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BIOMECHANICS

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This chapter provides an insight into the biomechanical mechanisms that cause and alter motion. This approach, which begins with an expansion of linear kinetics from 2A-2B, then explores the topic of angular kinetics, an area critical to the understanding of the mechanics of movement. A number of issues associated with fluid mechanics are then presented from an applied perspective.

PHYSICAL EDUCATION STUDIES 3A-3B
A TEXTBOOK FOR TEACHERS AND STUDENTS

The 5-step Analysis Framework

Students are challenged to re-visit the biomechanical analysis approach presented in 2A-2B, such that it can be applied to movement commonly seen in sport and exercise.

Step 1: Preparation

Understand the skill to be analysed, identifying the critical variables associated with ‘ideal performance’.

Step 2: Observation

Decide on the number of observations needed to ‘make a decision’ on critical variables. Remember, you will need to observe the action from different locations to assess different variables. Also observe performance under varied situations (fatigued vs non-fatigued).

Step 3: Evaluation

Compare critical variables of your ‘ideal performance’ with observed performance. Prioritise practice time with regards to strengths in performance and observed weaknesses.

Step 4: Intervention

Select the appropriate intervention to rectify weakness in performance. Provide feedback on the mechanical variables being practised.

Step 5: Re-observe

Check that intervention strategies have been successful in modifying the movement.

Linear Momentum (m·v)

This is the product of mass ***(m)*** and velocity ***(v).*** Remember velocity is a vector that has size (for example, 10 m·s^{-1} (m/s)) and direction (for example, 45° to the horizontal, either forward or back – the direction with respect to the 45° is called 'sense'). Let's consider animals that build linear momentum primarily through their mass or velocity.

Mass: The elephant has a mass of ~5,000 Kg, which when combined with the ability to run at moderate speed (e.g. 10 m·s^{-1} directly toward the person taking the picture), produces a huge linear momentum (50,000 kg·m·s^{-1}).

Velocity: The cartoon character Sonic the Hedgehog with a mass of ~20 kg is able to build linear momentum based on 'blistering' velocity (for example, 100 m·s^{-1}).

$$\text{Linear momentum (p)} = \text{mass} \cdot \text{velocity}$$
$$= 20 \text{ kg} \times 100 \text{ m}\cdot\text{s}^{-1}$$
$$= 2{,}000 \text{ kg}\cdot\text{m}\cdot\text{s}^{-1}$$

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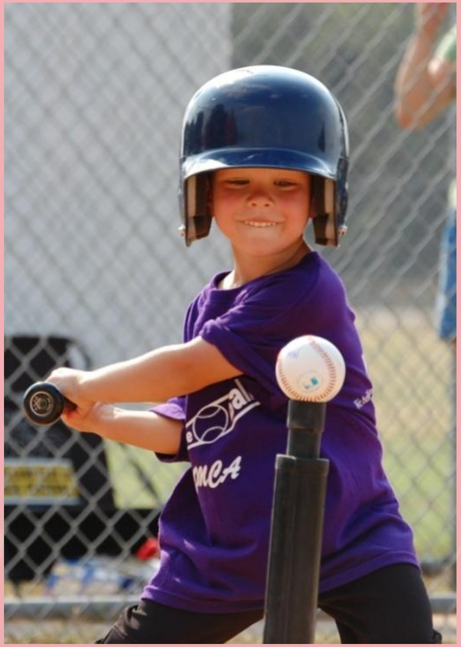
Conservation of Linear Momentum

Newton's 2nd Law (F = m·a) relates to the behaviour of objects when all forces are unbalanced, resulting in the development of acceleration. That is, to increase acceleration more force must be applied, assuming the mass is held constant. Conversely, if one increases the mass (e.g. using a heavier bat in cricket) but is unable to increase the applied force, then the resulting acceleration will be lower.

To create a ***change in momentum*** (m·v) force must be applied. Consider hitting the ball from the tee in tee-ball. In this situation, force is provided by the swinging bat. The momentum of the stationary ball, which is initially zero, as it sits on the tee, is increased following impact.

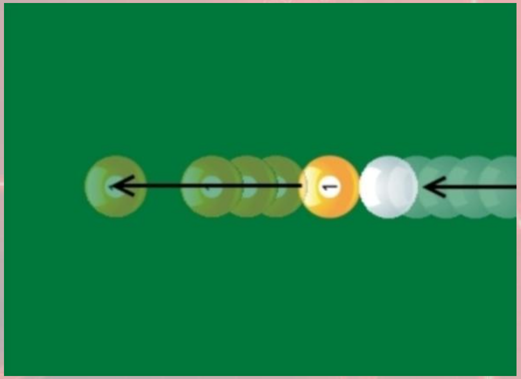


Force and Linear Momentum

Force is equivalent to *the time rate of change of linear momentum*.

The collisions between two objects may be perfectly ‘elastic’, in which case the total momentum of the ‘system’ (all objects combined) remains constant – *it is conserved*. This is the Law of Conservation of (Linear) Momentum. ***When two bodies collide, the momentum before the collision remains the same as the momentum after the collision and therefore, momentum is conserved.***

The cue ball impacting another ball in a game of pool is a situation where momentum post-impact is conserved.



Conversely, attempting to bounce a ball in a sand pit is an example of a perfectly inelastic collision – there is no bounce and therefore linear momentum is not conserved.

Conservation of Linear Momentum: When both objects are moving

Now let's first consider the situation where both objects are moving in a straight line both pre- and post-impact. Remember, this is just a basis for understanding the concept as these are NOT elastic collisions and some energy will be lost during the collision. In a baseball drive, where linear momentum is conserved, the velocity of the ball post-impact may be calculated when you know the:

- Mass of the bat and ball
- Linear velocity of impact point on the bat both pre- and post-impact
- Linear velocity of the pitched ball

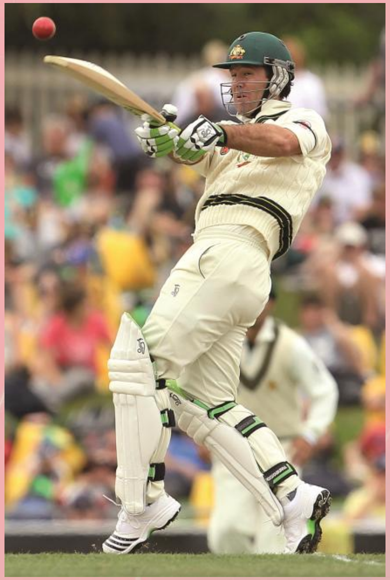
Momentum ($Kg \cdot m \cdot s^{-1}$)	***Pre-impact***	***Post-impact***
Ball	**Linear momentum**: $m_1 \cdot v_1$ Remember, velocity is a vector, so direction would be critical if calculations were to be performed	**Linear momentum**: $m_1 \cdot v_3$ v_3 = Velocity of the ball post-impact
Bat	**Linear momentum**: $m_2 \cdot v_2$ v_2 = Velocity of the bat pre-impact	**Linear momentum**: $m_2 \cdot v_4$ v_4 = Velocity of the bat post-impact

Pre-impact linear momentum (bat + ball) = Post-impact linear momentum (bat + ball)

Linear Momentum

Exam style question

For the last over of a one day cricket innings, with the scores close and the match in the balance, the fielding captain decides to ask the spin bowler, rather than a fast bowler, to bowl. Use biomechanical principles related to 'conservation of linear momentum' to justify this decision.



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Linear Momentum

Answer

For the last over of a one day cricket innings, with the scores close and the match in the balance, the fielding captain decides to ask the spin bowler, rather than a fast bowler, to bowl. Use biomechanical principles related to ‘conservation of linear momentum’ to justify this decision.

When two moving objects collide (cricket bat and ball) the linear momentum is conserved. By using a relatively slow delivery, when compared with a fast bowler, the momentum of the ball before impact is reduced. Therefore, the bat must be swung with greater velocity to generate maximum momentum after impact.

