KINEMATIC CONCEPTS OF HUMAN MOVEMENT
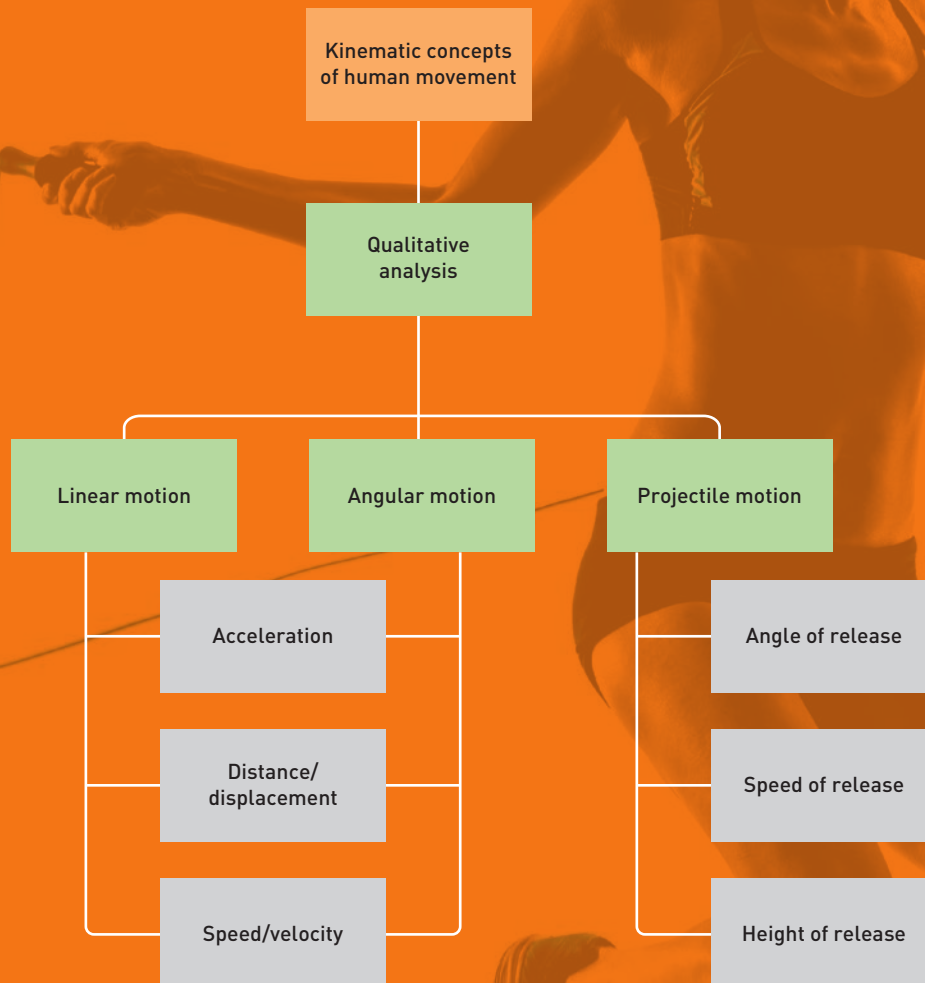
Key knowledge

» biomechanical principles for analysis of human movement including:
  • angular and linear kinematic concepts of human movement: distance, displacement, speed, velocity, acceleration and projectile motion (height, angle and speed of release)

Key skills

» perform a qualitative analysis of a movement skill using video and systematic observation to analyse and improve a variety of movement skills
» analyse, interpret and apply graphical, visual and physical representations of biomechanical principles to improve movement skills in a coaching context

Source: Extracts from VCE Physical Education Study Design (2017–2021), reproduced by permission, © VCAA.

iStock.com/OSTILL

Kinematic concepts of human movement

Qualitative analysis

Linear motion

Angular motion

Projectile motion

- Acceleration
- Distance/ displacement
- Speed/velocity

- Angle of release
- Speed of release
- Height of release

MOTION

Human movement involves many different types of motion. For example, a cricketer bowling the ball must first run in a straight line, using a combination of hip, knee and ankle movement. To bowl the ball, rotation of the shoulder, elbow and wrist joints is required. This complex combination of movements is called **general motion**. Nearly all human movement is considered general motion, which is a combination of both **linear** and **angular motion**. If the body or an object such as the ball leaves the ground, it will then experience **projectile motion**.
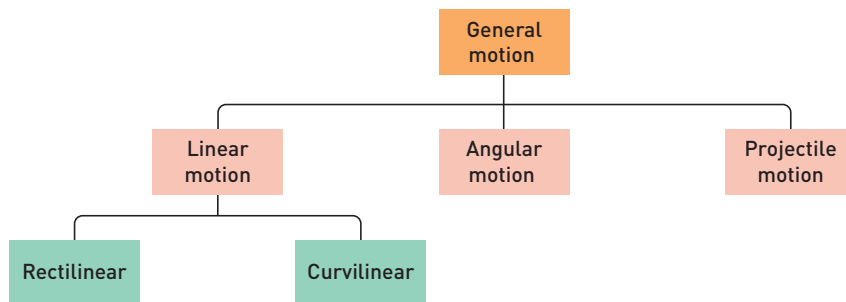
Types of motion in human movement

When looking at a skill or movement pattern from a biomechanical perspective, it is often easiest to break the skill down into its linear and angular components and analyse them individually. Linear motion occurs when all the body parts are moving at the same speed in the same direction along a curved or straight line. If the line is straight, the motion is called rectilinear. If the line is curved, the motion is called curvilinear. Angular motion involves movement around a central axis. The diagram above shows some examples of the different types of motion. Projectile motion will be looked at later in the chapter (see page 76).

LINEAR MOTION

As stated above, linear motion is the movement of a body along a straight or curved path where all body parts move in the same direction at the same speed. Describing this motion can be done by looking at the distance, displacement, speed, velocity and acceleration of the body. These characteristics are quantitative, which means they can be measured and/or calculated.

Linear distance and displacement

Distance and **displacement** both measure how far a body has travelled. However, they are quite different. Distance measures the path travelled from start to finish, regardless of direction. A netballer who weaves, dodges,
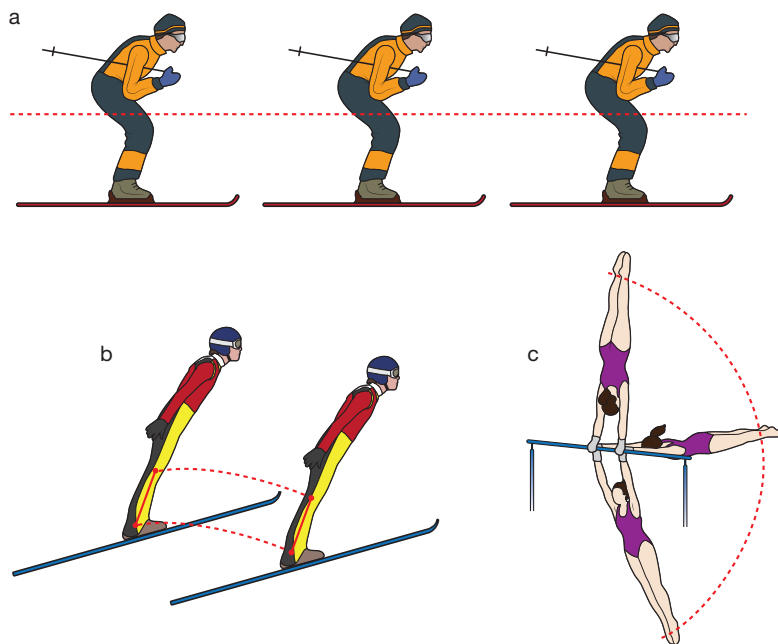
Types of motion: (a) rectilinear, (b) curvilinear, (c) angular

Wheelchair racing

Wheelchair racing is an excellent example of the combination of linear and angular motion. We see angular motion in the repetitive rotating action of the athlete's arms as they push the wheel rim, and in the resulting rotation of the wheels. The rotation of the wheels carries the athlete and the wheelchair in a straight line. This is an example of linear motion.

The combination of angular and linear motion is general motion.

