Exercise & Sports Biomechanics
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Week 06
Lecture 30
Principles of Rotational Mechanics

[Hello friends! Let us discuss the concept of torque in sports biomechanics]

Torque:

Torque represents the force that causes an object to rotate about an axis. Just as force causes an object to accelerate in a straight line, torque makes the object rotate about an axis with angular acceleration. Torque is a vector quantity whose direction depends on the force. Torque in sports refers to the rotational force applied to an object or the body around an axis.

It plays a crucial role in various athletic movements, influencing power, balance, and efficiency. Mathematically, torque is represented by a symbol called tau (τ), and $\tau = r*F$, where r is the distance from the axis of rotation to the point of force application, and we can call it the lever arm, and F is nothing but the force applied. The greater the torque, the higher the potential for rotational motion.

[Now let us analyze how torque is used in various sports].

Torque is the product of force and the distance of the point of application of force from the axis of rotation. Because it is the product of some distance and the physical entity like force, torque is also called the **moment of force**. r is called the length of the moment arm or the lever arm. Also, since the rotating object describes a circle, r is nothing but the radius of that circle. Notice that the longer the lever arm, the higher the torque. The Greek symbol τ represents torque. **The unit of torque is Newton**, and that of the distance is meter. Therefore, the unit of torque is Newton meter (Nm). Consider this as an example where a door is attached to a wall via a hinge here with this particular line. So, this line where the hinges are connected is nothing but the axis of rotation for a particular door, and the knob from where we are opening and closing the door is nothing but the point of application of force. So, the torque here is nothing but the force which we are applying at the knob multiplied by the distance of this knob to the axis of rotation.

The torque can be of two types: the static torque and the dynamic torque

A **static torque** does not produce angular acceleration. For example, pushing a closed door is a static torque. You are applying a force on the door, yet it does not rotate about its hinge or the axis because it is closed.

A dynamic torque produces angular acceleration. For example, the drive shaft of a racing car produces angular acceleration, allowing the car to race on its track. A wrench is activated by the force applied to one end, creating an unbalanced torque on the tightened element. Considering the concept of torque in human movement or the human body**, every joint in the human body functions as a rotational system**, with **the muscles generating torque to produce movement**.

Whereas the bone acts as a lever system, rotating around the joint. For example, the elbow flexion. If you see the elbow flexion, there are the angles which are getting changed at the elbow.

Applications of torque in sports:

Talking about events like baseball and cricket. So, when a batter swings, they generate torque by rotating their hips and torso before transferring energy to the bat. The longer bat increases the torque because it increases the r. 'r' means the radius. But only if the batter can still generate higher force. The pitcher or the bowler uses torque at the shoulder and elbow joint to generate fast ball velocity, maximizing the whip-like motion of the arm. Taking an example from golf, a golfer's swing is a perfect example of torque generation. The backswing stores potential energy by rotating the torso, which is then unleashed in the downswing. Torque is maximized by increasing the hip-shoulder separation and using a longer club.

In tennis and badminton, the forehand and the backhand involve torque from the shoulder, wrist, and the grip. The topspin shots require additional torque to generate spin, increasing ball control. Particularly in badminton, the wrist torque is crucial for deceptive shots and smashes.

In events like gymnastics and diving, the athletes generate torque by pushing off the ground while twisting their bodies. Controlling torque is essential for landing, as too much or too little can cause instability.

In artistic events like figure skating, the skaters create torque by applying force against the ice to start a spin. Pushing the arm inwards decreases the moment of inertia, increasing the spin speed.

Sports involving mechanical advantages, like cycling and rowing, depend on torque for power output. Particularly in cycling, the crank arm length, which is the r, affects how much torque a cyclist can generate. Longer cranks allow for more torque but require greater force. The paddling efficiency depends on the angle at which the force is applied. Cyclists maximize torque at around 90° of the crank rotation.

In the case of rowing, the rowers generate torque at the oarlock, where force is applied through the handle and transferred to the bottom. The longer oar increases leverage, generating more torque and efficient strokes.

In soccer, when a player kicks a ball, they generate torque at the hip joint using rotational force from the thigh. The larger range of motion increases the torque, producing a more powerful shot.

In shooting and pivoting, the jump shot involves torque at the elbow and the wrist, where force is applied to the ball at an optimal angle for accuracy. The pivoting involves torque generated at the ankle and knee joint, allowing quick direction changes.

The kicking techniques in taekwondo and karate rely on torque at the hip and knee joint to generate maximum force.

In throwing events like shot put, discus, and javelin, they require high torque to propel the object efficiently. In events like weightlifting, powerlifting, and wrestling, torque plays a key role in movement efficiency and force application. The barbell is lifted using torque generated at the hip and knee. A wider grip increases lever arm length, requires more torque, but also improves stability.

The throws in wrestling and Judo involve using torque to unbalance an opponent by leveraging their center of mass. The hip throws require a strong rotational force to lift and flip the opponent.

The concept of torque is influenced by many biomechanical principles, and one of them is the lever system. The human body operates through biomechanical levers where bones act as levers, joints serve as fulcrums or the axis, and the muscle generates the force.

There are three kinds of levers that we will be discussing in detail in the upcoming slides. So, for now, just consider the three kinds of levers: the **first-class lever**, which is found in movements like heading a soccer ball where the neck acts as a fulcrum. In the **second-class lever**, it is common in push-off movements like the gymnast's take-off. And the **third-class lever** is the most common in sports where the effort force is applied between the fulcrum and the load, like the baseball swing and the basketball shot. Similarly, the second principle, which we are discussing with reference to torque, is the moment of inertia and torque efficiency.