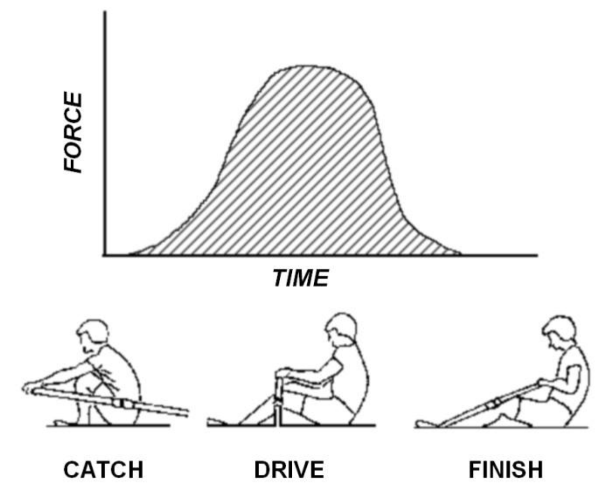
Impulse and Change in Momentum

The concepts of conservation of linear momentum and impulse are linked in Newton's 2nd Law, as shown in the formula $F = m\,[v_2 - v_1]/t$. If both sides of the equation are multiplied by **t** you get:

$$F \cdot t = m\,(v_2 - v_1)$$

Impulse = change in momentum (m·v)

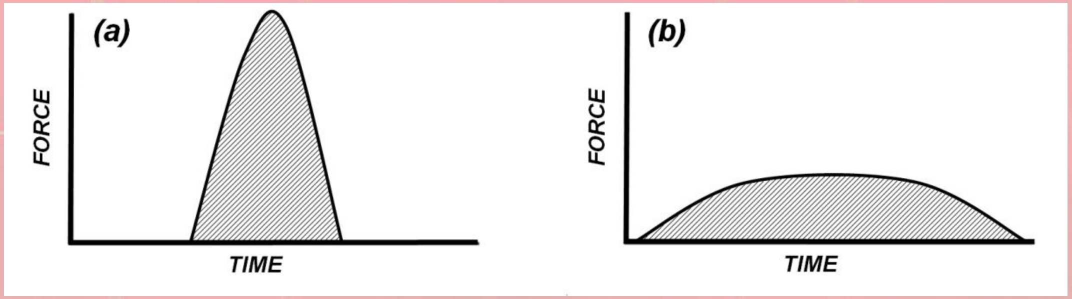
Impulse curve: Applying Force



Impulse curve: Absorbing force
Catching a ball

(a) With a short time period

(b) With a longer time period – give with the hands



Impulse and Change in Momentum

Exam style question

Explain, using diagrams, the resultant impulse for the netballer landing with:

(a) a straight leg (little knee flexion).

(b) the same action with considerable knee flexion.

In your diagrams, show the approximate peak force recorded during foot contact.

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Impulse and Change in Momentum

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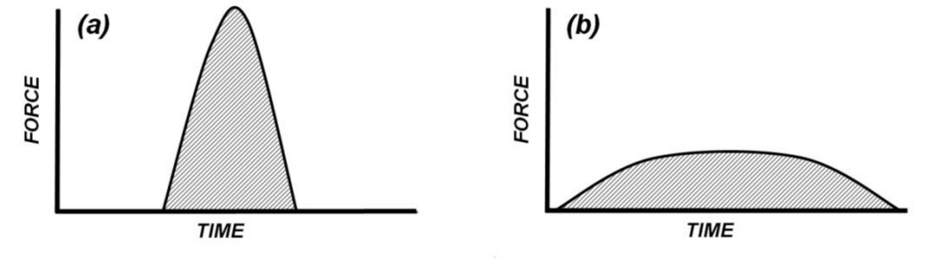


(a) The peak force would be relatively high. The force of foot contact with the ground has been absorbed over a relatively small amount of time.

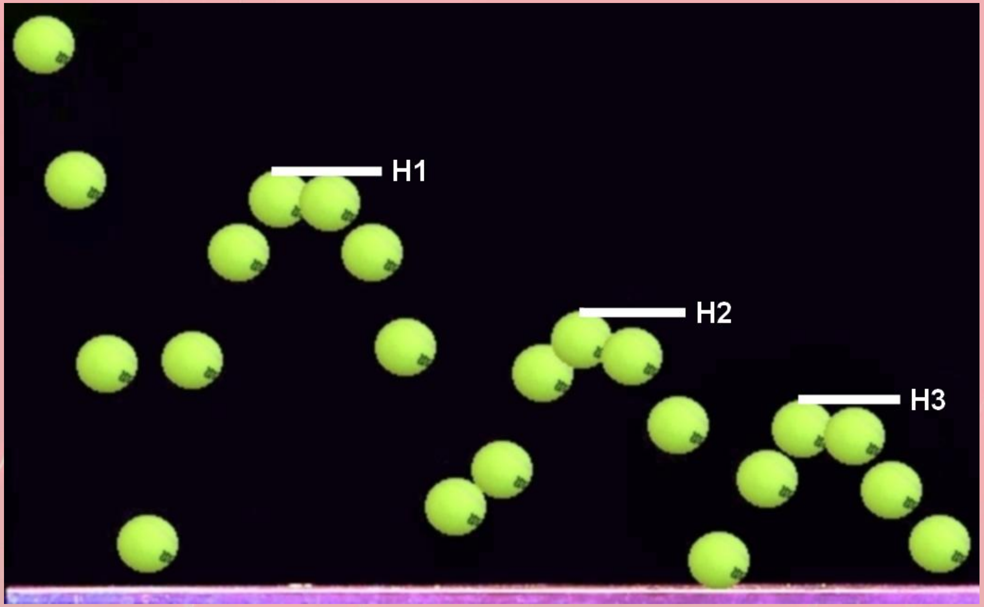
(b) Although the impulse under each curve is the same - the peak force would be relatively low when the force is absorbed over a longer period of time.

The Coefficient of Restitution (COR)

The coefficient of restitution (COR), or bounciness of an object is a value representing the ratio of the velocity after an impact compared with the velocity before the impact.

An object with a COR of 1 collides *elastically* (linear momentum fully conserved), while an object with a COR < 1 experiences an *imperfectly elastic collision*. For a COR = 0, the object does not bounce at all.

A bouncing ball is an example of an imperfectly elastic collision.



The Coefficient of Restitution

COR is influenced by 3 main factors:

***The materials of the interacting bodies*:** New tennis balls will have a higher coefficient than old and different surfaces (clay vs grass tennis courts) will also influence bounce height.

***The velocity of the collision*:** The velocity between the oncoming ball and the swinging implement will also alter the COR – higher velocities will reduce the COR because of the greater compression of the ball.

***The temperature of the materials involved*:** As the temperature of a ball increases so does the COR (think of the bounce height of a cold and hot squash ball).

How do you think COR is influenced by the materials used in a baseball bat and the speed of the pitched ball?

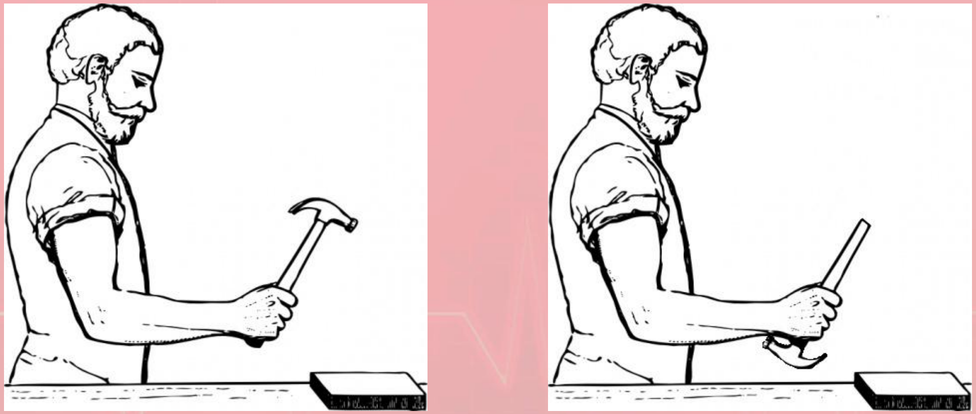
Angular Kinetics/ Moment of Inertia

In angular motion, while the mass of an object (bat, stick, or body) is important the critical factor in being able to swing this object is the ***distribution of the object's mass about the point that is used to rotate the object*** (the grip or centre of rotation). In angular motion this is termed the ***moment of inertia*** of the object (**I**).