The angular motion of the arms and wheels creates linear motion of both the athlete and the wheelchair.

baulks and then sprints forward to receive the ball may cover 15 metres in total, so the distance travelled is 15 metres.

Displacement is defined as change of position – how far it is from the initial position to the final position. When measuring displacement, the direction of motion is important. The displacement of the netballer in the previous example would be measured in a straight line from where they started to where they finished. Consider a running race on an athletics track. The distance covered by the runners is 400 metres but the displacement is 0 metres, because the start and finish points of the race are in the same place.
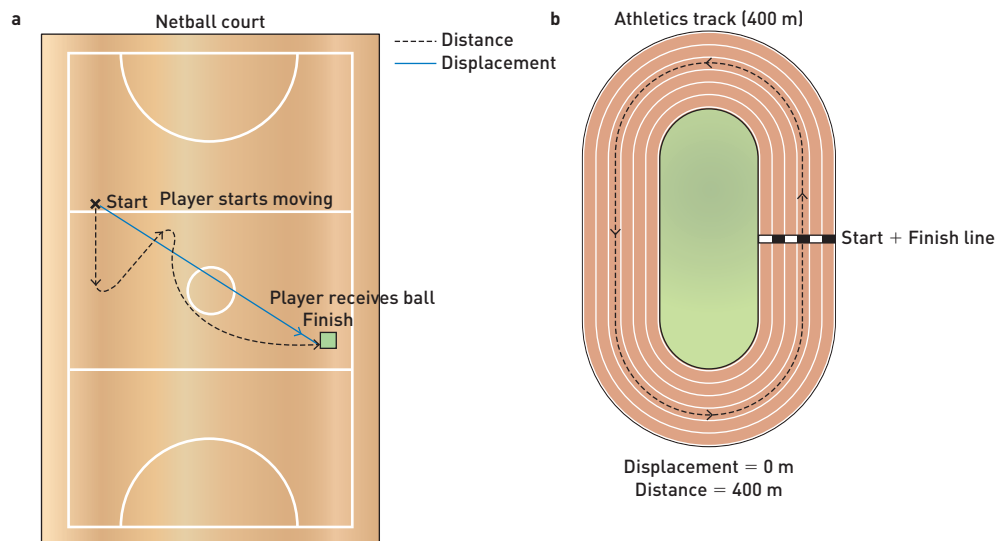
Distance and displacement both measure how far an athlete has travelled, either in total or from their starting point.

Either distance or displacement can be used to describe motion, depending on which will provide the most useful information. In many sporting situations, distance is a more important variable than displacement. A marathon runner will be less interested in their displacement than the distance they cover, because many marathons start and finish at a similar point. An Australian Rules footballer would be more interested in the total distance covered in the game.

Linear speed and velocity

The terms 'speed' and 'velocity' are often used interchangeably, but they mean very different things. **Speed** is defined as the ratio of the distance covered to the time taken (distance divided by time).

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

Velocity is the ratio of displacement, or change in position, to the time taken (displacement divided by time). Velocity has both a size and a direction.

$$\text{velocity} = \frac{\text{displacement}}{\text{time}}$$

The units for speed and velocity are metres per second or m/s. A change in velocity could be a change in speed, a change in direction, or both. A tennis ball hit at 30 m/s over the net and then returned at 30 m/s over the net has the same speed but has changed velocity because it has changed direction.

30 m/s to the right

30 m/s to the left
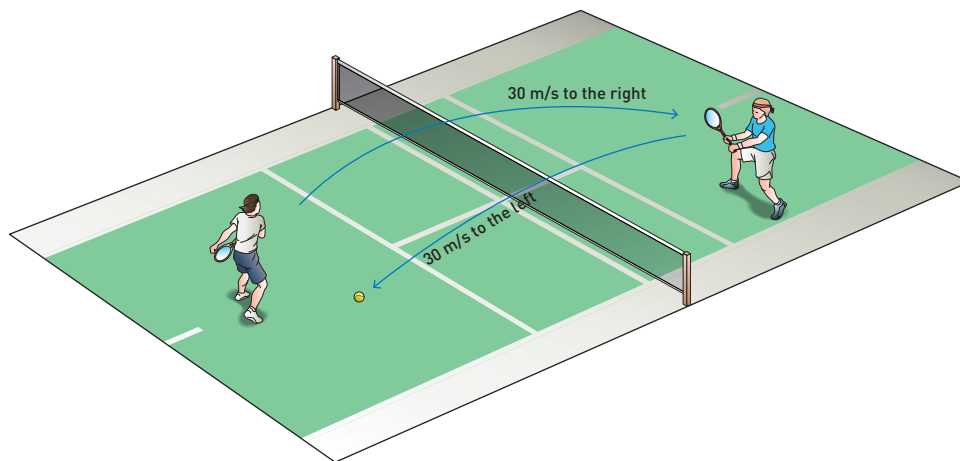
A tennis ball hit in one direction over the net and then returned in the opposite direction has changed velocity, even though it has not changed speed.

Analysis of the speed of human movement is important in sports such as swimming and athletics, where time is the determinant of a successful performance.

TABLE 4.1 5-kilometre split times and average speeds for each split for a female marathon runner

Distance (km)	Time (min:sec)	5 km split time (min:sec)	Average speed in each 5 km split (m/s)
5	15:47	15:47	5.28
10	32:17	16:30	5.05
15	48:34	16:17	5.12
20	65:55	16:21	5.10
25	81:03	16:08	5.17
30	97:27	16:24	5.08
35	114:07	16:40	5.00
40	130:26	16:19	5.11
42.195*	137:42*	7:16*	5.03*

*The time for the final 2.195 km of the race was used to calculate the average speed of 5.03 m/s.

1   Using the information in the table above, calculate the average speed for the whole race.
2   What can be said about the running speed of the athlete throughout the race? Use data to support your answer.
3   What was the average speed of the race in km/h?
4   Predict what a distance−time graph and a speed−time graph would look like for this event.
5   Marathons often have pace runners (the runners wearing 'Pace' on their bibs in the photo below) that help runners maintain an even pace for the duration of the race and finish by a target time. If the pace runners shown below aim to finish the marathon (42.195 km) in a time of 3 hours, 45 minutes, what pace will they need to set to achieve this target time?

Alamy Stock Photo/Simon Balson

Linear acceleration

Sport commentators often refer to an athlete's **acceleration**: 'He has accelerated out of the blocks'; 'She accelerated past her opposition to receive the ball'. Acceleration refers to a change in velocity in a given period of time (change in velocity divided by change in time). It can be a positive or negative figure – speeding up or slowing down. Acceleration is measured in units of m/s^2.

The ability to accelerate or decelerate is important in sport: A 10 000-metre runner who can accelerate in the last 1000 metres to catch and pass the lead runner has a distinct advantage. Decelerating into turns while mountain biking allows riders to maintain balance. Being able to accelerate in the first part of a sprint means the athlete can reach their top speed quickly, and then maintain it until the end of the race.

$$\text{acceleration} = \frac{\text{change in velocity}}{\text{change in time}}$$

It is important to remember that when acceleration equals zero, this does not mean that the athlete, the ball or the racquet, for example, has stopped moving. It just means that it is no longer speeding up or slowing down. An athlete or an object moving with zero acceleration will have a constant velocity. For example, a sprinter will accelerate out of the blocks, then try to maintain their maximum speed before decelerating or slowing down, because of fatigue, towards the finish line.

DATA ANALYSIS

THE 100-METRE SPRINT

Analysis of speed variation during short sprints such as the 100- and 200-metre sprints can provide coaches with useful performance information.

Key performance indicators for sprints are:
· time taken to achieve maximum speed
· maximum speed
· length of time that maximum speed is maintained
· difference between maximum speed and speed at the finish.

Usain Bolt ran the 100-metre sprint in a world-record time of 9.58 seconds at the IAAF World Championships in 2009. Table 4.2 shows the times for each 10-metre split. From this data, his average speeds (in km/h) were calculated and are graphed on the following page.

