Exercise & Sports Biomechanics
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Week 07
Lecture 32
Fluid Mechanics

[Hello, friends! And welcome to this course on exercise and sports biomechanics. In this section, we will be talking about fluid mechanics].

Fluid mechanics:

Fluid mechanics occupies a privileged position in science. It is taught in various science departments, including physics, mathematics, environmental science, mechanical, chemical, and civil engineering. Each highlights a different aspect or interpretation of the foundation and application of fluids.

- Have you ever wondered why some swimmers glide effortlessly through the water while others struggle?
- How does a spinning soccer ball curve mid-air?
- Why does a cyclist tuck into an aerodynamic position to gain speed?

The one commonality in all three scenarios is that the medium of motion is fluid in all three cases. Fluids include plasma, gases, and liquids, and they create forces on each other and the objects within them.

In relation to sports, we are particularly interested in the movement of objects through water and air. Within sports, the forces of the fluid upon objects and people impact performance. Athletes often spend lots of time practising, being able to manipulate these forces using variations in technique in order to refine their skills and improve their performance. So, we are talking about fluid mechanics.

What is fluid mechanics?

Fluid mechanics is a branch of physics that explores the movement of fluids and how they exert force on objects. It studies how fluids, mainly liquids and gases, behave and interact with moving objects. Fluid mechanics is a crucial aspect of sports biomechanics. It deals with how air and water interact with athletes and the environment.

By understanding fluid dynamics, athletes can optimize performance, reduce resistance, and improve efficiency. This concept is particularly important in sports like swimming, cycling, skiing, and ball games. Where motion through a fluid medium, obviously air or water, plays a major role. So, fluid mechanics helps athletes by enhancing speed, improving control, optimizing techniques, and designing better equipment.

The basics of fluid mechanics are that, fluids include both liquids and gases. They flow and take the shape of their container. In sports biomechanics, air and water significantly influence an athlete's movement, performance, and energy efficiency. In fluid mechanics, the movement of fluids around an object or body can be categorized as either laminar flow or turbulent flow. These concepts are crucial in sports biomechanics as they affect speed, efficiency, and overall performance. Talking about laminar flow occurs when fluid particles move in smooth parallel layers with minimal mixing.

This type of flow is streamlined and results in lower resistance. The characteristics of laminar flow may include smooth, orderly movement of the fluid and minimal mixing between fluid layers. It has the characteristics of low drag and resistance.

What is drag?

We will talk about drag in the upcoming slides, and it often occurs at lower speeds. These are a few examples of laminar flow. Particularly in swimming, a streamlined body position minimizes water resistance, allowing a swimmer to move efficiently. In cycling, a cyclist in a tucked position experiences smoother airflow that reduces drag.

In-flight skiing, a skier uses a specialized suit and a low posture to maintain laminar airflow and increase speed. Talking about turbulent flow occurs when fluid particles move chaotically, creating eddies and swirls. This type of flow increases resistance and energy loss. The characteristics of turbulent flow may include irregular, chaotic fluid motion.

There is high drag and resistance, and increased energy consumption often occurs at high speed or when an object has an uneven shape. Examples of turbulent flow include a poor body position, which creates turbulence and slows the swimmer down. In cycling, a cyclist in an upright position increases air turbulence, leading to greater drag. In events like golf, a smooth golf ball would experience turbulent air resistance, but dimples create a boundary layer that reduces overall drag.

Have you ever wondered why there are dimples on the ball?

However, when the ball is smooth, it gives rise to smoothing close to a laminar flow. In this case, the fluid flow downstream detaches from the surface of the ball in the form of vortices. This phenomenon is called flow separation, which gives rise to a viscous wake behind the ball that slows it down.

What do dimples do?