So, the moment of inertia is a fundamental concept in sports biomechanics that describes an object's resistance to rotational motion around an axis. It depends on both the mass of an object and how that mass is distributed relative to the axis of rotation. The moment of inertia, also known as the rotational inertia or the angular mass, is a physical quantity that resists a rigid body's rotational motion. It is analogous to mass in transitional motion. It determines the torque required to rotate an object by a given angular acceleration.

The moment of inertia is not restricted to a rigid body only. It also applies to a system of particles rotating about a common axis. For a point mass or a single body, the moment of inertia formula is given by the product of mass and the square of the object's perpendicular distance from the axis of rotation. So, mathematically it is represented as $I=\sum mr^2$, the summation of all the masses and the square of the distance of those masses from the axis of rotation. Where I is the moment of inertia, m is the mass, and r is the perpendicular distance from the axis of rotation. The SI unit of moment of inertia is kg m^2.

The application of moment of inertia in sports includes, for example, in gymnastics when the body is tucking and rotating. So, a gymnast performing a somersault can increase rotating speed but tucking in, or you can see by tucking in, they are reducing their r, lowering the moment of inertia, extending the body slows down the rotation due to an increase in the moment of inertia following the angular momentum conservation.

In events like figure skating or spin control, a skater starts a spin with arms extended with a higher moment of inertia. Because arms extended means more r. More 'r' means more moment of inertia. Then pushing them into increased spin speed. This is an example of the conservation of angular momentum.

In events like baseball, the bat swing and control, the bat swing with more mass concentrated at the barrel has a higher moment of inertia because mass is again directly proportional to the moment of inertia. Taking it harder to swing but delivering more power. The player adjusts grip position to control swing speed and precision.

The **key takeaway from the moment of inertia concept is** that a lower moment of inertia allows faster rotation but less stability. The higher moment of inertia provides more stability but makes quicker movement harder. Athletes and equipment designers manipulate the moment of inertia to optimize performance and efficiency.

The other principle which we are discussing with respect to torque is **angular momentum** and its **conservation in motion**.

Angular momentum:

Angular momentum is the rotational equivalent of linear momentum and is defined as the product of a body's moment of inertia and its angular velocity. It describes the quantity of rotation an object or athlete possesses and is a crucial concept in sports biomechanics. It is defined as $H = I*\omega$. Angular momentum is denoted by the capital letter H, I is the moment of inertia, and omega is the angular velocity or the speed of rotation. According to the conservation of angular momentum, if I, that is the moment of inertia, decreases, then omega, that is the angular velocity, increases and vice versa. We know that the formula for angular momentum is $H = I*\omega$, and the key factor influencing angular momentum is nothing but the moment of inertia. The angular velocity and the conservation of angular momentum are also key factors.

The moment of inertia is nothing but, as we already discussed, the resistance of a body to rotational motion, which depends on mass distribution relative to the axis of rotation. A more compact position, for example, a tuck-in position in a somersault, decreases the moment of inertia. **Angular velocity** is nothing but the speed at which the body rotates. A faster spin results in higher angular velocity.

The conservation of angular momentum:

The conservation of angular momentum states that if no external torque is applied, the angular momentum remains constant. Athletes manipulate their body shape to adjust their angular velocity. By this formula, we can rewrite it as $I = H/\omega$. So, by this expression, it is clearly understood that the angular velocity is inversely proportional to the moment of inertia or indirectly with the radius. The higher the radius means there will be less angular velocity and vice versa. The athlete controls the rotation by tucking to spin faster or extending to slow down. So, tuck-in means they are reducing their moment of inertia by reducing their radius.

And in the aerial maneuver, the twists are initiated by asymmetrical arm and leg motion. In figure skating, a skater pulls their arm inward to decrease the moment of inertia and increase omega. That is nothing but the angular velocity. And while landing from a jump, their extending limb increases the moment of inertia and reduces the angular velocity. The ground reaction forces also influence the torque generation.

Like in many sports, the torque generation starts from the ground through the ground reaction forces. The GRF provides the necessary force to initiate rotational movement. The torque generated depends on the foot positioning, balance, and the force application. Like in wrestling, the torque is used to off-balance an opponent by shifting their center of mass. In basketball, a player generates torque for a jump shot by pushing against the ground, transferring the force through the leg, torso, and arm.

In biomechanics, **controlling torque** is an important technique that ultimately helps in preventing injuries. **Mismanaged torque** can lead to joint injuries and muscle imbalances. In this particular example, if you see that excessive torque at the knee is leading to injuries like ACL injuries in soccer. **Shoulder torque** overload can lead to injuries like rotator cuff injuries in athletes involved in overhead activities. **Spinal torque** stress can lead to lower back injuries, and the strategies to prevent these injuries are nothing but the proper technique to distribute torque efficiently, strength training to improve joint stability, and flexibility and mobility work to allow smooth torque transfer.

So, **the key takeaway from the topic of torque is that** torque is a fundamental concept in sports biomechanics, influencing power, accuracy, and efficiency in athletic movements. Sports biomechanics examines how force, motion, and body mechanics interact to optimize performance and prevent injuries.

In this context, torque is analyzed alongside key biomechanical principles such as the lever system, moment of inertia, angular momentum, and ground reaction forces.

[Thank you. See you in the next video].