Moment of inertia (I) = ∑(Sum) mass · r^2

r = distance from mass concentration (e.g. head of hammer) to the axis of rotation (e.g. grip hand position on handle of hammer). If more than one mass concentration these must be added together.

Moment of inertia
This is higher when a hammer is swung by the handle than when swung with the metal end in the hand.



Moment of Inertia in Sport

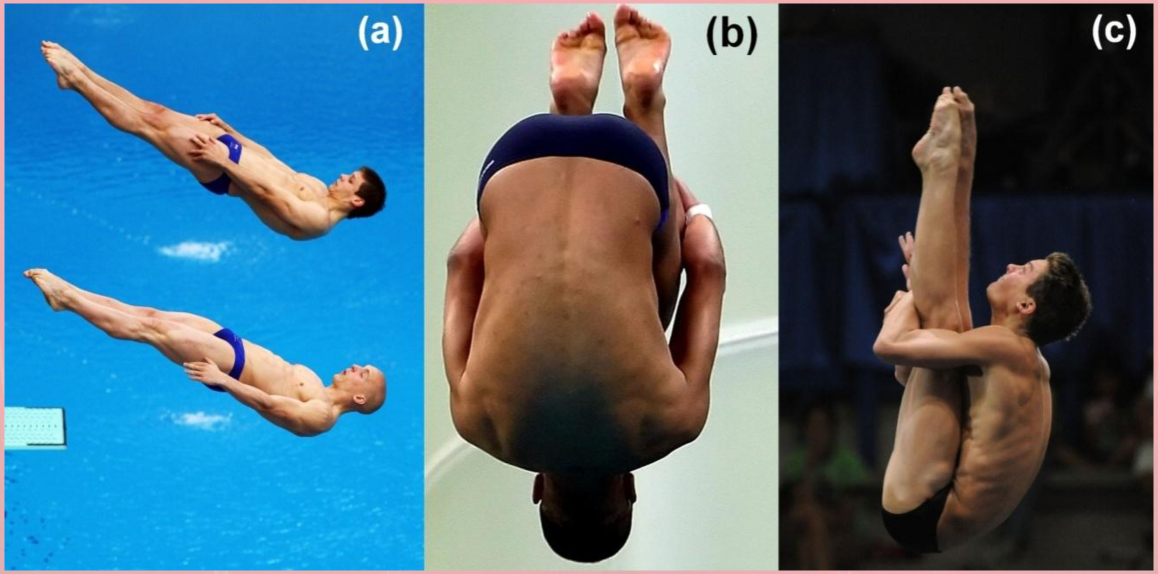
Moment of inertia of sporting equipment

The shorter handle used by the young tennis player (d), compared with the adult player (D) assists in manoeuverability of the racquet.

Moment of inertia of the human body during sporting activities

The diver is able to change his moment of inertia by changing his body shape. He varies the distribution of mass from the axis of rotation for a somersault.

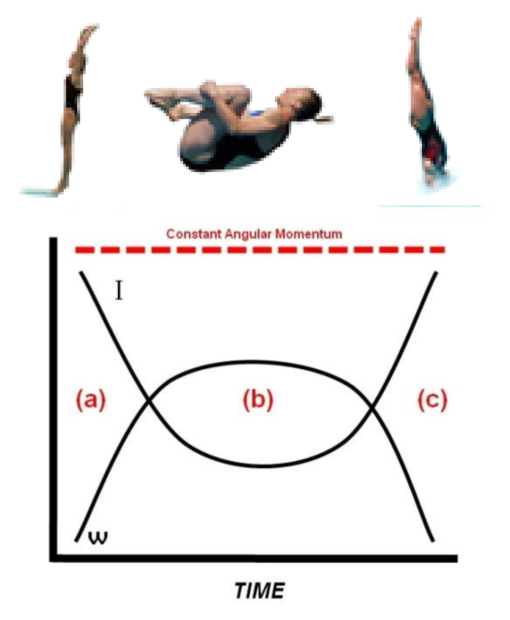
(a) Layout position - Highest moment of inertia
(b) Tucked position - Lowest moment of inertia
(c) Piked position - Intermediate level moment of inertia



Angular Momentum

Angular momentum (I·ω) is the angular equivalent of linear momentum (m·v)

Linear motion	Angular motion
Mass (m)	Moment of inertia (I)
Velocity (v)	Angular velocity (ω)
Momentum (m·v)	Angular momentum (I·ω)



Conservation of Angular Momentum

When in the air your angular momentum is constant.

However, moment of inertia and angular velocity may change depending on the shape of the body.

(a) On leaving the board the moment of inertia is high and the angular velocity low.

(b) In midflight the body is tucked reducing the moment of inertia and increasing the angular velocity.

(c) At water entry the diver again increases the moment of inertia to reduce the angular velocity for water-entry.

Angular Momentum

Angular momentum (I·ω)

Conservation of angular momentum also occurs about the long axis of the body when one rotates in dancing or ice-skating. The contact with the floor or rink is considered almost frictionless – so it is like you are in the air.

Arms close to the body =
high angular velocity - rotation

Arms away from the body =
lower angular velocity - rotation

Conservation of Angular Momentum

Exam style question

Using your understanding of biomechanical principles, explain why a child’s bat is shorter and lighter than that used by an adult.

Conservation of Angular Momentum

Answer

Using your understanding of biomechanical principles, explain why a child's bat is shorter and lighter than that used by an adult.

By using a relatively shorter and lighter bat, the child's bat has a lower moment of inertia and therefore is easier for the child to accelerate.

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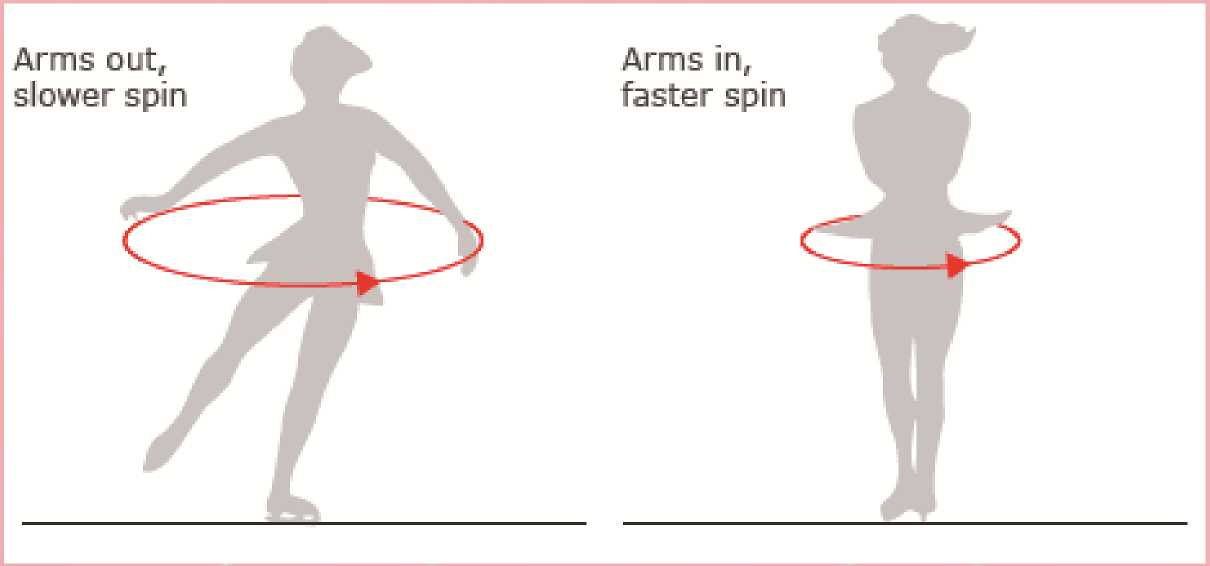
Conservation of Angular Momentum

Exam style question



Using your understanding of biomechanical principles, explain how the position adopted by the ice skater impacts on their rate of spin.

