coin in this case.

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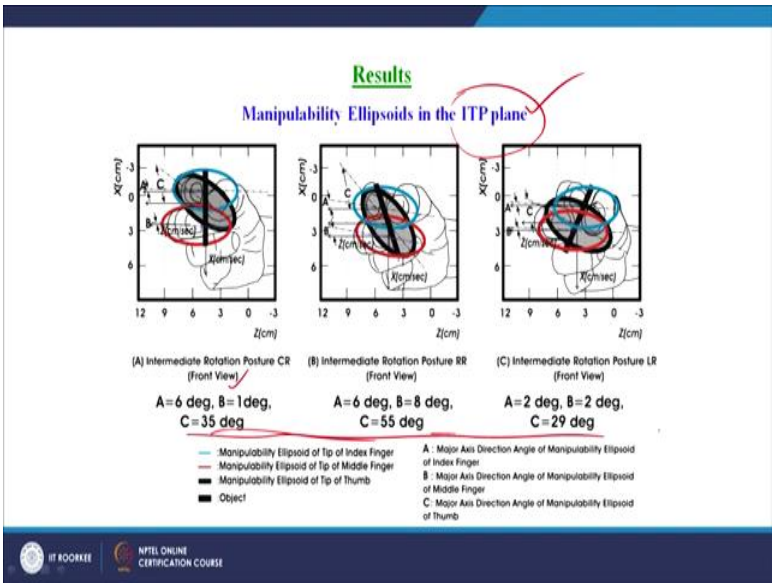

Now, coming to the results; yes, how these 30 subjects behaved? So, one of the subject's configuration is taken during the object rotational motion and first we have taken the results for a subject in the ETP plane; that is extended plane.

So, in that case you can see that in the figure in the left side that is figure A, figure B, figure C. In the figure A, we could see that in all the three figures I am explaining what is that; first of all, you can see that the ellipsoid, you can see the three digits or having a an object which is given here. This is; the black one is object and the ellipsoid having the color blue one is the ellipsoid of the index finger and the ellipsoid made up of the color red is the ellipsoid of the middle finger. Then we have the ellipsoid which is the thicker ellipsoid with a shaded part; it is the ellipsoid of the thumb which is black in color here.

And the object is shown here as I mentioned and their clearly explain in this bottom posture or bottom position of the slide here. And now angle A, B and C represents what? Yes, angle A represents the major axis direction angle of the thumb ellipsoid; sorry it is for the index ellipsoid. And angle B that is major axis direction angle of the manipulability ellipsoid of the digit middle finger. Then the angle C is a one that represents the major axis direction angle of the thumb ellipsoid. So, now you can see here that is from central

rotational posture to the right rotational posture; this is called motion 1 and from the right rotational posture to the central rotational posture to the left rotational posture it is called motion 2.

So, as you can see that we have the angle varying from this motion 1 to motion 2; as you can see that in motion 1; you have the variation of the ellipsoid angle of the thumb you can see the variation is from 29 degrees to 42-degree variation. Similarly, the variation in motion 2; it is 42 degrees to 22 degrees here.

And this variation in this criterion is very large compared to that of the index finger and middle finger. As you can see that the angle values for the angles A and B or 3 degrees and 4 degrees from that; it is having from central roast rotational posture to the right rotational posture that is motion 1; we have the difference is hardly 1 to 2 degrees only.

And similarly for motion 2; it is the same, it is hardly 2 degrees whereas, for the thumb it is having a larger variation that is varying from 29 degrees to 42 degrees and then 42 degrees nearly to 20 degrees. Does the variation of the thumb ellipsoid in this criterion that is the major axis direction angle has the greater variations from motion 1 and also in motion 2; that is from CR rotation posture to right rotational posture in motion 1 and in motion 2; that is from right rotation posture to the left rotation posture.

Then, similarly the results also been investigated in this motion or the performance of the behavior of these three digits also been investigated in intermediate plane that is ITP. Why we consider the ITP as a very important plane is; most of our tasks in the daily days or in the activities of the daily livings or performed in the comfortable region that is intermediate plane only and this investigation is carefully considered.

So, in this ITP plane also we have observed that the variation of the thumb manipulability ellipsoids angle; major axis direction angle is greater as compared to that of the index finger and the middle finger angles. And thus we have the variation almost to close to 20 degrees from motion 1 and also 20 degrees in motion 2.

