Exercise & Sports Biomechanics
Dr. Rahul Tiwari
High performance Analyst – Biomechanics, SAI
Netaji Subhas National Institute of Sports, Patiala (PB)
Week 09
Lecture 43
Measurement of CoG

[Hello friends! In this section, we are going to discuss about analytical procedure].

Analytical procedure:

We are talking about the **mathematical estimation**, we are talking about the **dynamic measurement**, and we are talking about the **digital tracking**.

In the **mathematical estimation**, we will talk about the **segmental methods**. So, there are total three methods, I will be talking one by one. In **dynamic measurement**, we will be talking about the **force plate analysis** and in the **digital tracking**, the **video motion analysis** and the **software-based analysis.**

Segmental method:

In contrast to the experimental method, it does not require the presence of the performer when the measurements are taken. So, the location of the center of gravity in two axes can be determined on a photograph or on a desired frame in the film. So, center of gravity can be determined in various body positions while executing any movement. This procedure is based on the principle of moments, which says the sum of moment of individual body segment about two axis is equal to the resulting moment of the total body about the same axis. And the moment can be calculated using segmental mass and the center of mass.

The segmental method is the estimation of the location of the body's total center of gravity. It is based on the concept that each individual segment has its own center of gravity. A standard set of values for mass ratio and the center of gravity for each body segment is used. And a Cartesian coordinations are obtained for each segment. A study on cadaver by the **Dempster in 1995**, it helps us quantify the body segments parameter.

The formula to calculate the center of gravity is CoG equals summation D multiplies by W divided by the summation W.

$$CoG = (\sum D * W) / \sum W$$

In other words, the formula is the location of the center of gravity can be found by summing the multiplication of distance by weight and dividing it by the summation of weight. So, for this, we need to identify the weight of all the segments like this, and then the distance from the particular axis. We will talk in detail in coming up slides. So, a study done on the cadaver, they collected the data on eight complete cadavers to determine the center of rotation of each joint, the segmental length and the mass and the volumes and they concluded that the CoG location for example for the hat is basically 59.8% from the vertex or I can say the 59.8% of the length from the vertex. And the relative mass is 6.97

percentage or I can say 0.007 percentage. So, approximate is coming around 0.007 kind of thing. And for the trunk, the length is 44.9% from the supersternale notch and the relative mass is 43.46% of the total weight or total mass because trunk is the biggest part. You can see the weight as well.

The upper arm is the center of gravity location is 57.7% from the shoulder of the length of the upper arm and the relative mass will be something like this. So, similarly they identify the center of gravity location for all the segments like for the head, trunk, upper arms, forearm, hands, thighs, shank and the feet and the relative mass for all those things. So, for this we need to first mark the anthropometrical points for all the segments.

Using the segmental method to measure Center of Gravity – Demonstration:

[So, let us have a demonstration for all these things first].

Let us take an example where we have this particular picture, and we need to identify the center of mass or center of gravity of this particular position.

1. In this position, **step one** will be to first make an educated guess about the location of the center of gravity. So, let us say I am making a guess somewhere around here—let us say, because he is coming down, the center of gravity may be somewhat lower, but let us take an example: this is my guess.

2. **Step number two** Now, carefully mark the following segment's endpoint on your drawing. So, the vertex will be somewhere around here. Let us change the color of the pen first. So, this could be the vertex. Then, the chin-neck intersection will be somewhere around here. Then, the suprasternal notch will be somewhere around here. The shoulder axis will be somewhere around here. The elbow will be around here. The wrist will be up around here, and the knuckle will be up around here. Similarly, the hip axis will be around the GT. The knee axis at the knee joint line, the ankle around the malleolus, the heel, and the toes. So, these could be the anthropometrical markings that we need to do. So, this is step number two.

3. **Step number three** will be to construct a stick figure by drawing straight lines between the appropriate endpoints.

4. **In Step four** measure this particular distance. What is the distance? Measure the distance as well, right? So, let us have a table something like this,

5. In **step number five**, using the length and data, express each body center of gravity as the percentage of the segmental length to calculate the CoG of each body segment. So, in the previous picture, just measure the length of the head segment. From the vertex to the intersection of your face and neck, the trunk, or whatever point we marked. So, have a length there like this. The center of gravity location, given as a previous model, is basically we know that 59.8% from the vertex for the head. So, just multiply this with the length. So, it will be a percentage. So, dividing by 100, it will come out to 0.598. So, the length multiplied by 0.598. So, the center of gravity for the head will come out like this. For the trunk, it will come out like the length multiplied by 0.449. For the upper arm, it will be coming like 0.577. For

the forearm, it will be coming like the length multiplied by 0.457, and likewise for all the segments.