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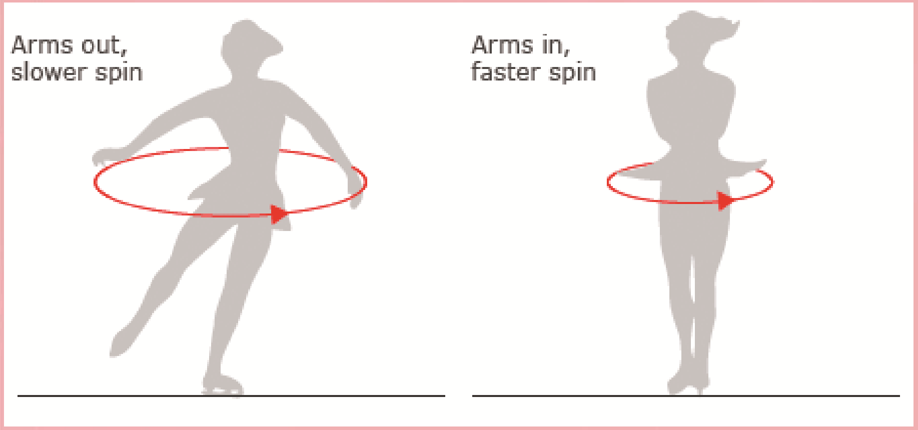
Conservation of Angular Momentum

Answer



Using your understanding of biomechanical principles, explain how the position adopted by the ice skater impacts on their rate of spin.

When the arms are moved close to the trunk, the mass is distributed closest to the axis of rotation, thereby reducing the moment of inertia, with a resultant increase in angular velocity. When the arms are extended, the moment of inertia is highest, and the angular velocity is reduced.

Levers in the Body

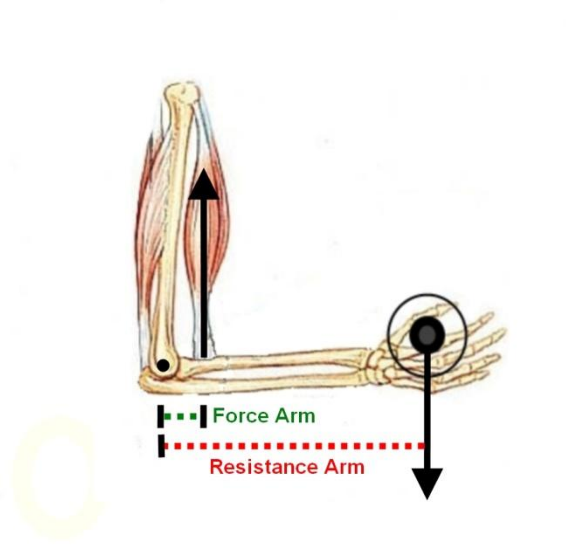
Components of a lever

To fully understand how levers benefit movement requires an understanding of the three components that make up a lever.

- A pivot point or axis: This is the point about which the two lever arms (force and resistance – discussed below) operate.

- A weight/load/resistance to be moved.

- The applied force required to move the weight/load/resistance.



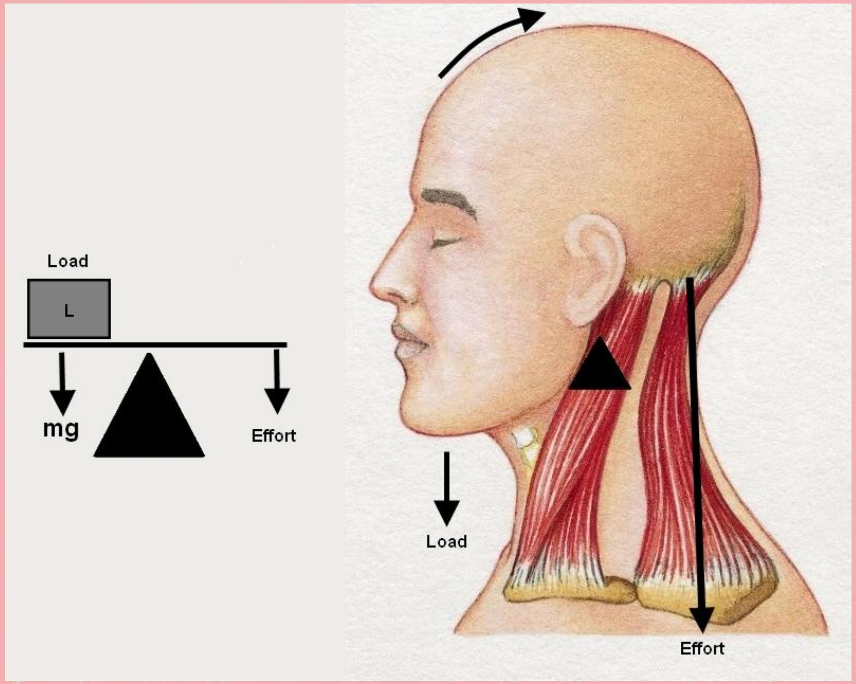
The distance between the force and the pivot point or axis of rotation is termed the *force arm*, whereas the distance between the weight/load/resistance and the axis of rotation is termed the *resistance arm*.

Types of Levers in the Body

1st Class

The axis of rotation (the fulcrum) is between the force (effort) and the load (for example, a seesaw).

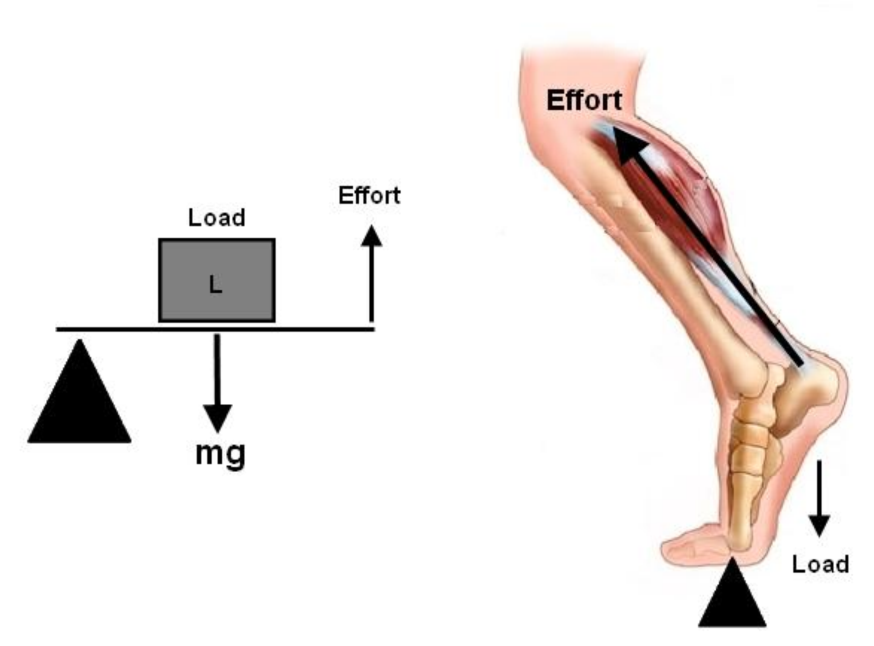
Functionally not many examples exist in the body; however, holding one's head erect is an example of this type of lever. The fulcrum, in the centre, is the connection between the head and the spine, while the load is the weight of the head acting through its centre of gravity, with the force being the muscle force pulling on the back of the skull.