They act as artificial turbulence, creating turbulence next to the ball's surface, giving rise to two layers of air going around the ball. The top layer is going faster than the bottom layer. That is, the air clings to the ball's surface, which creates turbulence, and this reduces the drag and helps the ball to travel farther than a smoother ball. So, if you want to compare the laminar and the turbulent flow, we can compare the fluid movement in the laminar, which is smooth and orderly, while in the turbulent it is chaotic and irregular. The resistance or drag in the laminar is low compared to that of the turbulent flow. The energy efficiency is higher in the **laminar flow** as compared to that of the turbulent flow. The laminar flow can commonly be seen in low-speed and streamlined sports. On the other hand, turbulent flows are common in high-speed and unoptimized movement.

The **examples of the laminar flow** are streamlined swimming and cycling aerodynamics. On the other hand, for the turbulent flow, the examples are the wind resistance in running and rough water in rowing. What is the importance of this in sports? So, maintaining laminar flow helps reduce the drag and improve efficiency. Unwanted turbulence can slow an athlete down and waste energy.

In some cases, controlled turbulence, such as the one created by dimples on a golf ball, can be beneficial. So, ultimately understanding the concept of laminar flow and turbulent flow will help coaches and athletes enhance performance. There are certain types of forces that need to be discussed in fluids. So, when athletes move through air or water, they experience different forces exerted by the fluid. And these forces play a crucial role in optimizing performance.

In sports such as swimming, cycling, skiing, and ball games. The main forces in the fluid include the drag forces, lift forces, buoyancy and pressure forces. Understanding forces in the fluid help athletes and coaches improve techniques, equipment design and overall performance. By optimizing the drag reduction, utilizing lift, leveraging the buoyancy and considering fluid pressure, the athlete can gain a competitive edge in their respective sports. So, let us begin one by one.

The drag force:

The drag is basically a resistive force that act opposite to the direction of motion. When an athlete or object moves through a fluid, that is obviously the air or water, it slows the athlete down and requires extra energy to overcome. So, in simpler word, it is nothing but the resistance to the movement that is being created by the fluids. Now, we know that drag is the force that the opposing athlete motions through a fluid, and there are three different kinds of drag that an athlete may experience. These are surface drag, also called frictional drag, form drag, pressure drag, and wave drag.

So, the surface drag is caused by friction between the fluid and the body surface. For example, swimmers shave their bodies to reduce the surface drag. The form drag or the pressure drag is created by the differences in the pressure around an object. For example, a cyclist used the aerodynamics helmet to reduce the form drag. Wave drag occurs at the interface of two fluids, air and water.

For example, the swimmer minimizes the drag by maintaining a streamlined body position. Talking in detail about the surface drag, we know that it is caused by the friction between the surface of an object, such as the athlete, and the fluid. So, the surface of an object or the fluid, or the body surface of an athlete or the fluid. The smoother surface reduces the surface drag. For example, swimmers shave their bodies and wear smooth suits to reduce the surface drag.

Cyclists wear helmets that are aerodynamic, as well as tight, aerodynamic clothing to reduce friction with the air. The form drag, which is the pressure drag, is caused by a difference in pressure. At the front and the back of an object moving through a field. A streamlined shape helps reduce the form drag. For example, a cyclist uses an aerodynamic helmet and body position to minimize air resistance.

A skier crouches to reduce the pressure difference and move faster. The wave drag occurs at the boundary between the air and the water, where the two fluids interact and create waves that increase resistance. For example, a swimmer reduces wave drag by staying underwater longer before diving or turning. The rowers keep their oars close to the water surface to reduce wave formation.

There are several factors that affect the drag. So, drag is the resistance force that opposes the motion of an object or an athlete moving through a fluid, and reducing drag is crucial in sports like swimming, cycling, skiing, and running, where speed and efficiency are key.

The amount of drag experienced depends on several factors, like the speed of an object, surface texture, shape of an object, and density of the fluid. Let us discuss them one by one. So, the speed of an object or the speed of an athlete—as it increases, the drag increases with this force.

The first factor is the speed of an object or the athlete, so it obviously increases with force and is quadratic in nature. That means, for example, a cyclist moving at 30 km per hour experiences four times the drag compared to one moving at 15 km per hour. The swimmer must exert more force as they increase their speed.