6. As **step number six**, mark the segment center of gravity location on your diagram. So, let us say, this is coming up something like—so let me just change the color of the pen again. So, mark the point which is coming as the center of gravity of the particular segment like this. You can see the marking here. Right, you can see the marking here. Kind of thing. Yeah, here as well. Here as well. Here, everywhere, right? And here as well.

7. **Step number seven**: plot the horizontal and the vertical axis. Then, for each segment, measure the horizontal and vertical distance from each CG location to each axis. So, have a Y-axis, plot the vertical axis here, and the horizontal or X-axis will be here like this. And measure the distance of each segment from both the vertical and horizontal axis like this. So, this is the distance from the vertical axis, and this will be the distance. So, this will be from the vertical axis, this will be from the horizontal axis like this, something like this, something like this, like this, like this, like this, for all the segments. Both the vertical as well as the horizontal axis.

8. **Step number Eight** will be to find each segment's moments about each axis: multiply the relative mass of each segment by its distance from the axis. So, the distance from the axis needs to be measured first. So, just have a table for better understanding. So, the relative mass will be something like this. This is in percentage. And the horizontal center of gravity distance—the distance from the head segment—will be noted down here, from the trunk, from the upper arm, and so on for everything. And when you multiply this distance by the relative mass, the percentage mass, right? So, this will come to around 0.007 as an approximate figure—something like that. So, for all the distances, just multiply the relative mass with the horizontal distance from the x-axis, so it will result in a horizontal moment. Similarly, from the y-axis, we will get a vertical moment. So, the distance from the vertical axis will be noted here. Then, sum all the values here—the sum of all the values will come up here like this—and for the y-axis, it will come up somewhere around here.

[Now, as the next step]

9. **Step Nine**, calculate the x and y coordinates for the total body center of gravity by dividing the sum of segment moments about each axis by the total relative body weight, which is 100, representing 100% of the body.

10. **Step ten** Plot the center of gravity location on your diagram. Check against your estimated base. So, it will be like this. If the coordination value will be coming up like this on the X and Y will be coming like this. So, the intersection point will be considered as the location of the center of gravity. So, it is far far far from the point where we estimated earlier.

Joint point method:

Another method is the joint point method. This is also a segmental method only. So, this procedure is also based on the principle of moments. The sum of moments of individual body segment about two arbitrary axis that is x and y is equal to the resultant moment of total body about the same axis and to compute the moments of individual body segment masses of these segments and their mass center that is the segmental center of gravity should be known. As to obtain the data on segmental mass and their mass centers for every individual is very time consuming usually the ratio over the percentage are taken. So, these values have been obtained from various methods as discussed earlier and are presented in the coming up slides. So, for this particular method we need to have a two axis again. The y axis something like this and the x axis will be something like this. So, the two axis are drawn on the photograph.

Just take a photograph and make a two axis and joint of the bodies are marked. So, mark all the joints which are needed like this, like this, like this on both the sides. You can see the shoulder, elbow, wrist. I think we need to have a knuckle as well. The hip, knee, ankle on both the sides, right?

Determination of CoG – Joint point method:

[Have some table ready like this. So, like the body parts, the relative weight. Just mention all the things like the head, shoulder joint, elbow joint, wrist, hand, hip joint, knee joint, ankle joint, and the foot].

So head is okay one and for the both the joints mention the right and left sides separately like this because we are having two sides and we are going to calculate the segmental center of mass for all the sides right and left, right? And the relative body weight has come from the previous table. For example, this is a segment. This is a head. Okay. So I know the. So, this is a point, for example and if this is a y axis, this is a x axis. So, the distance from the x axis will be written somewhere around here and the distance on the y axis will be written somewhere around here. The moment will be basically the distance multiplied by the weight. So, this will be this will be coming as a moment for x and again that weight distance from the y and multiplied by x will be coming up around here. Like this and like this.

So do a summation for both the things here. The summation will be coming up here. So, you will be getting an x coordinate here and you will be getting a y coordinate here as well. So, for this particular plot, let us say on the y-axis the value is coming here, on the y-axis, x-axis it is coming up here. So, the intersection point of this two, whatever, and so this will be the center of gravity of the particular object or particular person.

Let us have a demonstration. I always suggest having graph paper for this kind of analysis because the measurements will become much easier. So, let us take a photograph like this, okay? And have an x-axis, y-axis, and alongside the x-axis, have a table ready beside you— the same table, okay? Mark all the points as mentioned, like the head, shoulder, and all the other points, and measure the distance of each point from the y-axis. Similarly, do this. And from the x-axis, something like this. So, the distance from the x-axis will appear here.

