1.3.b – Linear, angular & projectile motion

Learning objectives

To be able to describe linear motion and the descriptors affecting it.

- To understand graphical representation of linear motion.
- To be able to explain angular motion around axes of rotation.
- To understand the definitions, calculations and units of measurement for angular motion descriptors.
- To be able to explain the relationship between moment of inertia, angular velocity and momentum.
- To be able to describe the factors affecting fluid mechanics and projectile motion.
- To evaluate the impact of the Bernoulli principle and the Magnus force on an object.

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Linear, angular & projectile motion





Linear Motion

Biomechanics is the study of human movement and the effect of force and motion.

Linear motion is motion in a straight or curved line, with all body parts moving the same distance at the same speed in the same direction. *i.e. the javelin moves in a curved line.*



Think. Pair. Share - What is Newton's first law of motion?



Linear Motion

Linear motion results from a direct force being applied to the centre of an object's mass.

There are a number of key descriptors linked to linear motion:

- Distance
- Displacement
- Speed
- Velocity
- Acceleration/deceleration





Measurements used in Linear Motion

These measurements can be split into two groups:

Scalar quantities are described in terms of size or magnitude - mass, inertia, distance and speed are scalar quantities.

Vector quantities are described in terms of size and direction - weight, acceleration, deceleration, displacement, velocity and momentum are vector quantities.





Distance and Displacement

Distance and displacement are measurements that are used to describe a body's motion.

Distance is the length of the path a body follows when moving to a point. *e.g. 400m runner*



Think. Pair. Share - Is distance a Scalar or Vector quantity?



Distance and Displacement

Displacement is the length of a straight line joining the start and finish points. *e.g. 200m race on the track. The displacement will be the number of metres as the crow flies from the start to the finish.*



Think. Pair. Share - Is distance a Scalar or Vector quantity?



Distance and Displacement

Displacement is a vector quantity because it describes both size and direction.



Think. Pair. Share - Can you think of any other sporting examples of distance and displacement?



Speed and Velocity

Speed is the **rate of change** of position. It is a scalar quantity because it does not consider direction. Speed can be calculated with the following equation:

Speed (m s⁻¹) = <u>distance covered</u> (m) time taken (s)



Speed and Velocity

Velocity is the **rate of change of position** with reference to **direction**. This means that it is a more precise description of motion and is a vector quantity. It can be calculated with the following equation:

Velocity (m s⁻¹) = <u>displacement (m)</u> time taken (s)



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Acceleration and Deceleration

Both these terms can be defined as ...

"the rate of change of velocity"

Acceleration occurs when velocity increases and deceleration occurs when velocity decreases. They are vector quantities.





Acceleration and Deceleration

The **change in velocity or acceleration** can be calculated with the following equation:

Acceleration= $V_{f} - V_{i}$ or final velocity - initial velocity (m/s) t time taken (s)



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Acceleration and Deceleration

Deceleration is when the rate of change in velocity is a **negative** or a **decreases** over time.





Graphs can easily represent the motion of an object.



Think. Pair. Share – What do the graphs tell you about what is happening to the object?



Distance/time graphs show the distance travelled over a period of time. The gradient of the line shows the speed of the object.



A = Shows constant speed. B = This represents either rest or in a stationery position. C – Acceleration out of the blocks in a sprint race. **D** - Deceleration after the finish line.



Speed/time graphs show the speed of an object over time. This graph can be used to calculate distance covered.



Think. Pair. Share – What does each point on the graph tell you about what is happening to the object?



Speed/time graph:

O: Stationery O-A: Acceleration A-B: Constant speed B-C: Deceleration



Velocity/time graphs show the velocity of an object over time. The curve indicates the acceleration of the body. A negative curve below the x-axis shows a change in body's direction.



Angular motion

Linear motion is rare in sport as movements are often dynamic and the effects of friction and air resistance regularly act on a body.







How does Angular Momentum assist a golf swing?



Angular motion

Angular motion is movement around a **fixed point** or **axis** *i.e. a gymnast performing a somersault.*

Angular motion
 occurs when a force
 is applied outside the
 centre of mass.

• An off-centre force is referred to as an eccentric force (this is otherwise known as **torque**)





Torque

Torque (moment) is a rotational force. It causes an object to turn about its axis of rotation.





Axes of rotation

There are three axes of rotation:

- the longitudinal axis, which runs from top to bottom
- the frontal axis, which runs from front to back
- the transverse axis, which runs from side to side across the body



Angular Motion

There are a number of key descriptors linked to **Angular motion**:

- Angular velocity
- Displacement
- Moment of inertia
- Angular momentum





Angular velocity is a vector quantity as it makes reference to direction. Angular velocity refers to the angular displacement that is covered in a certain time.



Angular velocity (rad s¹) = <u>Angular displacement (rad)</u> Time taken (s)



Inertia is a resistance to change in linear motion. **Moment of inertia** (MOI) is therefore **resistance of a body to angular motion**. MOI depends upon 2 main factors:



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1. Mass of the body/object

The greater the mass, the greater the resistance to change and therefore the greater the moment of inertia.