TABLE 4.2 Usain Bolt's times in the 100-metre sprint in 2009

Distance (m)	Time (s)	Split times
10	1.89	1.89
20	2.88	0.99
30	3.78	0.90
40	4.64	0.86
50	5.47	0.83
60	6.29	0.82
70	7.10	0.81
80	7.92	0.82
90	8.75	0.83
100	9.58	0.83

QUICKVID

You can watch Bolt's record-breaking run via http://vcepe34.nelsonnet.com.au

Weblink
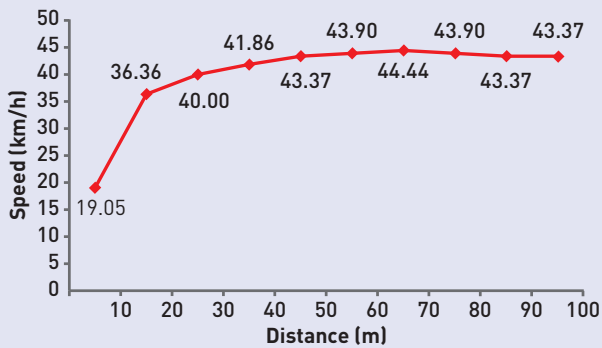
Graph of Usain Bolt's average speeds in the 100-metre sprint

QUESTIONS

Use the data in the table (on previous page) and the graph at left to answer the following questions.

1. What distance did the race cover? Is this different from the displacement? Explain.
2. What was Bolt's maximum speed? How long did it take him to achieve this speed?
3. Calculate the speed in m/s of each 10-metre split. (Remember: speed = distance/time.) You could use an Excel spreadsheet or similar to calculate the speeds.
4. Calculate the average speed for the race. Why is the average speed different from the individual split speeds?
5. Define the term 'constant velocity'. Support your answer with data from the table or the graph. Which predictor of performance does this data provide information on?
6. In which 10-metre split was the runner's acceleration the greatest?
7. What is the difference between Bolt's maximum speed and his final speed? Why is this a significant predictor of race performance?
8. From the graph, identify in which periods Bolt's acceleration was positive, zero and negative.
9. With your knowledge of acceleration and speed, suggest a suitable race strategy for a 100-metre runner.

CHAPTER CHECK-UP

Cliff divers dive from great heights, hitting the water at high velocities.

Scaffold

1. Using a triathlon event as an example, define the terms 'distance' and 'displacement'.
2. In sprinting, runners can run into a headwind or with a tailwind. Explain why the term 'velocity' would be used rather than 'speed' when commenting on the effect of wind on an athlete's performance.
3. A runner completes the first lap of an 800-metre race (run on a 400-metre track) in 54 seconds, and the second lap in 52 seconds. Calculate the average speed for each lap, and for the whole race. Record your calculations in a table.

Lap	Time (s)	Distance (m)	Average speed (m/s)
1			
2			
Total time			

4. A diver leaving the 10-metre platform will enter the water at approximately 14 m/s (52 km/h). Discuss the relationship between distance, change in velocity and acceleration in platform diving.
5. Cliff divers can dive from as high as 45 metres above the ocean. Calculate the velocity at which they will strike the water if the time taken to hit the water is 3 seconds. Include correct units in your answer.
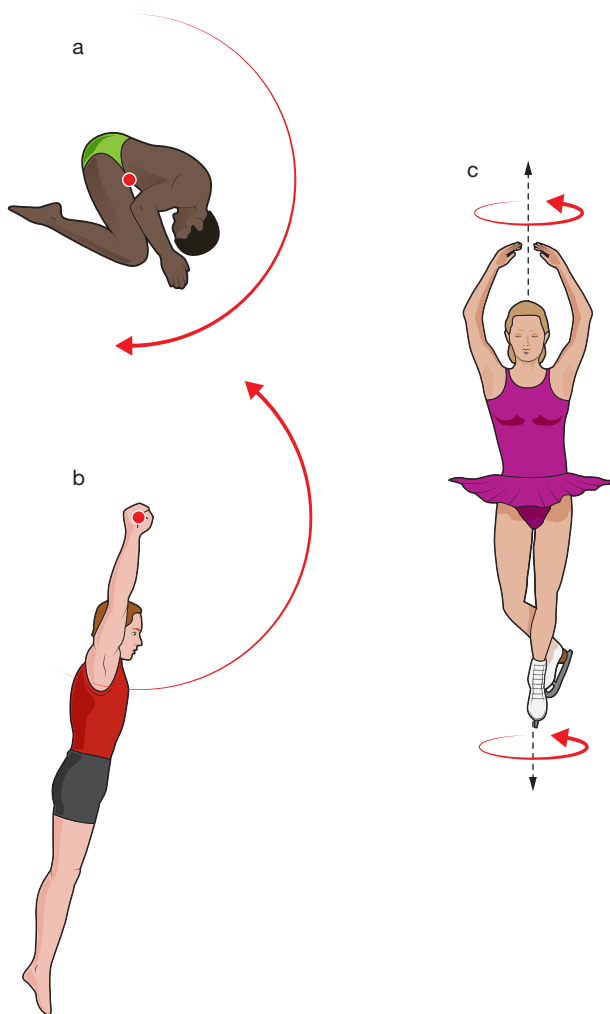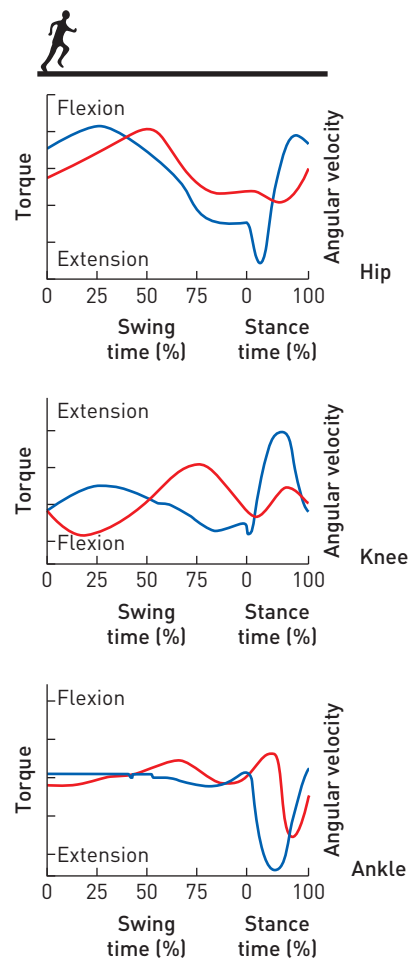
ANGULAR MOTION

Angular motion is a component of general motion and involves rotation around a central axis or a fixed point. Many linear body movements such as walking, running, cycling and rowing result from the angular motion of the body parts. Angular motion of the limbs results in linear motion of the whole body. For example, when we run, the thigh rotates around the hip axis, the lower leg rotates around the knee axis and the foot rotates around the ankle axis; these in turn cause linear motion of the body. That is, the body moves forward in a straight line. The graphs at right demonstrate the relationship between the joint **torques** of the hip, knee and ankle and the angular velocity during running.

The axis of rotation can be real or imaginary, internal or external. Examples of internal axes are the joints of the body. An external axis could be the centre of gravity. This is also an example of an imaginary axis (diagram a). The body rotates around the imaginary point. The axis of rotation is external when performing a rotation on a high bar, where the axis is the bar itself – in other words, it is a real axis (diagram b).

Angular motion can be described using the same measurements as for linear motion, except we now refer to angular distance and displacement, angular speed and velocity and angular acceleration.