Types of Levers in the Body

2nd Class

For this type of lever the weight/load/resistance is located between the fulcrum and applied force, such as in a wheelbarrow.

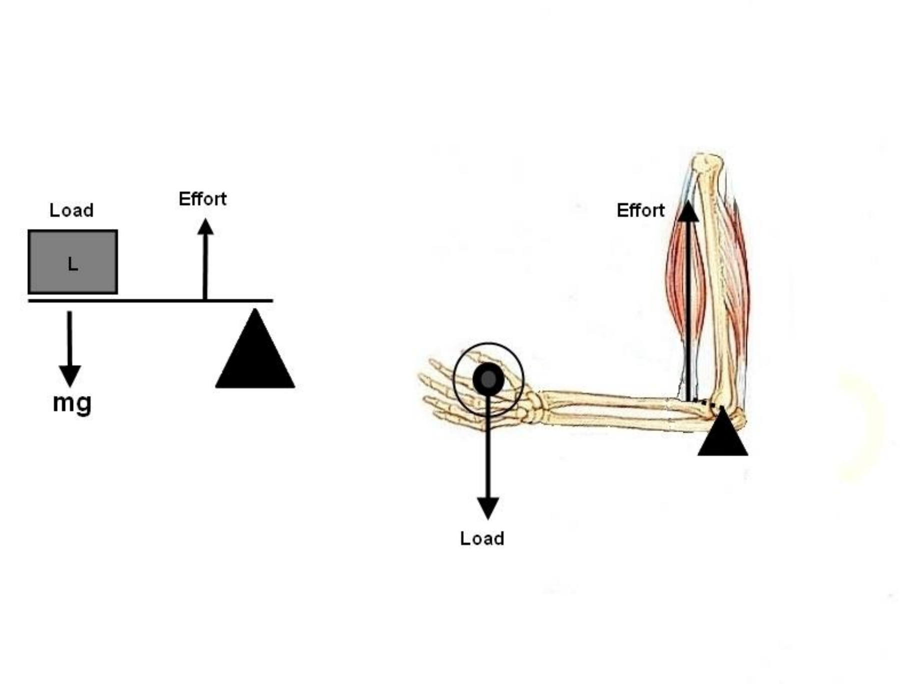


Again this lever type is not common in the body though a good example is a when an individual takes a walking step. The toes act as the fulcrum and the body weight (for part of the walking cycle) is positioned centrally, as the gastrocnemius muscle contracts and pulls upward – ‘effort’. As the weight of the body (line of the centre of gravity) moves forward of the toes (fulcrum) in walking, this 2nd class lever then becomes a 1st class lever.

Types of Levers in the Body

3rd Class

This is the most common type of lever in the body, with the applied force (the muscle attachment - effort), somewhere between the axis of rotation (e.g. the elbow) and the weight/load/resistance (for example, a dumbbell in the hand).



A biceps curl is an excellent example of a 3rd class lever. Think of throwing a softball for distance. The ball represents the resistance in the hand, the shoulder acts as the fulcrum and the muscle(s) attachment needed to create the motion is between these two ends.

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Modification of Lever Lengths during Sporting Activities

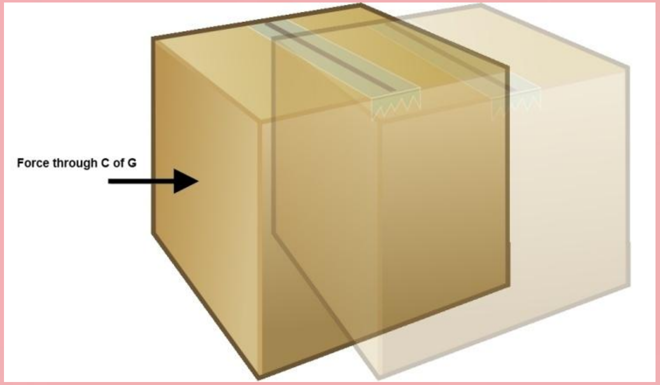
If the body comprises primarily 3rd class levers then humans are typically not mechanically efficient – the force arm is always going to be shorter than the resistance arm.

In an attempt to overcome this deficiency we try to reduce the length of the resistance arm as much as possible when performing ‘force related activities’, such as in weight/power lifting or when attempting to increase the force on an object (for example, the water – as shown in picture during the pull in freestyle swimming). This reduction in the effective length of the resistance arm is our attempt to increase the effectiveness of the force arm.

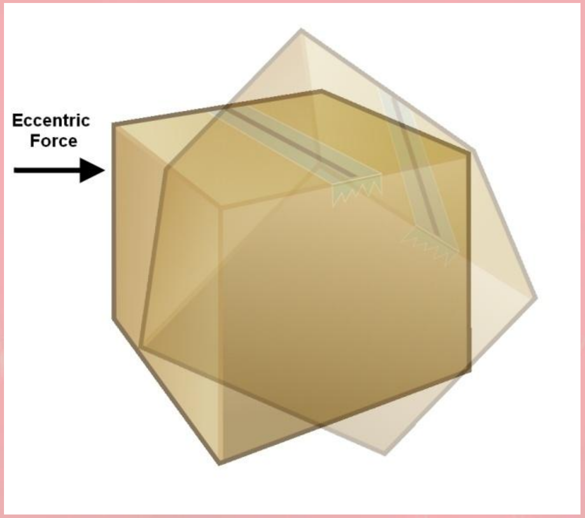
However, where speed of an end point such as in tennis or cricket bowling is required, we extend the length of the lever to increase speed of the hand/foot or racquet.

Moment of Force (Torque) – Turning Forces

If a force is applied directly through the centre of gravity of an object no rotation will occur and the object moves in a straight line (it translates).



However, if a force is applied away from this point (off-centre) you get a combination of linear and angular motion, unless one end is fixed where in that case, you only produce a turning effect.



Creating Turning Forces

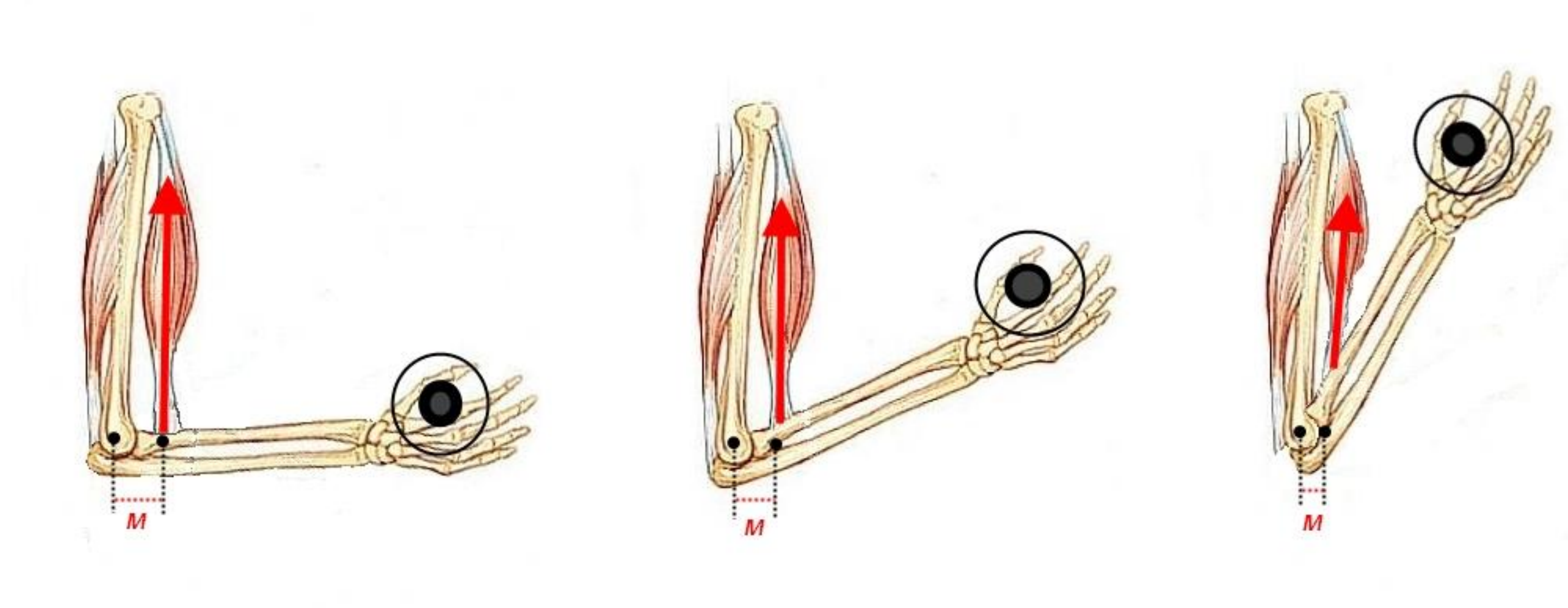
Moment of force (N·m) = Applied force (N) x perpendicular distance (m) between the line of the force and the axis of rotation.