The second factor we are talking about is the shape and size of the object. So, the larger the cross-sectional area, the more the drag. A streamlined shape reduces drag by allowing air or water to flow smoothly around the object. A larger cross-sectional area increases the drag. For example, a cyclist uses an aerodynamic helmet to reduce air resistance. A swimmer keeps a streamlined body position to minimize drag. A skier bends forward to create a sleek shape and reduce resistance. Another factor is the roughness of the surface. So, a smoother surface reduces friction. A smoother surface reduces the friction between the fluid and the object. A rough surface creates more turbulence, increasing drag. For example, a swimmer shaves their body and wears a specialized swimsuit to reduce friction drag. Golf balls have dimples to create a thin turbulent boundary layer, reducing overall air resistance. A cyclist wears tight-fitting clothing to minimize air drag.

Another factor we are discussing here is the **density and viscosity** of the fluid. The higher the density of the fluid, the more drag there is. So, since water is denser than air, moving through water creates significantly more drag than moving through air. The fluid viscosity, which is the thickness of the fluid, also affects drag. For example, a swimmer experiences more resistance in water than a runner does in air. Because water is more viscous than air, an athlete in humid or high-altitude conditions may experience slightly different air resistance than in less humid or low-altitude conditions.

The flow type, like laminar flow and turbulent flow, may also affect the drag. In laminar flow, the smooth and streamlined flow reduces the drag. In the case of turbulent flow, the chaotic swirling flow increases the drag. For example, a cyclist in an aerodynamic position maintains more laminar airflow, which reduces the drag.

A swimmer who is not streamlined creates more turbulent water flow, increasing the resistance. The clothing and equipment design also affect the drag. Specialized equipment can minimize the drag. Swimmers wear full-body suits that reduce water resistance. Cyclists use aerodynamic bikes, helmets, and skiing suits.

Skiers wear smoother wind-resistant suits. By optimizing factors like body position, equipment, and technique, athletes can reduce drag and improve performance.

[Now, moving to the second type of force]:

The lift force:

A lift is a force acting perpendicular to the direction of motion, helping an object or athlete stay in the air or move more efficiently. The lift is governed by **Bernoulli's principle and the Magnus effect**.

What is Bernoulli's principle?

Bernoulli's principle states that as the speed of the fluid increases, its pressure decreases. This principle is crucial in sports where lift, air resistance and fluid motion impact performances. It explains how objects like balls, discs and athletes interact with the air or water, affecting speed, trajectory and stability.

There are three basic factors on which Bernoulli's principle works. These are the lift force and the aerodynamics, the **Magnus effect** that is nothing but the spin-induced lift, the curve, the fluid resistance, and the speeds.

So, talking about the lift force and aerodynamics, the faster-moving air creates low pressure while the slower-moving air creates high pressure. This pressure difference generates lift, which helps objects stay in the air longer or move more efficiently. For example, the skier angles their skis to create lift, increasing the air time. In the discus throw, a tilted discus moves through the air with the pressure difference allowing it to stay in the air longer.

In cycling, the aerodynamic helmets and the body position help reduce pressure difference, minimizing the drag. Talking about the Magnus effect is nothing but a spin-induced lift and the curve. When a ball spins, the Bernoulli principle explains how pressure causes it to curve, and it says that the ball moves towards the higher pressure area, and this is **known as the Magnus effect**. For example, a soccer ball, a spinning ball curves in the air due to the pressure differences on either side.

In tennis, topspin creates a lower ball trajectory by reducing the air pressure on the top, so there is more pressure on the bottom, causing the ball to dip. In sports like baseball, a curveball dips as differential air pressure alters its trajectory. Fluid resistance and speed affect this, and Bernoulli's principle reduces drag by ensuring smoother airflow over surfaces. Athletes use streamlined equipment and posture to minimize high-pressure zones. For example, car designs use aerodynamics to control lift and drag. In swimming, swimmers stay streamlined to allow water to flow smoothly, reducing resistance.