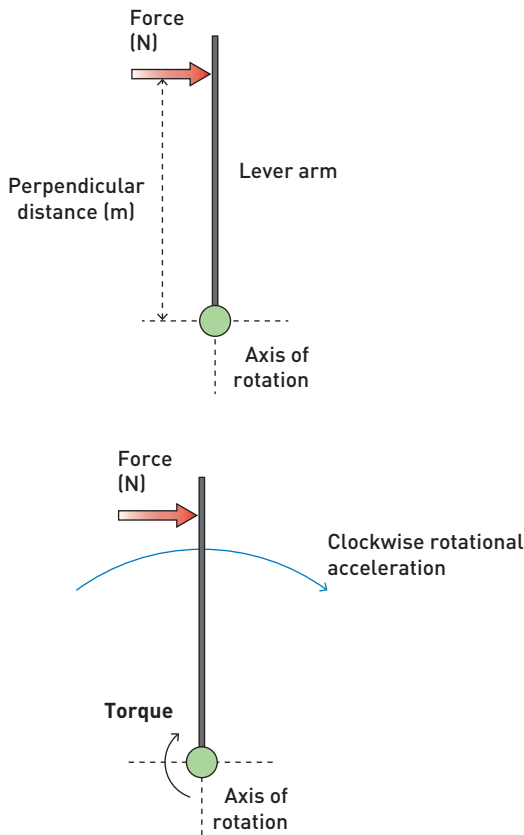The relationship between the joint torques and angular velocity in running

Angular motion: (a) rotation around an imaginary external axis, (b) rotation around a real external axis, (c) rotation around an imaginary internal vertical axis

Perpendicular distance (m)

Force (N)

Lever arm

Axis of rotation

Force (N)

Clockwise rotational acceleration
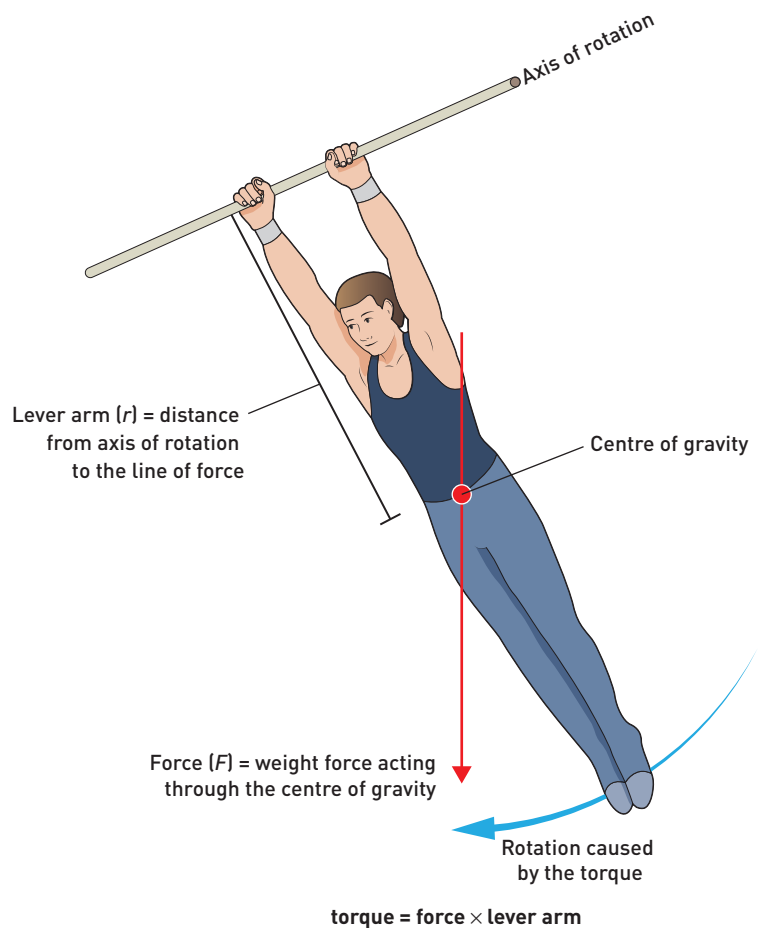
Torque

Axis of rotation

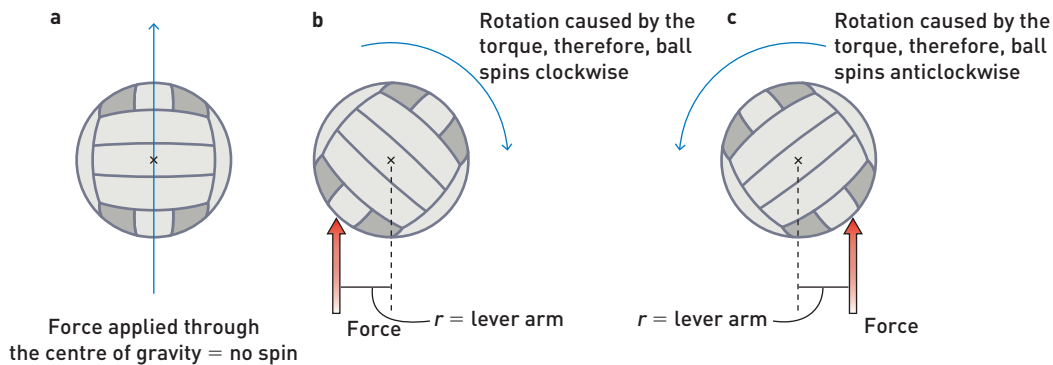Torque: the force applied at a distance from the axis causes a turning effect.

Torque

Angular motion is caused by an **eccentric force**, which is a force that does not act through an object's centre of gravity. Eccentric forces cause objects to rotate and move forwards. This effect is known as torque, which refers to the tendency of an object to rotate. Torque, sometimes called moment of force, can be calculated by multiplying the force by the lever arm of the force. The lever arm is the perpendicular distance from the axis of rotation to the line of action of the force. Torques cause rotation about an axis and cause angular acceleration; the greater the torque, the greater the angular acceleration.

The size of the torque is determined by two factors: the length of the lever arm and the size of the applied force. Increasing the rotation of an object can be beneficial in sport. Spin is created by the athlete applying an eccentric force. If the force applied to a ball is not directly through its centre of gravity, then it will rotate or spin, as shown in the diagram at the top of page 73.

Axis of rotation

Lever arm (r) = distance from axis of rotation to the line of force

Centre of gravity

Force (F) = weight force acting through the centre of gravity

Rotation caused by the torque

torque = force × lever arm

Torque will cause the gymnast to rotate around the bar.

a

Force applied through the centre of gravity = no spin

b

Rotation caused by the torque, therefore, ball spins clockwise

Force   r = lever arm

c

Rotation caused by the torque, therefore, ball spins anticlockwise

r = lever arm   Force

Eccentric forces cause objects to spin.

Eccentric forces also cause objects to deviate from their original path. Bouncing straight up and down on a trampoline is achieved by applying the force through the centre of gravity. However, if an eccentric force is applied, the resulting motion will be angular, a torque will be created and the trampolinist will rotate. Elite trampolinists will control and use this rotation to initiate different movements, such as somersaults. However, young children on a trampoline often fly off in different directions because they have not landed on the mat with their weight over their feet.

Shutterstock.com/Libor Fousek

Enclosed trampolines are safer for children

PRACTICAL ACTIVITY

GENERATING SPIN IN BALL SPORTS

Participate in a game of volleyball. Experiment with different types of overhead serves by striking the ball at different angles.

From your observations in the game, answer the following questions.

1   Explain, in terms of application of force, how you could cause the ball to rotate in different directions and generate side spin, top spin and back spin.
2   Think about how spin is generated in other sports. When is spin beneficial in sport?
3   Mis-hits and poorly cued kicks are often a result of an eccentric force. Using a specific sporting example, explain what happens when a force is not applied through an object's centre of gravity.

Bent elbows in swimming

Olympic freestyle swimmers have used biomechanical analysis to view and modify their technique. Increased understanding of biomechanical principles such as torque has led to improved performance. Elite level swimmers now use a very pronounced bent elbow action in the pull phase of freestyle. Previously, they used an extended straight arm to pull through the water, thinking that the greater lever length would generate more force and propulsion. However, this placed excessive torque and loads on the shoulder joint, making it susceptible to injury. The bent elbow action allows swimmers to pull through the water with maximum propulsion while protecting the shoulder joint. The swimmer shown at right demonstrates this technique.

Increased elbow flexion increases propulsion in freestyle swimming. Notice the bent elbow position at the beginning of the pull phase of the stroke.