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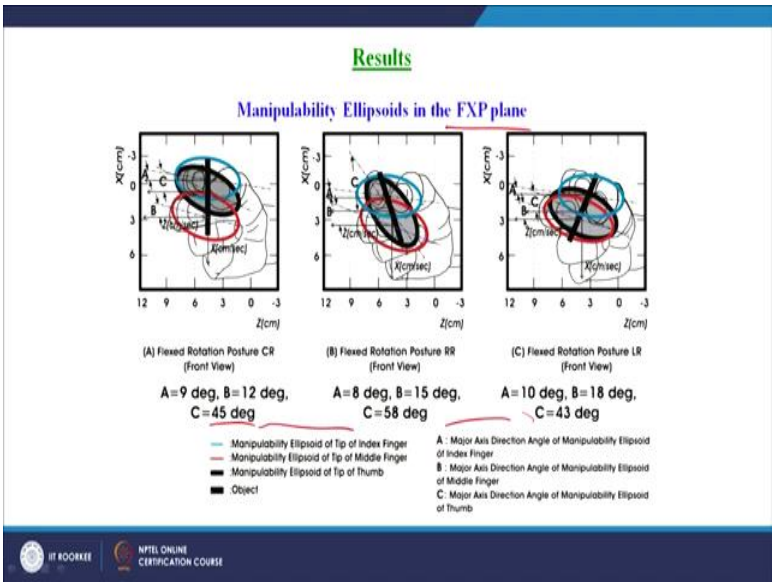

Likewise, we have observed the behavior in the FXP plane; that is the flexed plane. There also been could observe that the thumb exoskeleton thumb ellipsoids major axis direction angle has greater variation in motion 1 and also greater variation in motion 2; compared to that of the index and middle fingers, where they are hardly wearing 2 to 3 degrees.

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Variation in Criteria	Motion I								
	ETP			ITP			FXP		
	Thumb	Index	Middle	Thumb	Index	Middle	Thumb	Index	Middle
Major Axis Direction Angle (deg)	20.00 (3.50)	4.00 (1.00)	5.00 (2.00)	20.00 (3.00)	2.00 (1.00)	5.00 (2.00)	13.00 (2.00)	4.00 (1.00)	2.00 (1.00)
Minimum/ Maximum Radii	0.10 (0.02)	0.02 (0.01)	0.10 (0.01)	0.18 (0.02)	0.03 (0.01)	0.10 (0.02)	0.13 (0.02)	0.08 (0.02)	0.09 (0.02)
Ellipsoid Volume	0.13 (0.05)	0.05 (0.01)	0.20 (0.01)	0.12 (0.02)	0.02 (0.01)	0.13 (0.01)	0.10 (0.04)	0.06 (0.03)	0.05 (0.06)

Now, coming to the criteria differences of the three digits in motion 1 of all the three planes for all the 30 subjects; so first we take the criterion that is the major axis direction angle in

the ETP plane. We have the mean variation for the thumb is 20 degrees and the mean variation for the index and the middle finger are hardly 4 and 5 degrees respectively.

And this variation is more for the thumb ellipsoid in all the three planes ETP, ITP and FXP. Likewise, we take the second criterion that is the minimum to maximum radii criterion which is the one which indicates the shape of the; the ellipsoid. Here, also we could see that the middle finger has greater variation compared to that of the index finger and also the thumb has greater variation compared to that of the index finger.

And then we have the thumb in the ITP greater than index finger very significantly and the thumb is also and the middle finger is also greater than the index finger significantly. Then in the FXP, the variation for a middle finger and the index finger are almost to same whereas, the thumb has greater variation compared to that of the other two fingers.

Then the manipulability ellipsoid; that is the manipulability measure that is the ellipsoid volume is happening what; and here we could observe that the manipulability ellipsoid volume is more for the middle finger in all the cases except the case of FXP. So, in both the ETP and ITP; the criterion of manipulability ellipsoid volume is higher for the middle finger and only in the FXP; the thumb is higher than the other two digits. So, thus we could say that both the thumb and the middle fingers having greater variation in all these three criteria compared to that of the index finger.