Boats have sleek shapes to maintain laminar flow and minimize drag. Bernoulli's principle plays a key role in optimizing movement, aerodynamics, and ball control in various sports. Athletes use this knowledge to enhance performance, reduce resistance, and generate lift or spin for strategic advantages. These are the factors that affect lift force: the density of the fluid, the shape of an object, the angle of attack, and the speed of motion. Lift is greater in denser fluids like water compared to air.

Curved surfaces generate more lift than smoother surfaces. The angle at which an object meets the fluid affects lift, and faster movement enhances lift effects.

Another kind of force is buoyancy:

Buoyancy is the upward force exerted by a fluid on an object submerged in it. It determines whether an object floats or sinks based on its weight and the amount of fluid it displaces. So, this concept of buoyancy is governed by Archimedes' principle, which states that an object submerged in a fluid experiences an upward buoyant force equal to the weight of the fluid it displaces. So, there are some factors that affect the buoyant force. So, if an object is denser than the fluid, it sinks. If an object is less dense than the fluid, it obviously floats.

For example, a rock sinks in water because it is denser than the water. A wooden log floats because it is less dense than the water. A swimmer with more body fat tends to float better due to lower overall density. The buoyancy force is also affected by the volume of the object. A larger object displaces more water, increasing the buoyant force.

This is why boats and ships float despite being heavy. They displace enough water to create an equal upward force. A flat, wide shape spreads weight over a large area, increasing water displacement and buoyancy. This is why a swimmer lying flat floats better than one in a vertical position. There are a few more factors which affect an athlete's performance pertaining to buoyancy force, such as body composition. Since fat is less dense than water, athletes with higher fat content float more easily than those with less fat.

The muscles are denser than the water, making leaner athletes more prone to sinking. The breathing control obviously, inhaling deeply, increases lung volume, enhancing buoyancy. Exhaling reduces buoyancy, aiding in diving.

Equipment and technology. Weight suits add buoyancy in triathlon and open-water swimming. Buoyancy-added life jackets help maintain flotation in water sports.

There are three kinds of buoyancy: positive buoyancy, neutral buoyancy, and negative buoyancy. The effect of positive buoyancy is that the object will float, like a swimmer floating on the water. Neutral buoyancy has the effect that the object stays suspended in the fluid, like a scuba diver maintaining their depth.

Negative buoyancy has the effect that the object will sink, like a heavy stone dropped in the water. So, talking more about the Magnus effect, as we now know, the Bernoulli principle states that a curved ball will move toward the higher-pressure area, and this effect is called the Magnus effect. The Magnus effect is well explained in sports when discussing topspin and backspin in tennis. We are talking about the curved free kick in soccer. Talking about the curveball and sliders in baseball and spin bowling in cricket.

All of this movement is being affected by or governed by the Magnus effect. And how does this Magnus effect work? It works as a spinning object. The rotation of the ball or the object alters the airflow around it. So, as the ball keeps on rotating, the air around that object will get dispersed to the other side of that particular spinning object.

It allows the airflow speed differences around the layer of that particular object, so one side experiences faster-moving air, and that is the low-pressure area. In contrast, the other side has slower air, and that is the high-pressure area. As a result, the object moves towards the low-pressure side, creating a curved path instead of a straight-line motion.

So, in short, the Magnus effect is like if the ball is spinning, it moves towards the side that basically has more pressure or the slower air, which is basically trapping down from that particular side. The other type of force that we are discussing here is the pressure force in the fluids. The pressure in the fluid is the force exerted by a fluid per unit area. It acts in all directions and increases with depth.

The formula for pressure in the fluid is P fluid, which equals the sign called rho, rho gh.

$P_{fluid} = \rho gh$

Where P is nothing but the pressure that is in Pascal (pa). The rho (ρ) is the fluid density, which is in kilograms per meter cubes (kg/m^3). The g is the gravitational acceleration, which is 9.81 m/s^2, and h is nothing but the depth in the fluid and that is in meters. So, by looking at the formula itself, you can see that the pressure in the fluid is directly affected by the density as well as by the height. As the density and the height or the depth of the fluid increase, the pressure in the fluid increases. For example, in swimming, the water pressure increases with depth, affecting the stroke technique.