Getty Images/FRANCOIS XAVIER MARIT

Angular distance and displacement

The **angular distance** covered by a rotating body is the sum of all of the angular changes the body undergoes. For a gymnast performing 1½ giant circles on the high bar, as shown in (a) below, the angular distance covered is the sum of the angular distance of one full rotation (360°) plus half a rotation (180°). The total angular distance is 540°.
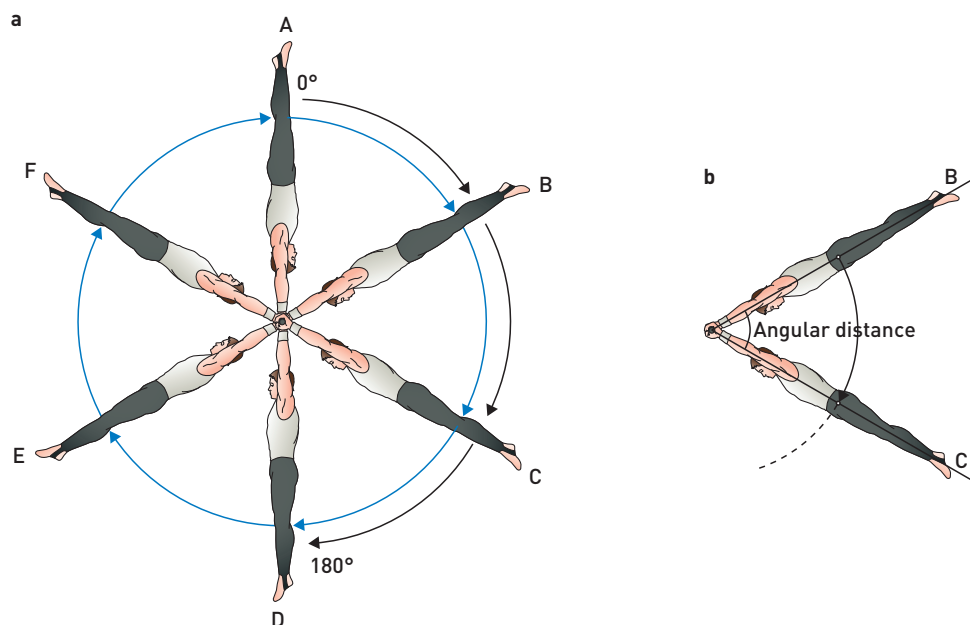
(a) Angular displacement and (b) angular distance

The **angular displacement** is the difference between the initial and the final angular position of an object; the direction of the angular motion needs to be considered.

For the example of the gymnast performing 1½ giant circles, the initial position is taken as 0°, which is point A in the first diagram on previous page. The final position is point D, so the angular displacement is 180°.

Angular speed and velocity

Angular speed is defined as the angular distance covered divided by the time taken to complete the motion. **Angular velocity** is the rate of change of the angular displacement of a body over time. Angular speed and velocity are measured in degrees per second. If the gymnast in the previous example took 3 seconds to complete the 1½ giant circles, the angular speed would be 180° per second, but the angular velocity would be 60° per second, in a clockwise direction.

Speed of rotation is important in sports such as diving, gymnastics and dancing, where athletes need to complete rotations during limited flight time. Studies have shown that an ice skater performing a triple axel (3½ rotations, see right), will increase their angular velocity to more than 1800° per second. Angular velocities increase with the difficulty of the skill being performed. The angular velocity required to complete a single rotation is not as great as the angular velocity required to complete a triple rotation. (The methods that athletes use to increase their speed of rotation were discussed in chapter 3.) Notice that the figure skater shown at right has decreased her moment of inertia by crossing her legs and bringing her arms in close to her body so that she can spin faster and complete the rotation before landing.

In order to increase a ball's linear velocity when it is thrown, it is important to increase the angular velocity of each body segment used in the throwing motion, as this will increase the final velocity at the point of release. The relationship between linear and angular velocity is given by:
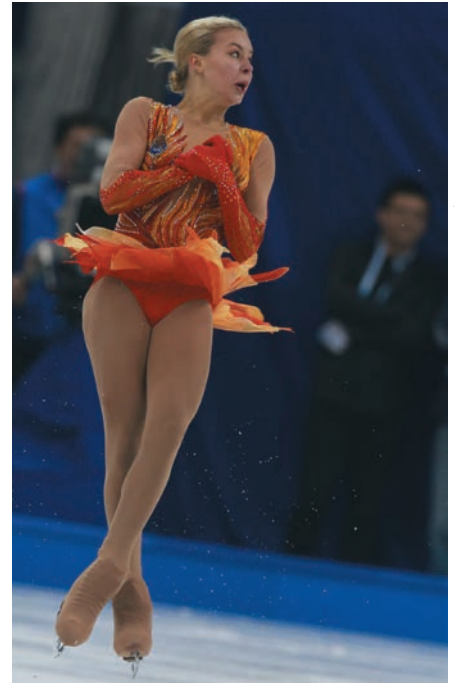
<div style="text-align:center">linear velocity = radius of rotation × angular velocity.</div>

What is the relationship between increasing the number of rotations performed and the speed of the rotations?

The summation of speed principle suggests that movement is initiated from the larger, slower-moving body parts to the smaller, faster-moving body parts (see chapter 3). As each part of the body approaches extension, which is the point at which both linear and angular velocities are maximal, the next body part begins its movement. Highly skilled athletes have precise coordination, which leads to exceptional timing of the movement of each body segment.

When hitting a ball, increasing the radius of rotation results in an increase in the linear velocity imparted to the ball. The most practical way to do this is to increase the length of the implement being used. Linear velocity is equal to the radius of rotation multiplied by the angular velocity. All other aspects being equal, the greater the radius of rotation, the further the ball being struck will travel. This explains why drivers in golf are longer than 9 irons, why elite players prefer longer baseball bats and why a tennis racquet can hit a ball further than a bat used to play bat tennis. However, if the longer bat or racquet is too heavy to be swung as quickly as a shorter bat or racquet, the angular velocity will be compromised by the increase in radius of rotation. (Lever length will be discussed in more detail in chapter 5.)

Angular acceleration

Angular acceleration is the rate of change of angular velocity, or how quickly a body changes its angular position. Angular acceleration can be positive, negative or zero. Changes in angular acceleration can be made by changing the size or direction of the acceleration. Zero acceleration means that the angular velocity of the body is constant – it is not speeding up or slowing down. The units of angular acceleration are degrees per second squared (°/s^2).

BIOMECHANICS OF A VERTICAL JUMP AND STANDING BROAD JUMP

Work in small groups. Two students from each group will perform a vertical jump (one at a time). Other members of the group should observe the two students from a side-on position. Video their performance (to replay), or have each subject repeat their jump a number of times. Measure the height jumped by each performer. The second pair of students perform a standing broad jump. Again, record the jump if possible, or have the subject repeat the jump a number of times. Measure the distances jumped by each performer.

	Student 1	Student 2
Vertical jump (cm)		
Standing broad jump (cm)		

OBSERVATIONS AND DISCUSSIONS

1 Carry out a qualitative analysis of the vertical jump and the standing broad jump by comparing the outcome of each jump for each student.
2 Which subject jumped higher or further?
3 Is the force applied in a vertical jump eccentric? Is the force applied in a standing broad jump eccentric? Explain why the answer to one of these questions is yes, and how this impacts on the direction of the jump.
4 Write a description of the jumps, commenting on the angle of the ankle, knee and hip joints. Identify the biomechanical principles being applied in the movement.
5 How does the angular motion of each body segment translate into linear (rectilinear or curvilinear?) motion of the body during the jump?
6 From your description, suggest a reason why one jump was higher/further than the other.

CHAPTER CHECK-UP

1 Select three sports. Identify and classify the motion performed in each sport as linear, angular or general.
2 Using a sporting application, draw a diagram to explain torque. Identify the axis of rotation, the lever arm, the force and the direction of the rotation caused by the torque.
3 Explain biomechanically why a gymnast may over-rotate a landing from a vault.
4 A gymnast using the uneven bars rotates once in a full layout position and then dismounts, performing a 1½ somersault prior to landing. Identify the axis of rotation and angular distance covered in each movement.
5 Explain why a junior baseball player should not use a full-size bat.

PROJECTILE MOTION

An object or body that is launched into the air and affected only by the forces of gravity and air resistance can be considered a **projectile**. Projectile motion looks at the factors that influence the flight path of the projectile. In sport and physical activity, the human body is often a projectile – there are many examples where the aim of the activity is to move through the air. In athletics, diving and gymnastics, athletes must often project themselves into the air and then complete a movement or sequence of movements. Divers use the spring from the diving board, and gymnasts the beat board or mini-tramp, to gain extra height.