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2. Distribution of mass from the axis of rotation The closer the mass is to the axis of rotation, the easier it is to turn - so the moment of inertia is low.

Increasing the distance of the distribution of mass from the axis of rotation will increase the moment of inertia.



Think. Pair. Share – What sporting example can you think of to illustrate this?



A somersault in a straight position has a higher moment of inertia than the tucked somersault. This is because in the straight position the distribution of the gymnast's mass is further away from the axis of rotation.





Moment of inertia is calculated with the following equation:



Moment of inertia (kgm²) = mass (kg) x distribution of mass from the axis (m²)



Angular momentum is spin. It involves an object or body in motion around an axis. It depends upon the moment of inertia and angular velocity.

If moment of inertia increases, angular velocity decreases, and vice versa.



Angular momentum (kgm² rad/s) = MOI (kgm²) x Angular Velocity (rad/s)

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Conservation of angular momentum: Angular momentum is a conserved unless an external torque acts upon it.

i.e. When an ice-skater executes a spin there is no change in his angular momentum until they use their skates to slow the spin down.





The conservation of angular momentum can be shown with a break dancer.

Moment of inertia while spinning on their head can be can manipulated by bringing in their arms and legs closer to the axis of rotation, resulting in a large moment of inertia and a large angular momentum.



Newton's Laws of Motion and Angular Motion

Newton's laws of motion also apply to angular motion:

Newton's first law:

A rotating body will continue in its state of angular motion unless an external force (torque) is exerted upon it.

Think of an ice-skater completing a spin. They will continue to spin until landing. The ground exerts an external force which alters the state of angular momentum.



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Newton's Laws of Motion and Angular Motion

Newton's second law:

The rate of change of angular momentum of a body is proportional to the force causing it and the change that takes place in the that direction.



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i.e. leaning forwards from a diving board will create more angular momentum than standing straight.



Newton's Laws of Motion and Angular Motion

Newton's third law:

When a force is applied by one body to another, the second body will exert an equal and opposite force on the other body.





i.e. in a dive, when changing position from a tight tuck to a layout position.



Angular velocity, momentum & MOI graphs

Angular motion descriptors can be plotted on a graph and represent movement patterns:

At take off: the diver creates angular momentum from an eccentric force around a transverse axis.

Straight body position: moment of inertia is high and angular velocity is low (the rotation is slow)

Tucked body position: distributed mass is close together, MOI is decreased and angular velocity increases causing a faster spin.



Fluid Mechanics and Projectile Motion



Watch me





Fluid Mechanics

Fluid mechanics is the study of the forces acting on an object through the air or water. **Air resistance** and **drag** are two important forces to consider for sportsmen and women.

Air resistance:

This is a force that opposes the motion of a body travelling through the air.





Drag:

Resistance in the water is referred to as drag. Drag will depend on the environment.



Fluid Mechanics

Air resistance and drag depends upon:

 The velocity of the moving body a greater velocity results in a greater resistance





2. The cross-sectional area of the moving body - the larger the crosssectional area, the greater the air resistance. *i.e. ski jumpers*



Fluid Mechanics

3. The shape and the surface characteristics of the moving body. A stream-lined shape results in less resistance.





Think. Pair. Share – In what sport/s is streamlining a vital part of the event?



This refers to the motion of either an object or the human body being 'projected' into the air at an angle.



Think. Pair. Share – Can you think of projectile motion examples in sport?

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There are 3 main factors that will determine the horizontal distance that a projectile can travel.



Think. Pair. Share – What factors are likely to affect a projectile motion or path?

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Angle of release

To achieve maximum horizontal distance, the angle of release of the projectile is important. The optimum angle of release is dependent upon release height and landing height.

When both the release height and the landing height are equal then the optimum angle of release is 45°.



A release height of 90° will accelerate vertically and come straight back down = 0m



Angle of release

Greater than 45° the projectile will reach its peak too quickly. Lower than 45° the object thrown will not achieve sufficient height.



Speed of release

The greater the release speed of a projectile, the greater the horizontal distance travelled. This is why athlete train to increase maximum power in the arms *i.e. javelin throwers*.





Height of release If the release height is greater than the landing height, the optimum angle of release is less than 45° *i.e.* A shot putter.





If the **release height is below** the **landing height** the optimum angle of release is **greater than 45°** *i.e.* A basketball set/jump shot.





A greater release height results in an increase in horizontal distance. This means that when fielding the taller the fielder the further the distance they will throw the ball.



In order for a smaller fielder to achieve the same distance, he will have to change the angle or speed of release.



Projectile in flight

The flight paths are described as a **parabolic shape**. While in flight a projectile will be affected by **weight** and **air resistance**.



If **weight** is the dominant force the **air resistance** is less effective and a **parabolic flight path** occurs. If **air resistance** is dominant over the **weight** a **non parabolic flight path** will occur.