In scuba diving, divers experience higher pressure as the depth increases. In rowing, the water pressure affects the force needed to push the oar through the water. These are the factors that affect the fluid pressure, like the depth of the fluid. That is the h in the equation. We all know the equation is rho gh. So, the deeper an object is submerged, the greater the pressure it experiences. This is why divers feel more pressure as they go deeper into the water.

The second factor is the density of the fluid, that is, the rho in the equation. So, the denser fluid exerts more pressure. Water exerts more pressure than air because water has more density than air.

And the last factor which we are discussing here is atmospheric pressure. So, air itself exerts pressure due to its weight. At higher altitudes, the air pressure decreases, affecting the athletes. Thus, the fluid moves from high-pressure to low-pressure areas. This principle is used in aerodynamics, where pressure differences help lift objects. Understanding pressure forces in fluids helps athletes and coaches optimize performance, from adjusting breathing at high altitudes to improving underwater movements.

Let us discuss projectile motion in a fluid medium:

Projectile motion refers to the movement of an object, or projectile, through a fluid medium under the influence of gravity and fluid forces. In sports, projectiles include balls, javelins, arrows, and even athletes like divers and skydivers. Unlike motion in a vacuum, fluid forces such as drag and lift significantly affect projectile motion, altering trajectory, speed, and range. I am sure you have already covered projectile motion in previous weeks. There are a few factors that affect projectile motion, such as air resistance (which slows down the object), spin (the Magnus effect, which alters trajectory), and the angle of release (which affects distance and height). For example, in javelin throw, the athlete uses the optimal release angle to counteract air resistance. In golf, backspin helps the ball stay in the air longer.

In sports like basketball, the shooter applies spin to control the ball's trajectory and bounce. These are the factors that affect projectile motion in a fluid medium, such as initial velocity, speed, and angle of release. A faster projectile travels farther. The optimum launch angle for maximum range depends on the projectile's situation, as we have already discussed in previous weeks. But air resistance can modify this.

So, in sports, the angle varies when we talk about the javelin throw, the basketball shot, or even when we discuss jumps like the long jump and the triple jump. Another factor is the air resistance or the drag force. So, it slows down the projectile and reduces its range. Drag force is proportional to the speed and the surface area. For example, a golf ball's dimples reduce the drag by controlling airflow.

A smoother soccer ball experiences more air resistance than a textured one. The next factor is the Magnus effect, which we already discussed in the previous slide. So, it is nothing but the spin and the lift force. A spinning projectile experiences a curved path due to pressure differences. For example, a swerving football free kick.

A tennis topspin shot drops faster due to the downward lift. A baseball curveball deceives better with an altered trajectory. And the last factor we are discussing here is buoyancy and water resistance, mainly in aquatic sports. So in water sports, water resistance alters the projectile's path more than that in the air. The water drag slows down the motion, requiring more significant force for throwing.

The concept of the projectile in the fluid can be applied to many sports, but the key takeaway here is that drag and lift affect the projectile trajectory in air and water. The spin alters motion via the Magnus effect. Optimizing launch angle and speed improves performance in sports. Not only does fluid mechanics affect the motion of an athlete, but it is also an important concept when discussing equipment design in sports. It helps us design equipment aerodynamically by reducing drag through shape optimization, surface texture, and material selection.

In this section of this particular segment, let us talk about the difference between the Bernoulli principle and the Magnus effect. The difference between the Bernoulli principle and the Magnus effect is that the Magnus force describes the deviating flight path of a spinning object, such as a table tennis ball. The Magnus force is based on the same logic and fluid dynamics as the Bernoulli principle. In fact, the Magnus force can be considered an applied Bernoulli lift force but specifically applied to spinning projectiles. To understand this, we need to talk about spin.