There are numerous examples of projectiles in sport and physical activity. Balls, shuttlecocks, arrows, javelins and discuses all act as projectiles when they are thrown, kicked, shot or hit. The goal is often to throw, kick or hit as far or as accurately as possible, to hit a target or pass the ball to another player.
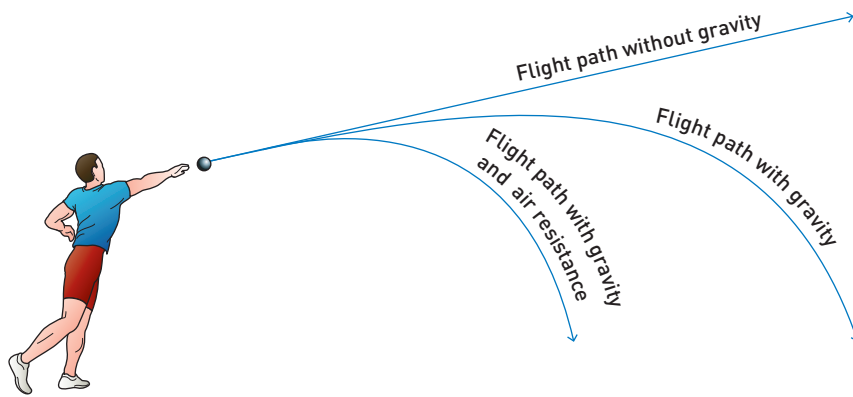
Projectile paths with and without gravity and air resistance

Divers become projectiles when they are in the air. The only forces acting on them are gravity and air resistance.

Vertical and horizontal components

Anything that can be considered a projectile will have horizontal and vertical components. The outcome of a long jump depends on maximising the horizontal displacement of the body, whereas the high jump requires the vertical component to be as great as possible. Events that are judged on accuracy need to manipulate both components in order to ensure the projectile hits the target. For example, a footballer would need to consider the distance to the goals as well as the height required to clear the player on the mark. Netballers often use a lob pass, maximising the vertical component of a pass to get the ball over the head of a defender. To analyse motion biomechanically, it is easiest to break it down into its horizontal and vertical components.

Vertical component

The vertical component of projectile motion is influenced by gravity and the vertical component of the initial projection velocity. Gravity is a force that acts on all bodies

FYI

If you drop one ball and throw another ball from the same height at the same time, they will both hit the ground at the same time because they have the same vertical component of motion.

Maximising the vertical component of the body's motion aids in completing a successful jump in high jump (a), but for long jump (b) the horizontal component needs to be maximised!

a

b

c
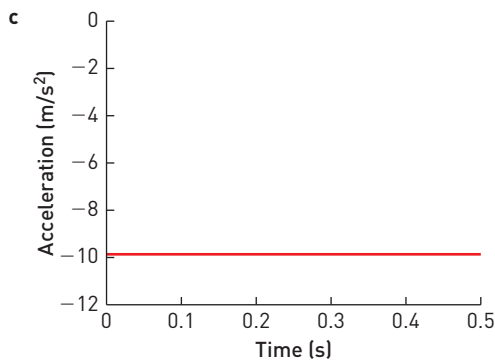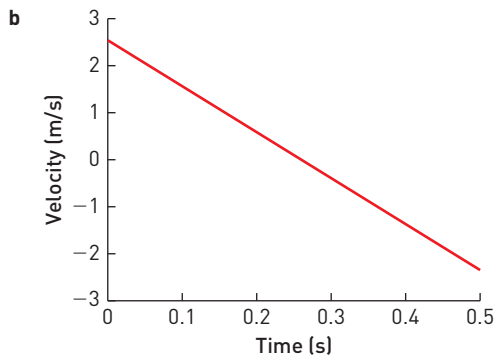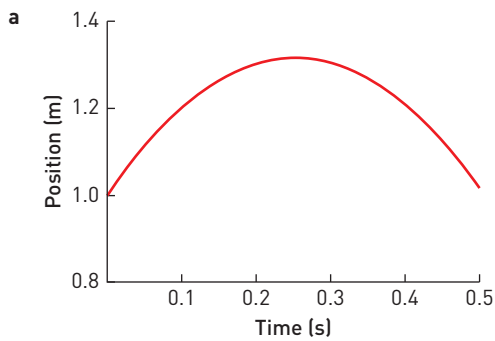
(a) Vertical position, (b) velocity and (c) acceleration of the centre of gravity of an athlete during the flight phase of a standing vertical jump

close to the Earth's surface, causing objects to accelerate towards the Earth at a rate of 9.81 m/s^2. Gravity gives projectiles their parabolic flight path. Acceleration due to gravity is constant for any object, regardless of size, shape or weight. This means that a medicine ball and a tennis ball dropped from the same height will reach the ground at the same time (ignoring the effects of air resistance).

The vertical component of motion relates specifically to the height reached by the projectile. If there were no gravity, a projectile would just keep going, following the same path it was projected with. The vertical speed of an object decreases as it goes up and then increases as it comes back down. If the object is thrown and caught at the same height, the final speed will be the same as the initial speed.

Horizontal component

The horizontal component of projectile motion is affected by air resistance and relates to the horizontal distance covered by the projectile. Without air resistance, the horizontal velocity of a projectile would remain the same. When analysing sports and activities quantitatively, often air resistance is not taken into account, or is considered negligible. However, in a number of sports air resistance is very important, as it affects the horizontal component of the projectile's velocity. The time of a sprinter who runs with a tailwind may not be recognised because it was 'wind affected'. The same can be said for throws and jumps, as the air resistance becomes an external force that has assisted the athlete to gain extra horizontal distance or velocity.

DATA ANALYSIS

GRAPHICAL ANALYSIS OF A THROW

A cricket ball is thrown upward with a release velocity of 10 m/s from a height of 2 metres. The flight time, velocity and displacement are provided in the table at right.

Getty Images/Darrian Traynor

Time into flight (s)	Velocity (m/s)	Displacement (m)
0	10.0	2.0
0.2	8.04	3.80
0.4	6.08	5.22
0.6	4.11	6.23
0.8	2.15	6.86
1.0	0.19	7.10
1.2	−1.77	6.94
1.4	−3.73	6.39
1.6	−5.70	5.44
1.8	−7.66	4.12
2.0	−9.62	2.38
2.2	−11.58	0.26
2.222	−11.80	0.00

Note: The negative sign shows that the ball is travelling downward

QUESTIONS

1   According to your first graph, what was the greatest vertical height reached by the ball?
2   What was the velocity of the ball at the highest point? Explain why this is not shown in the table.
3   State the two forces acting on the ball while it is in flight.
4   What acceleration will the ball experience? What force is causing the ball to accelerate?
5   Provide an example of a sport where the projectile (e.g. the ball) needs to travel vertically to allow for a successful performance.

Using a spreadsheet program such as Excel, plot each of the following graphs:
- displacement–time
- velocity–time.

The data from the table is available online in an Excel spreadsheet, to make plotting your graphs easier. Go to http://www.nelsonnet.com.au and use your login code.

Scaffold

LABORATORY

INVESTIGATING AIR RESISTANCE AND GRAVITY

Experiment with a number of different pieces of sporting equipment (for example, different sized balls, frisbees, rubber chickens, beanbags, poly dots, shuttlecocks) to investigate the effects of air resistance and gravity. Drop each object from the same height and time how long it takes for it to reach the ground. (Safety: ensure that there is no one below when dropping the equipment!)

1   Construct a table that identifies the size, shape and weight of each object and the time taken to reach the ground.
2   What conclusions can you make about the effects of air resistance on different objects and their acceleration due to gravity?

## Factors affecting the path of a projectile

The path of a projectile depends on three factors:

» angle of release
» speed of release
» height of release.

Coaches and athletes can manipulate these variables to find the best combination for optimum performance. That might be to gain the greatest horizontal distance in long jump, the most accurate goal shooting in basketball or the best position for catching a pitch in baseball.