This turning effect occurs during all sporting activities.

Creating Turning Forces: Changes in moment arm length

Moment of force (N·m) = Applied force (N) x perpendicular distance (m) between the line of the force and the axis of rotation.

The ability to apply force will alter as the moment arm (M) changes in length.



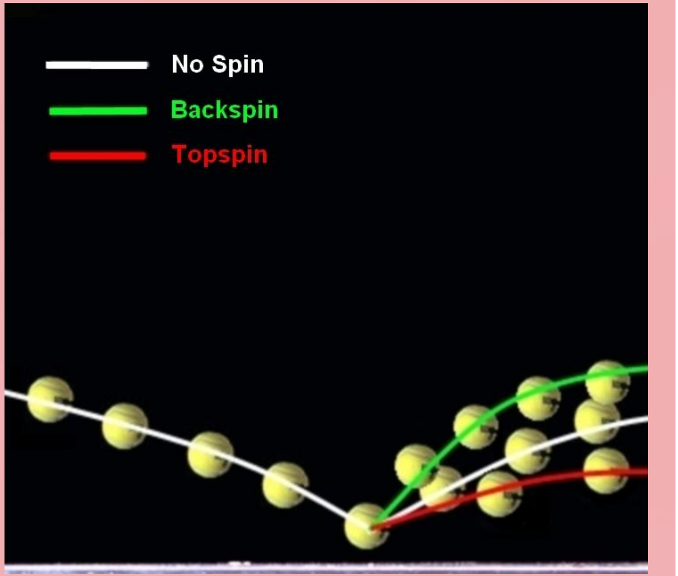
Fluid Mechanics: Drag

In an endeavour to enhance performance by ‘shaving’ fractions of a second from a race time athletes attempt to reduce the affect of air resistance or drag in the following ways.

Reduce air resistance by modifying equipment such that the athlete is more ‘streamlined’.

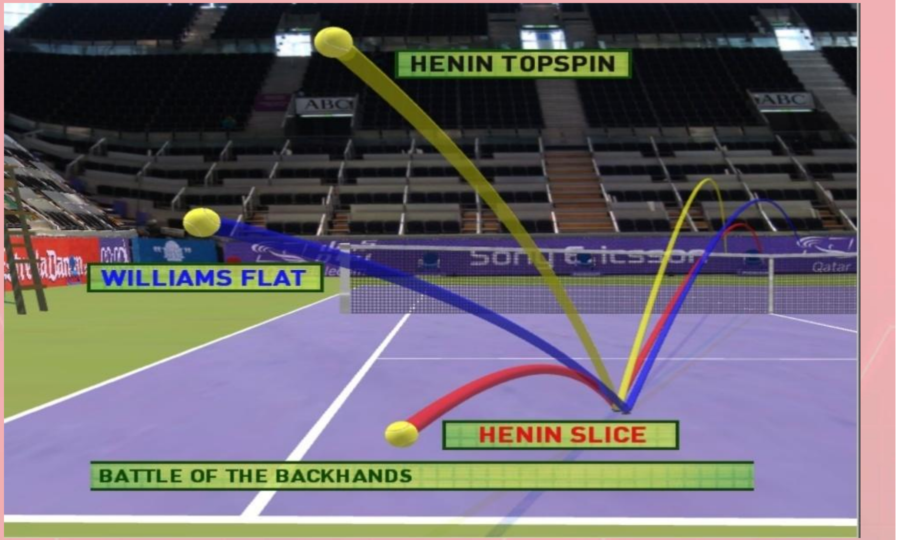
Reducing the influence of air resistance through modification to technique – e.g. ‘drafting’.

Magnus Effect and Spin



If the ball was to come in at the same approach angle then the type of spin the ball possesses will influence the rebound angle. If one compares the topspin and backspin rebound with the no spin situation you find that the ball bounces with a steeper rebound for the ball with backspin and lower for the ball hit with topspin.

In tennis, where the ball will approach at varying angles you typically get rebounds as can be observed for topspin, flat and slice (backspin) rebounds.



Remember, the curving effect of spin on the flight of a ball is termed the Magnus effect.

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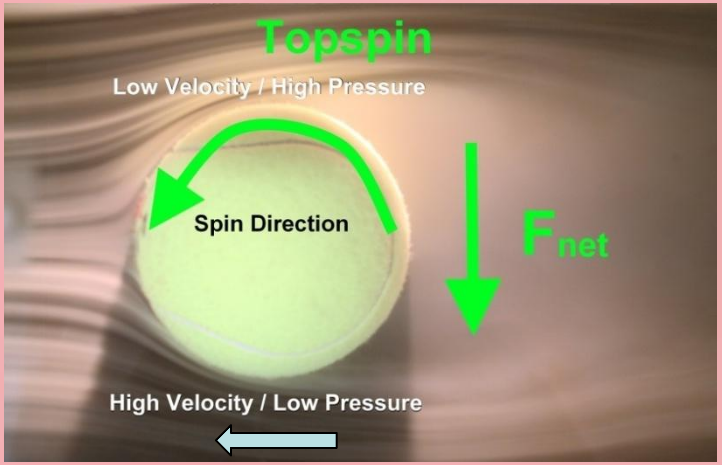
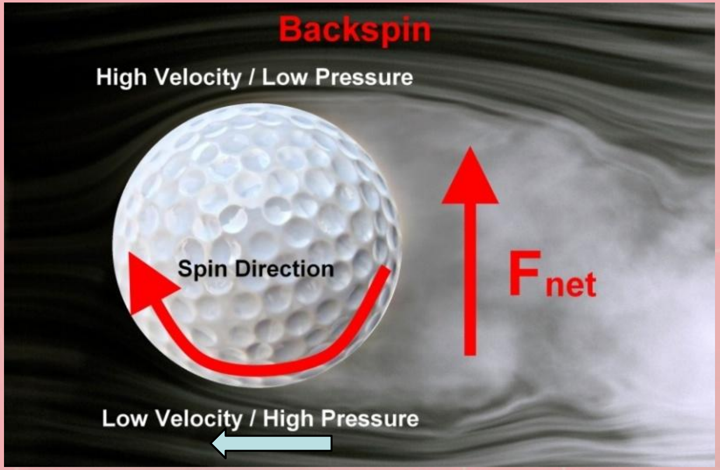
Bernoulli's Principle

Bernoulli's principle states that an increase in the speed of fluid occurs simultaneously with a decrease in pressure.