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Table 2: Criteria differences in Motion II of the three fingers in all the planes

Variation in Criteria	Motion II								
	ETP			ITP			FXP		
	Thumb	Index	Middle	Thumb	Index	Middle	Thumb	Index	Middle
Major Axis Direction Angle (deg)	19.00 (3.0)	3.00 (1.00)	8.00 (1.00)	22.00 (4.00)	3.00 (1.0)	4.00 (1.0)	14.00 (1.00)	5.00 (1.0)	5.00 (1.00)
Minimum/ Maximum Radii	0.09 (0.03)	0.08 (0.01)	0.17 (0.02)	0.18 (0.02)	0.07 (0.03)	0.14 (0.04)	0.13 (0.02)	0.10 (0.01)	0.18 (0.02)
Ellipsoid Volume	0.18 (0.05)	0.14 (0.03)	0.25 (0.04)	0.14 (0.01)	0.13 (0.03)	0.23 (0.01)	0.11 (0.02)	0.08 (0.02)	0.20 (0.01)

Similarly, in motion to the variation of these criteria are shown precisely here such that the thumb and the middle fingers have greater variations as compared to that of the index finger. So, you can see that the index fingers variation is significantly lesser than these two digits in all these three planes. In all the three planes, we compare that each of these criteria; we see that either the middle finger or the thumb or both the middle finger and the thumb or greater or having greater variation than that of the index fingers variation of these three criteria both in all ITP, ETP and FXP planes.

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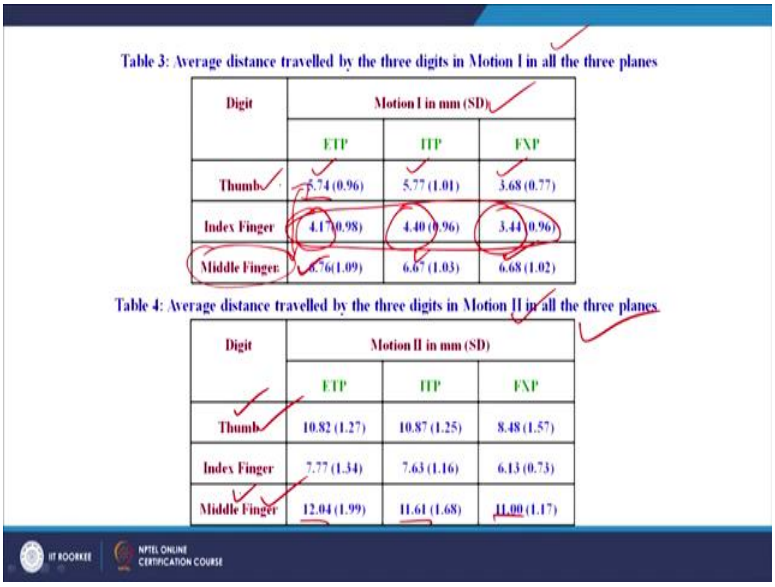

Now, we could also compute the average distance travelled by the three digits in both motion 1 and in motion 2. So, compared to the distance travelled by the three digits in the motion 1 and motion 2; first in motion 1 the thumb has the distance travelled 5.74 unit compared to that of the other digits.

So, you can see that here also we could see that significantly the mean value of the index finger for all the 30 subjects is lesser compared to that of the mean value of the distance travelled by the other two digits. We could observed that compared to all the three digits; the middle finger has greater distance travelled that is nearly 6.76 unit than the other two digits.

And there is no much difference between the distance travelled by the two digits that is thumb and the middle finger; whereas, there is a distance that is a significant difference

between the middle finger and index finger and also the thumb and the index finger. Thus, the index finger has moved lesser compared to these two digits.

Also in motion 2, we have observed the same both the thumb and index finger have significantly greater distance moved in the both to; in the both motions that is motion 1 and motion 2; we have observed that both the digit's thumb and index finger have moved greater distance than that of the; thumb and middle finger have moved greater distance than that of the index finger.