TABLE 4.3 Factors influencing projectile motion

| Variable	Factors of influence
Flight time	Initial vertical velocity Height of release
Distance (horizontal)	Horizontal velocity Height of release
Distance (vertical)	Initial vertical velocity Height of release
Flight path	Initial speed Angle of release Height of release

a

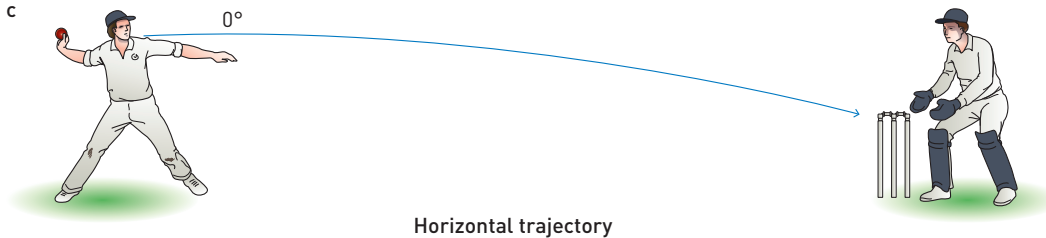Vertical trajectory

90°
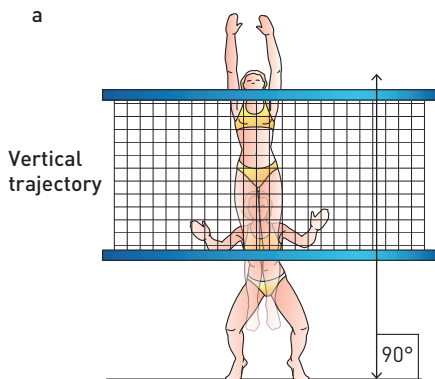
Angle of release

The **angle of release** is the angle (with respect to the horizontal) at which an object is projected into the air. This angle will determine the flight path of the projectile. There are three shapes that a flight path can form, depending on the angle of release.

The first is a purely vertical shape where the body or object goes straight up and comes straight back down again. An example would be performing a vertical jump, where the performer jumps straight up and returns to the ground in the same path.

The second flight path is parabolic. This occurs when the angle of projection is between 0 and 90 degrees.

b

Oblique trajectory

45°
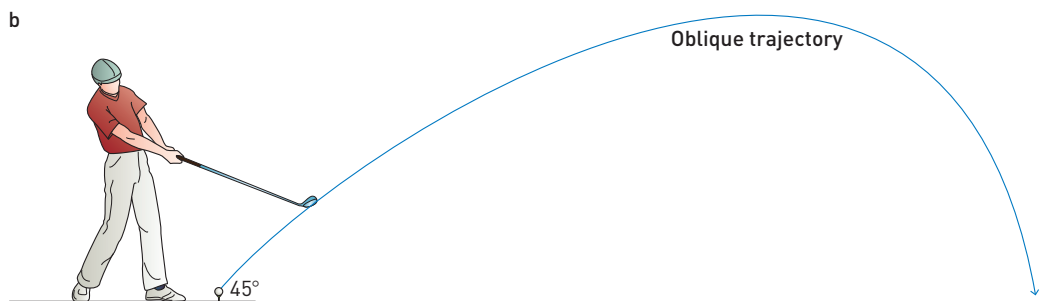
The final shape determined by the angle of release is half a parabola. An object projected at 0 degrees, or perfectly horizontal, will follow this path.

Horizontal trajectory

The effect of angle of release on the flight path of a projectile

The angle of release of a projectile affects the horizontal distance covered. For any given release velocity, where the projectile lands at the same height from which it was released, the best angle of release, to result in the greatest horizontal distance, is 45 degrees. Table 4.4 shows how varying the angle and speed of release changes the distance the projectile will travel.

TABLE 4.4 Effect of projection angle and speed of release on the distance a projectile will travel

| Projection angle (degrees)	Distance travelled (m) at different projection speeds		
	10 m/s	20 m/s	30 m/s
10	3.49 m	13.94 m	31.38 m
20	6.55 m	26.21 m	58.97 m
30	8.83 m	35.31 m	79.45 m
40	10.04 m	40.15 m	90.35 m
45	10.19 m	40.77 m	91.74 m
50	10.14 m	40.15 m	90.35 m
60	8.83 m	35.31 m	79.45 m
70	6.55 m	26.21 m	58.97 m
80	3.49 m	13.94 m	31.38 m
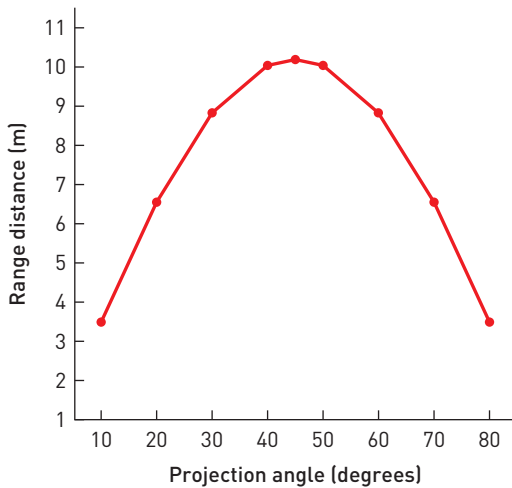
The effect of angle of projection on the distance covered by a projectile released at 10 m/s from a constant height

Source: Hall, 2007

Speed of release

The speed at which an object is thrown, kicked or propelled into the air is referred to as the speed of release. Projectiles have both a vertical and horizontal component of release speed. The vertical component determines the height reached and the flight time of the projectile, and the horizontal component determines the horizontal distance covered by the projectile. The greater the speed of release, the greater the horizontal range of the projectile.
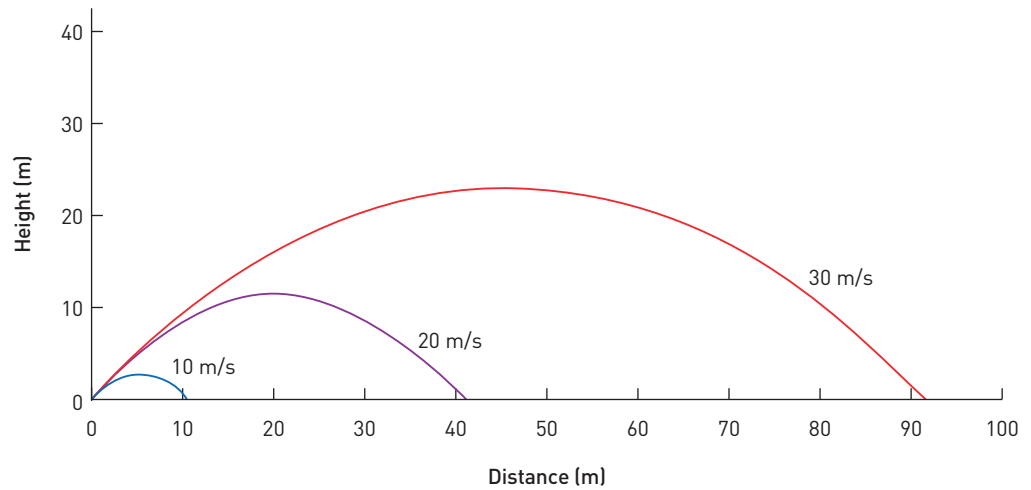
The effect of speed on the distance covered by a projectile released at 10, 20 and 30 m/s from a constant angle (45 degrees)

Height of release

The height of release is the difference between the height that a projectile is released from and the height at which it lands or stops. When the height of release is zero (a, left), the projection height equals landing height, and the optimal angle of release is 45 degrees. When the height of release is greater than zero (b), the projection height is greater than the landing height, and the optimal angle of release is less than 45 degrees. When the height of release is less than the landing height, the optimal angle of release is greater than 45 degrees (c).
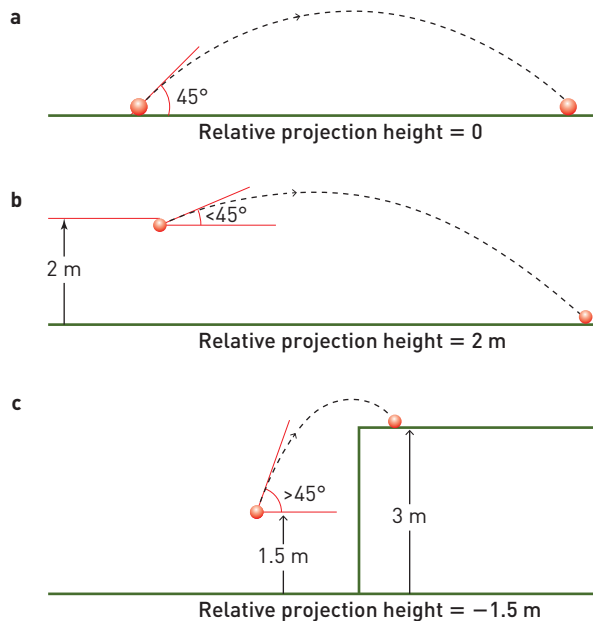
The optimal angle of release depends on the relative height of release. Relative projection height is: (a) 0 m, (b) 2 m, (c) –1.5 m.