For a topspin shot, hit from right to left, as the boundary layer rotates with the ball, the particles on top of the ball decrease in speed (crash into the particles of air that the ball is moving through). Conversely the particles under the ball increase in speed, as they are moving in the same direction as the general airflow, producing a decrease in pressure.



For a backspin shot the reverse is true.



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Spin

Exam style question

Use your knowledge of forces, spin, horizontal and vertical displacement in the air and after landing, to respond to and explain the following. Use diagrams where possible to assist your answer.

(a) In tennis, you want to hit a ball deep into the opponent's court with a large ‘error margin’ at the net.

(b) Your volleyball serve is hit with backspin.

(c) You slice the golf ball off the tee. As a right handed golfer the ball curves to the right.

Spin

***Answer:** Answers are provided with different foci to assist student learning.*

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(b) Your volleyball serve is hit with backspin.

(c) You slice the golf ball off the tee. As a right handed golfer the ball curves to the right.

(a) Hit the ball with topspin, which will allow the ball to be hit high over the net, but the greater force ‘on top of the ball’ will assist to drop the ball back into court inside the baseline.

(b) Back spin – the ball has been hit off-centre – an eccentric force. It will travel with linear and angular motion. The ball will have a high velocity on top with low pressure and on the bottom of the ball – the velocity will be low and the pressure high. Therefore, the ball will experience lift and have a greater horizontal competent than a ball hit with no spin. That is, it will float.

(c) Sidespin, eccentric force (off-centre) is applied to the ball – low velocity and high pressure on the side of the ball that is closer to the golfer, therefore, the ball moves to the right.

Biomechanical Analysis

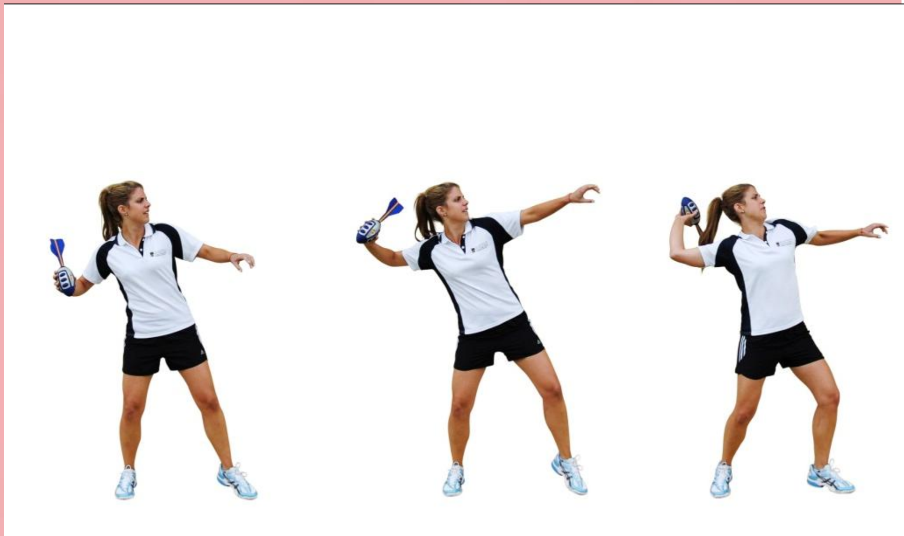
Discuss the variables as they apply to throwing

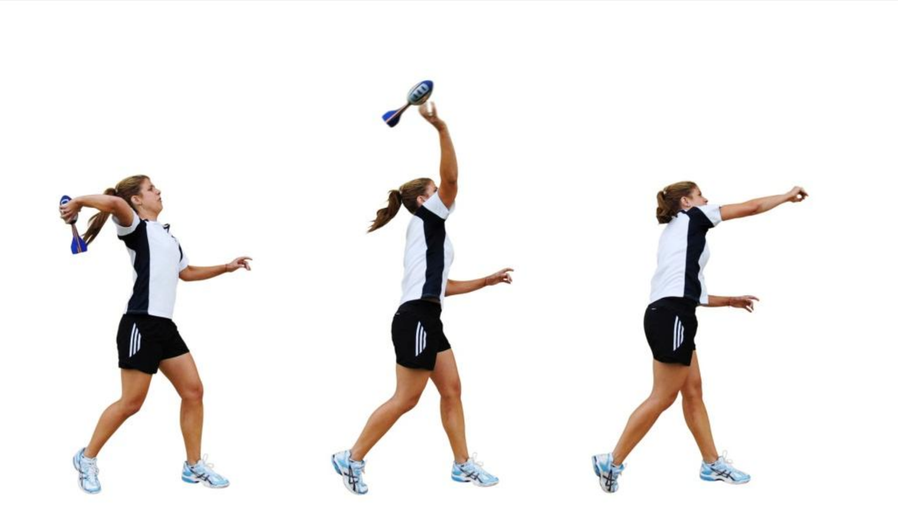
Moment of inertia (**I**) – The distribution of mass.

Angular momentum: Combination of moment of inertia and angular velocity (rotational speed).

Levers: Three levers in the body - mostly, 3rd class.

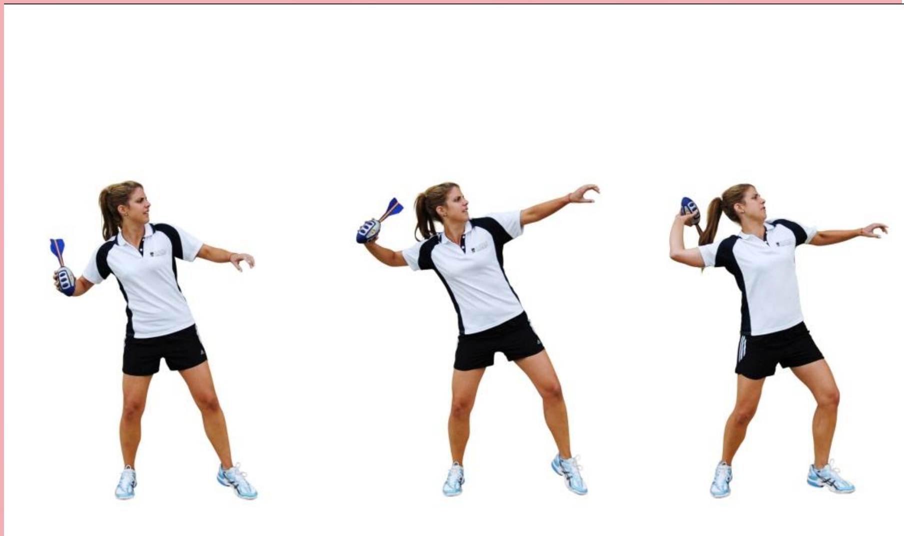
Torque: A product of force and a moment arm (perpendicular distance to line of the force).