Let us start with a ball. So, if this ball is tugged with force away from the centre of mass of the ball, that is nothing but a centric force. The ball will spin around its axis. Like, just look at this and notice that the orange vector does not pass through the center of mass. Rather, the ball has been hit below the centre of mass. We call this a slice, a chop, or even a push in table tennis. In other words, it is a backspin or a backspin is being applied to the ball, and the ball will both travel through the air and spin around its axis like this. Right?

[Now, what I am about to explain here is very important when it comes to the Magnus force because without grasping it, the concept is not understandable. Here we go].

The surface of the ball is very, very rough. It may feel smooth, but it really is not. The molecules that... form the mixture of gases, that is, in the air are absolutely tiny, and as a result, when the ball spins, it creates a boundary layer of spinning air with it. Going back to Bernoulli's principle, it is worth noting that the table tennis ball is a uniform shape; it is round. Therefore, presenting an angle of attack is not possible. Rather, the table tennis player, in our example, can use spin to create pressure differences. Going back to Bernoulli's principle, it is worth noting that the table tennis ball is a uniform shape; it is round. Therefore, presenting an angle of attack is not possible. Rather, the table tennis player in this particular example can use spin to create pressure differentials.

Notice how the airflow below and above the ball is at a different speed? Therefore, a pressure differential is created because of the backspin, and the Magnus lift force is generated. Because of this lift force, the flight path of a table tennis ball is extended horizontally. Notice the following about the shot with backspin. It travels lower over the net, causing the opponent to lift the ball to some degree. It travels deeper on the table, pushing the opponent back. It travels more slowly through the air (not visible in this particular clip), allowing the player time to recover their position. Therefore, we can begin to understand why a table tennis player would use backspin. It produces a defensive shot. It is chosen when the player is out of position. The ball travels low over the net.

It causes the opponent to need to lift the ball over the net. The ball travels slowly through the air. It allows the player more time to recover before the ball comes back. It is also considered a controlling shot or a more accurate shot because the ball travels more slowly. It can help to change the cadence of a rally.

In sports like tennis, topspin can dominate to such a degree that more shots are hit with similar pacing. Introducing backspin can add variety to that. It is excellent for the drop shot because of the effect of backspin on the bounce. Talking about topspin, it has the same mechanism as backspin but in the reverse direction. Notice how topspin is caused by once again an eccentric force, but this time causing the ball to rotate around its axis in the opposite direction.

[You can see here. So, as you already know], the ball spins with the boundary layer. Therefore, we can describe how topspin is achieved like this. As a result, a Magnus force downward is created, and the ball deviates from its flying path. Notice the following about the shot with topspin.

It travels higher over the net, meaning there are fewer unforced errors by hitting the net. It has a shorter flight path, meaning it can be hit harder without the fear of missing the back of the table. It travels more quickly through the air, allowing the player time to attack an opponent who is out of position. So, the characteristics of the topspin are that it produces an attacking shot. It is chosen when an opponent is out of position. The ball travels high over the net. It is unlikely to hit the net. The ball travels quickly through the air. It allows the opponent little time to respond.

And this principle applies equally to tennis and table tennis. And finally, side spin. So, we know that there is one more kind of spin, which is side spin, and I am not going to take you through the whole process of how to create the side spin because the process is identical to that of the backspin and the topspin. The eccentric force is applied to the left and the right of the vertical or the longitudinal axis of the ball. The side spin causes a ball to deviate in its flight, somewhat like this in the picture.

Notice how the ball hit with the hook or the draw allows a ball to deviate to the left for a right-hander, and this can be really helpful for a golfer. Say who might need to avoid an object or even play a shot to counteract a strong wind from the left. Likewise, the slice shot allows exactly the same in the opposite direction. If a golf hole is structured like this, as you can see in the picture, the hook and the slice could be very useful, as shown in the first image. Equally, a footballer wishing to curl, swerve, or slice a ball around an object—such as an opponent or even a defensive wall—can use the same principle to cause the ball to deviate.

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