Projectiles and free body diagrams

Projectile flight can be illustrated with **free body diagrams**. This is a snapshot of the forces acting on the object at **3 phases of motion** during the flight (Start, mid & end)



Projectiles and free body diagrams

Projectiles with a lighter mass, such as a shuttlecock, are affected by air resistance much more and this causes them to deviate from the parabolic pathway.



Parallelogram of forces

Consider the **resultant forces** acting on each of the projectiles (Shot and Shuttle) This is the net force of **air resistance (AR)** and **weight (W)** and highlights which is the more **dominant**.



Lift to a projectile (Bernoulli principle)

In fluid dynamics, **Bernoulli's principle** states that the **higher the velocity of air flow** the **lower the surrounding pressure**. This principle is the reason additional **lift force** can be applied to a projectile when thrown.



This can lead to better results in the discus event in athletics and the ski jump event in the winter Olympics.

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Lift to a projectile (Bernoulli principle)

An **aerofoil** shape has a curved upper and a flat underneath surface. The resultant effect is a **low pressure above** the object and a **higher pressure below** it. All fluids move from a **high** to **low** pressure and therefore creates additional '**lift**'



This is the same principle as a aeroplane wing.



Lift to a projectile (Bernoulli principle)

A ski jumper will attempt to adopt a aerofoil position to maximise the amount of 'lift' possible. This includes a **curved upper** area and a **flat underneath**.



Bernoulli principle – downward lift force

This principle also works in **reverse** if the aerofoil is inverted. Formula 1 and track cyclists spend large sums of money and time tweaking and improve the **downward force** that holds the object to the track.



During a track cycling race the key objective is to achieve a flat back position and draw air in below the bike to create a low pressure.



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What is the Magnus force?



You see the **Magnus effect** at work in the **curved flight path of balls** that are thrown, hit, or kicked and at the same time are given a spin. Golfers, baseball pitchers, football and table tennis players all employ this effect to curve the flight path of the ball.







Applying an **external force outside the centre of mass** results in **spin** (angular momentum).

There are 4 types of spin that can be applied to an object:

1. Topspin – Eccentric force applied above the centre of mass (Spins downwards)

 Backspin – Eccentric force applied below the centre of mass (Spins upwards)





3. Sidespin – HookEccentric force applied to the rightof centre of mass (Spins left)





4. Sidespin – SliceEccentric force applied to the leftof centre of mass (Spins right)



The **Magnus** effect works the same as the **Barnoulli principle**. As a force is applied off centre a **pressure gradient** is formed each side. The spin and additional **Magnus force** creates a **nonparabolic flight path**.

Spin in Tennis:

Tennis Topspin





Tennis Backspin





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Side spin is regularly used in football when taking free kicks or corners. For a left footer, the ball rotates to the right (**low pressure** on the right side of the object) and increases resistance on the left side (**high pressure**)



Sidespin is common in the game of golf. This will enable the player to move the ball around obstacles such as trees or the contours of the course. Side spin is also an important part of tennis and table tennis to confuse the opposition.







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Exam questions

1. A footballer taking a free kick may apply sidespin to the ball to make it swerve. Draw and label an airflow diagram of the ball in flight. Explain how spin causes the flight path of the ball to deviate. [5]



Exam questions

2. Fig.3 shows a gymnast performing a back somersault. Explain how angular velocity is controlled by the gymnast during take-off, flight and landing.



Exam questions

3. Identify two factors that affect the horizontal distance travelled by a projectile. [2]



Marks Scheme:

1. Five marks from:



- wider airflow lines on side away from direction of swerve / narrower on side of direction of swerve
- higher pressure where airflow lines are wider / lower where lines are narrower
- direction of spin matches direction of swerve
- (Effect of swerve is) magnus force/effect
- caused by pressure gradient from high to low
- air travels further on low-pressure side of ball / or opposite
- air travels faster on low-pressure side of ball / or opposite





Marks Scheme:

2. Six marks from:

- (analogue of Newton 1) A body will continue to rotate with constant angular momentum unless acted upon by an external torque/moment (AO1)
- (momentum) Principle of conservation of angular momentum (AO1)
- (AM) AM = Iw / angular momentum = moment of inertia x angular velocity (AO1)
- (take-off) gymnast generates angular momentum off floor (AO2)
- (MI) Moment of inertia high as body is extended (AO2)
- (AV) therefore angular velocity (w) / rate of spin is low (AO2)
- (flight MI) MI is reduced as body is tucked (AO2)
- (AV) therefore angular velocity / rate of spin increases (AO2)
- (entry MI) MI is increased as body is extended (AO2)
- (AV) therefore angular velocity / rate of spin is reduced (AO2)
- to prevent over rotation / controlled landing (AO2)



Marks Scheme:

- 3. Two marks from:
- height of release
- speed/velocity of release
- angle of release
- air resistance/shape of object/spin of the object