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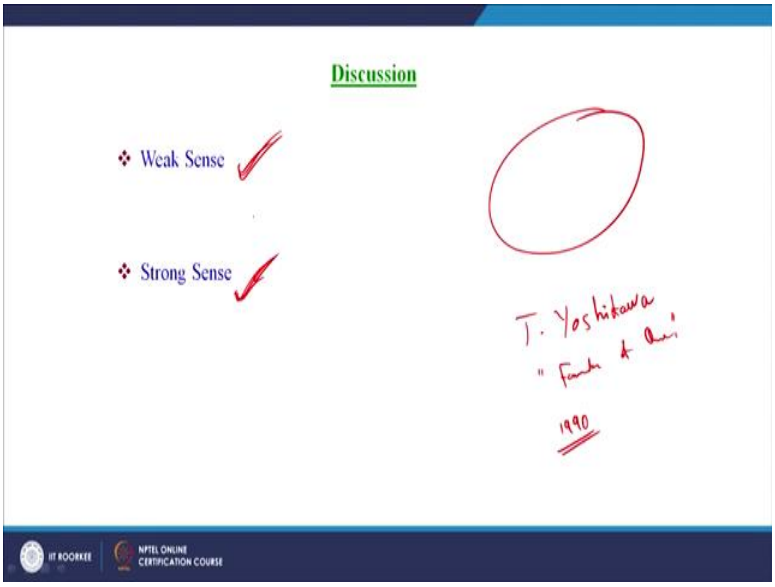

Now, coming to the quick discussion about the weak sense and strong sense; as I mentioned that we have considered the ellipsoid criteria based on the weak sense.

So, what is weak sense and what is strong sense? So, we have seen that; we have mentioned that we have taken the ellipsoid, from the ellipsoid we could able to get the ellipsoids major axis direction angle by this method only. We have what we have done because we have sliced the ellipsoid and we have projected it back on the plane of interest to obtain the major axis direction angle.

And hence we have sliced it and the projected onto the plane of interest to measure the major axis direction angle. This method we involved in our study is coming under the category weak sense. If this method is not used that is directly we use the ellipse without projection; then that method is called strong sense; strong sense. And the greater that is a

detailed explanation of this weak sense and strong sense is given by the book by Tsuneo Yoshikawa; that is Foundations of Robotics in 1990; the first print has come out; by this book we could able to get more about this weak sense and the strong sense.

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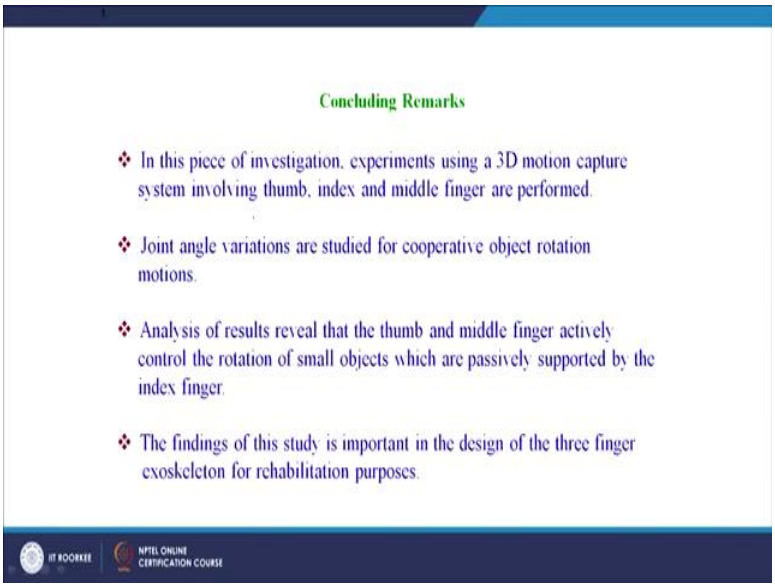

Now, coming to the concluding remarks; so in this piece of work or investigation, the experimental using 3D motion capture system having the human subjects for a total of 30 subject have been used to perform this cooperative object translation task.

The object used here is a fine object which is a coin in this case and we have studied the joint angular variations for this cooperative object rotational motions and we have considered both the motion 1 and motion 2; that is motion 1 which is having the rotational motion from central rotation posture to the right rotation portion and the motion 2 from right rotation portion to the left rotation portion. The analysis of the results reveal that; both the middle finger and thumb or active; whereas; the index finger is acting passively to support the other two digits.

Now, coming to the point what is a definition; what is activeness and passiveness of a digit? Activity of a digit is nothing, but the in independency of a digit or the digit when it is active; it does not depend on the other digits; whereas, when I digit is called passive its motion depend on the motion of the other digits. And the findings of this investigation will be helpful in designing and developing a finger exoskeleton for rehabilitative purposes.

Thank you.