The distance from the y-axis will appear here. So, the distance from the y-axis will be this distance. From the x-axis, it will be this distance. For the right shoulder, it will be the smaller line, this one. The left side will be this one.

The distance from the x-axis for the left and right—left and right—the y-axis will appear here, and the moment will be the x multiplied by the relative body weight, like this. The y will be the y-distance multiplied by the body weight, like this. Similarly, we need to fill up all the places here, all the places here, all the places here, and all the places here. And in the end, we need to have a summation of the x-coordinates and the summation of the y-moments.

Let us say the x-coordinate will be coming up around here. And the y-coordinate will be coming up somewhere around here. So, the intersection point of these two will be the point where the center of gravity of this particular person is located.

Main point method:

[Moving to the next method, which is called the main point method].

In a modification to the joint point procedure, the force acting on the mass center of each segment is divided into two parts. And each force acts on the proximal and the distal joint. So, in place of the partial mass, the force acting on the two adjacent joints is used, and the moments are computed about the two arbitrary axes by multiplying the force with the distance from the axes. The measurement and computational procedures are similar to the previous methods. This procedure is called the main point method, and as in the previous method, a table is used to record and calculate the position of the center of gravity. Such a working table for the same will be presented here. Like this. So, the table is somewhat different from the earlier one. So, we are having the same body parts.

 But here we have the upper arm and forearm, the same kind of thing is here. But we are dividing the whole body segment into different proximal and distal segments like this. So, for example, if this is a head. So, just measure the length of the head first and divide it into 3 proximal and 1 distal part. So, the easiest thing is 3 and 1 become 4. So, divide it into 4 parts. The 3 fourths proximal. So, this will be proximal, right? So, this will be from the proximal point. So, here the 3 parts will be somewhere around here.

So, this will be the center of the mass of that particular object. Similarly, from the trunk for the upper side—the upper arm, lower arm or forearm, the upper leg, lower leg, the foot, and the hands—will be calculated, right? And the total length will also be needed here. So, the total length will be calculated here. For example, the total length here will be 12 centimeters.

The proximal part will be 12 cm; if I divide it into 4 parts, 3 parts will be 9. Right, and the one part will be 3. Let's say this is the trunk—let's say it is 10 centimeters, for example. The three-part proximal will be 6, and the distal will be 4. This way, we basically calculate the measurements, and this part will be marked. On the particular picture as the center of rotation of that particular point, the relative weight we all know from the previous table, okay? We need to calculate the distance of this particular point from the x-axis and the y-

axis, this particular point from the x-axis and the y-axis, and it will be written here like this. Like this.

This is the distance from the x and y axes. So, here the moment will again be the x multiplied by the weight and the y multiplied by the weight. Simple. In the end, we get the summation similarly, and the intersection point of these two coordinates. This will be the center of gravity. So, let's have a demonstration. Again, as previously suggested, have a graph paper, have a picture attached, have an axis drawn, and have a table side view like this. First, mark all the anthropometrical points, like this and then mark this center point. You can see this yellow point. This is basically based on this calculation, 3 fourths from the proximal. So, this yellow point is basically the center of rotation or the center of mass of that particular segment. This is based on the researches that has been done on the cadavers. And then we need to measure the distance of this center from the y-axis and similarly on the x-axis. So, like this, the distance need to be measured like this from all the points and from the x-axis as well.

The distance will be coming on the y will be coming here. Sorry, this is approximately, sorry, the x will be coming up here and the y will be coming up here. So, the moment will be the x distance multiplied by the weight and the y multiplied by the weight and in that end we are basically getting the summation of the x coordinates and the summation of the y coordinates. And the intersection point will be the point where the center of gravity is located. It is as simple as that.

In the next part of the video, we will have a practical demonstration of this as well. So, this is just an explanation here. I will have a session where I will demonstrate this on an exact graph paper.

Dynamic measurement:

The next method which I will discuss here is the dynamic measurement, and that can be done by using the force plate analysis. So, this method uses the force plate to measure ground reaction forces and determine the center of gravity shift during the motion. So, to measure the center of gravity on a force platform, a person stands on the force plate while it records the ground reaction forces at multiple points across their feet, allowing for the calculation of the moment arm and subsequently determining the center of gravity location by applying the principle of moments. So, essentially, finding the point where the sum of all the moments around it becomes zero, and this is typically done through specialized software that analyzes the force data and calculates the CoG position based on the platform's design and the measured forces. So, in the previous stages, what we did was basically all the manual method.