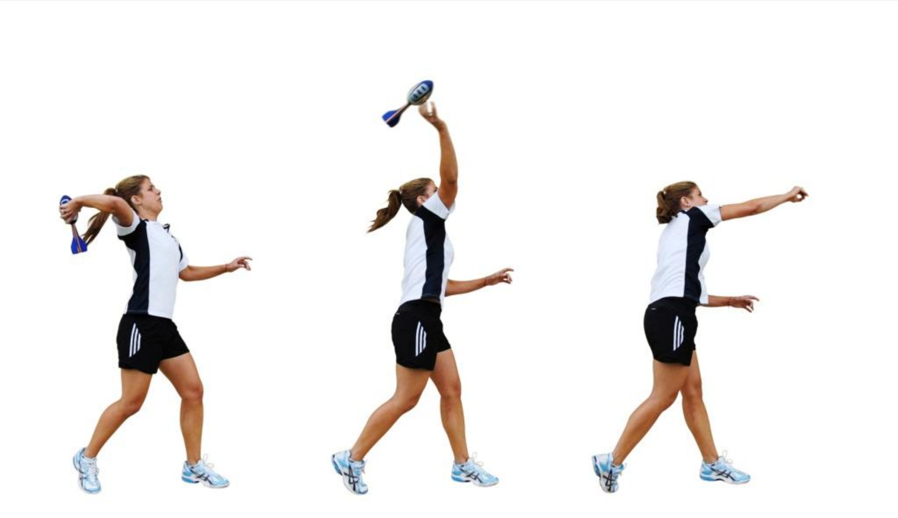




Biomechanical Analysis

Discuss the variables as they apply to throwing





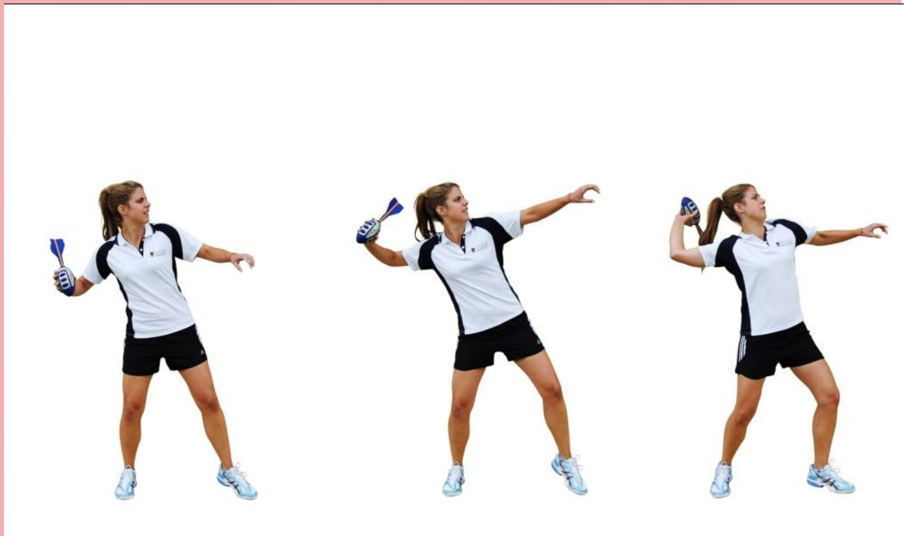
Balance: May be static or dynamic (position of C of G to base of support).

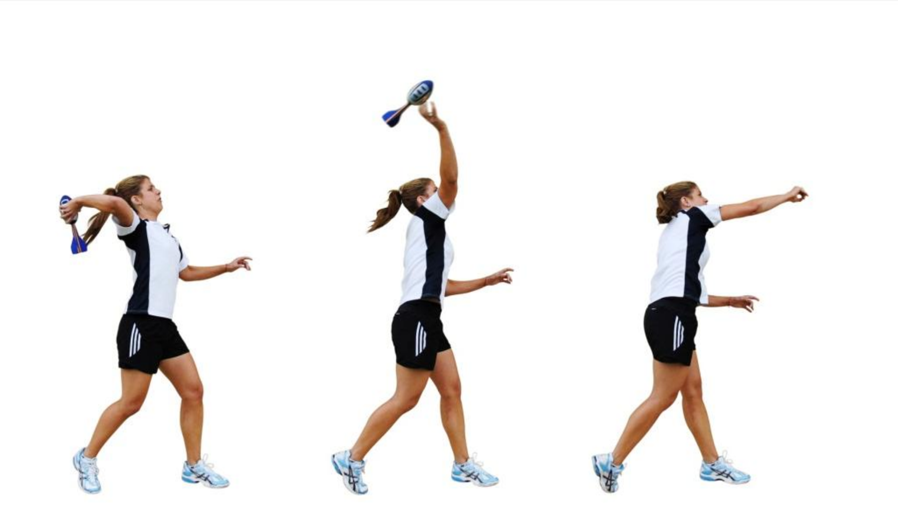
Coordinated movement: Either velocity (sequential) or accuracy (as one) based.

Force-time: Impulse - the application of force over time (Impulse: force x time).

Biomechanical Analysis

Discuss the variables as they apply to throwing





Inertia: The reluctance of a body to move.

Optimal projection: Related to height of release and landing.

Range of motion: Total range of movement at key joints related to the activity.

Spin: If possible consider spin in the air and bounce following landing.

Biomechanical Analysis

Discuss the variables as they apply to running

Moment of inertia (I)*:* The distribution of mass.

Angular momentum: Combination of moment of inertia and angular velocity (rotational speed).

Levers: Three levers in the body - mostly, 3rd class.

Torque: A product of force and a moment arm (perpendicular distance to line of the force).

Biomechanical Analysis

Discuss the variables as they apply to running

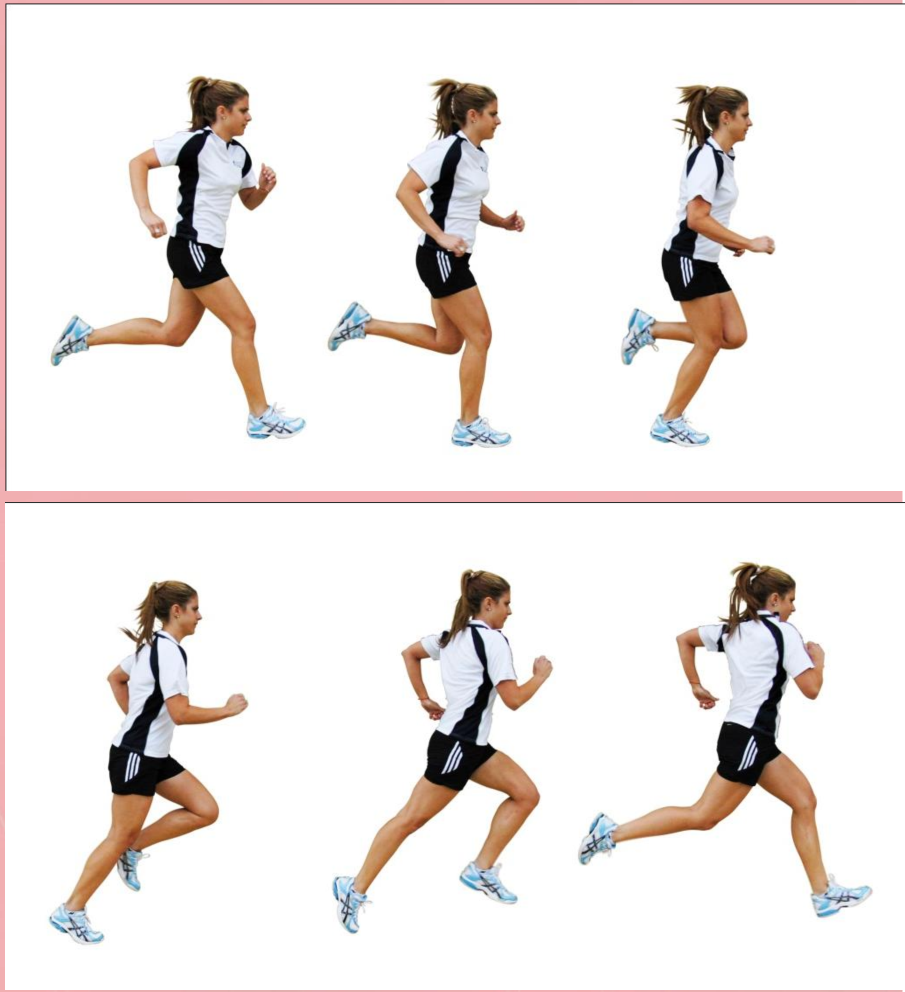
Balance: May be static or dynamic (position of C of G to base of support).

Coordinated movement: Either velocity (sequential) or accuracy (as one) based.

Force-time: Impulse - the application of force over time (Impulse: force x time).

Biomechanical Analysis

Discuss the variables as they apply to running



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