We identified the moments of the particular segment, and we basically identified the coordinates of the X and Y axes. But here, the software is doing everything for us. We just simply need to stand on the force plate and click the button of the mouse. That is it, right? The principle is the same.

The CoG is computed by analyzing how weight is distributed over the plate in real time. It is commonly used in sports performance analysis, gait studies in rehabilitation, and

jumping and landing mechanics research. The advantages are that they are highly accurate, useful for dynamic movements, and the limitations are that they are very expensive and require a specific laboratory setup to conduct the test.

Digital tracking:

Coming to the last segment, which is digital tracking, we will be discussing the video motion analysis system and software-based analysis.

1. **video motion analysis system:**

Talking about the **video motion analysis system**, it uses high-speed cameras and motion capture software to track body movement and estimate the center of gravity. Reflective markers are placed on key anatomical landmarks to analyze the shift in the center of gravity. The software calculates the center of gravity changes across different frames in dynamic activities such as gymnastic routines, diving, high jumps, and sprint starts. Examples of this kind of method are that they are useful for complex movements. They provide detailed analysis. But they have limitations, such as requiring specialized software and calibration. On the other hand, it is very costly and requires a full laboratory setup to conduct the test.

2. **Software-based analysis:**

Talking about some of the **software-based analysis**, we are discussing two software programs here. One is called **Tracker**, and the other is called **Kinovea**. Both of them are Open source software. So, there are several techniques used to measure the CoG in both static and dynamic conditions.

Tracker:

Talking about the tracker software, it is an open-source video analysis and modeling tool used to estimate CoG during movements. It allows researchers and coaches to track body motion, analyze displacements, and determine the center of gravity trajectory in sports movements.

Let us have a look at this, we need to put up the marker first and then track it. Again, we will have a detailed discussion about all these things in the coming videos. I will show or demonstrate how to do that. Right.

The steps are: first, video recording. So, record an athlete's performance while performing a movement like jumping, running, or flipping, using a high-speed camera, and do marker placement. So, define key anatomical positions or points on the body to track movement. The software tracks the movement of markers and calculates the center of gravity based on segmental analysis. So, again, it uses the same principle.

It generates a motion graph showing the CoG displacement over the time and it can be compared result to assess balance, stability and efficiency in motion. This kind of software can be used to analyze the CoG shift in the sports like gymnastic, diving and the martial arts and evaluating the running mechanisms and the sprint starts as well. It can be used in

studying the balance and posture in the rehabilitation program. They have several advantages like they are non-invasive and easy to use for field-based assessment. They provide the visual feedback for athletes and the coaches and they support the integration with the biomechanical models for advanced motion analysis.

The limitations, it has several limitations as well like it requires the high quality videos and the proper calibrations for accurate result and the less precise than the force plate analysis for real time CoG measurement because ultimately we are estimating the things.

Kinovea:

The second software I am discussing here is called Kinovea. Kinovea is another open-source video analysis tool widely used in sports biomechanics for motion tracking and CoG estimation, and it provides a user-friendly interface for tracking body movement and calculating the CoG shift. So, in the Kinovea it will be like uploading a high-speed video for athlete performance performing a movement first and then we need to use the Kinovea's tracking tool to mark the key body landmarks or the segments like the head, torso or the limbs or else in the Kinovea we are having a function called the body diagram or the human model. So, we can simply put that human model and it will be basically help us finding out all the segmental length and all. The software calculate the CoG by averaging segment position based on the body proportion and so it will be like you know.

You can see this is a human model which is basically having a segment like this. All the segments are automatically coming up. We just need to line up with our actual model and based on the segmental length it is basically giving you this coordinate. This is nothing but the center of gravity. So, it is giving you the value of gravitation here as well as the position of center of gravity from the ground.

It is basically based on the calibration point. So, if the calibration is calculated, it basically gives you the accurate value. So, it is always suggested to have a calibration point somewhere around here so that it will give you the value from here only. I will discuss all these things in the next video in detail.

This kind of procedure can be applied to analyze balance and stability in rehab programs, for assessing sprinting mechanisms and jumping techniques, and for tracking postural control in sports like weightlifting, gymnastics, and skating. It has several advantages, like being free and very easy to use, making it accessible for coaches and athletes. It allows for real-time motion tracking, replay analysis, and customizable tools for segmented tracking and video annotations. But on the other hand, it has several limitations as well. Like, it requires manual input for accurate CoG tracking, and it is less advanced than high-end motion capture systems in biomechanics labs.

 [Thank you, and see you in the next video].