Table 4.5 shows the different release angles for different sporting events. The goal of high jump is to gain as much vertical height as possible and therefore a higher projection angle is required. In shot-put, where the height of release is greater than the landing height, the angle of projection decreases to about 36 degrees.

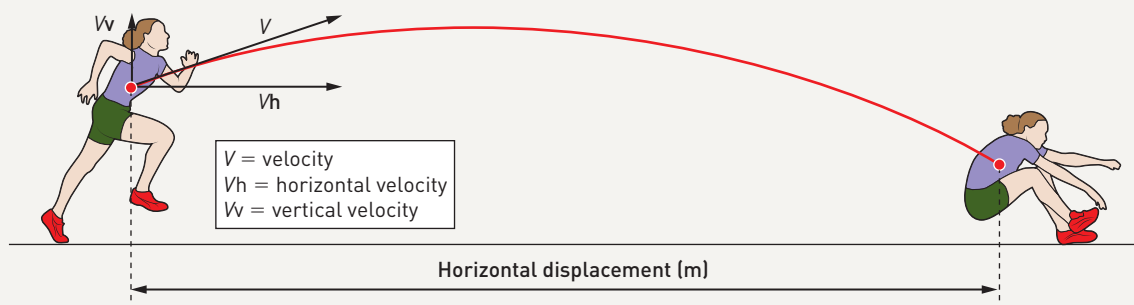**TABLE 4.5** Optimal angle of release for different sporting events

Sport	Optimal angle of release
Long jump	15–27°
High jump	40–48°
Shot-put	36–37°

Flight path of a long jump

An analysis of men's long jump has shown that the theoretical optimal release angle (45 degrees) for maximal horizontal displacement (longest jump) is different to the actual release angle (15−27 degrees). Part of the reason for this is the height of the centre of gravity. The height of the centre of gravity at take-off is greater than on landing.

Additionally, to achieve the predicted optimal angle of 45 degrees, the athlete would need to decrease their take-off velocity by half, which would then decrease the overall horizontal distance achieved in the jump. Through training, athletes optimise their height, leg length, strength and power to achieve the optimal combination of take-off velocity and take-off height. This has resulted in a take-off angle of between 15 and 27 degrees.

V = velocity
Vh = horizontal velocity
Vv = vertical velocity

Horizontal displacement (m)

CHAPTER CHECK-UP

1 List and explain the three factors that influence the flight path of a projectile.
2 Identify sporting situations where different angles of release achieve the desired outcomes.
3 When is 45 degrees the optimal angle of projection? Using specific sporting examples, explain why 45 degrees is not always the optimal angle of projection.
4 In basketball, players often have to shoot from various distances from the basket, and with defenders in close proximity. Explain how changing the angle of release can assist the player in making a successful shot.
5 In both springboard and platform diving the height of release is greater than the landing height. Compare and contrast the way both forms of diving use the factors associated with projectile motion to maximise performance.
6 Using the data in Table 4.4, explain the relationship between angle of release, speed of release and distance travelled.

INVESTIGATING PROJECTILE MOTION

AIM
To investigate the variables that affect projectile motion

EQUIPMENT
Garden hose with nozzle close to grassed area, tap (preferably connected to a tank), large protractor, measuring tape

METHOD
1   Connect the hose to the tap and turn it on so that the spray lands on the grass.
2   With constant water pressure and the hose nozzle at ground level, measure the horizontal distance the water covers when the angle of the nozzle is at 15°, 25°, 45°, 65° and 75° with the ground.
3   With constant water pressure, and keeping the angle of release the same, raise the hose nozzle 1 metre off the ground. Measure the horizontal distance covered by the water. Change the height of the hose nozzle to 50 cm and 2 metres off the ground.
4   Keeping the hose nozzle on the ground at a constant angle of 45°, turn the tap on to vary the water pressure. Measure the horizontal distance covered by the water each time.

RESULTS
1   Record the measurements.
2   Graph your results as:
    • distance vs angle of release
    • distance vs height of release
    • distance vs projection velocity.

DISCUSSION
1   Draw the flight path of the water in each of steps 2–4.
2   What is the relationship demonstrated between each of the variables and the horizontal distance covered?
3   How could you increase the vertical component of the projectile's motion? What would be the benefit of increasing the flight time (the vertical component) in activities such as diving, dancing or gymnastics?
4   As the coach of a junior baseball team, how could you apply the principles of projectile motion to instruct your batters to hit a line drive?
5   Select a sport or activity and identify when optimal performance would require a change in either angle of projection, height of release and/or projection velocity.
6   How could you modify this activity to investigate the effect of each of the variables on the vertical displacement of a projectile?

PRACTICAL ACTIVITY

OBSERVATION OF HIGHLY SKILLED, MODERATELY SKILLED AND UNSKILLED PERFORMERS

Scaffold

1   Select a sports skill where ability level differs within your class. It might be kicking a drop punt, shooting for goal in netball, a push pass in hockey or a pass in volleyball.
2   Observe three individuals performing the skill: a highly skilled, a moderately skilled and an unskilled individual.
3   Qualitatively describe the differences observed (use correct terminology in your description).
4   Provide relevant feedback/cues to each performer to improve or refine their performance.

Sport skill selected: _____

	Highly skilled performer	Moderately skilled performer	Unskilled performer
Observations			
Cues provided			

QUICKVID

If you did not watch this video in chapter 3, go to your student website via http://www.nelsonnet.com.au and use your login code. In the resources for page 85 is a video interview with Dr Elaine Tor, a biomechanist from the Victorian Institute of Sport, discussing the role of biomechanics in sport.

Video

QUICKVID

Watch a clear explanation and summary of angular motion by one of the authors. Go to your student website via http://www.nelsonnet.com.au and use your login code. Then look at the resources for chapter 4, page 85 and choose the 'interactive'.

Video

CHAPTER SUMMARY

- There are two main forms of motion – linear and angular motion. Most movements of the human body are a combination of linear and angular motion, called general motion.
- Rectilinear motion is where all the body parts move in the same direction at the same time in a straight line.
- Curvilinear motion is where all the body parts move in the same direction at the same time in a curved path.
- Distance and displacement are measures of how far an object or a body has travelled. Both measurements are recorded in metres.
- Speed and velocity measure how fast an object is travelling. Velocity identifies the speed as well as the direction.
- Acceleration is a measure of how quickly an object or body changes its velocity. Acceleration can be positive, negative or zero (this occurs when velocity is increasing, decreasing or constant, respectively). Athletes manipulate their acceleration to optimise the outcome of their performance.
- Angular motion is the rotation of an object or body around a central axis. The axis of rotation can be internal or external, real or imaginary.
- Rotation and angular motion are caused by the application of an eccentric force. Eccentric forces are those that are applied at a distance from the centre of gravity of an object.
- Torque is the turning effect of the force that has been applied. It is the product of force and the lever arm.

- Angular motion can be measured and analysed by the same variables as linear motion but from an angular perspective: angular distance and displacement, angular speed and velocity and angular acceleration.
- Increasing angular velocity and/or the radius of rotation leads to an increase in linear velocity of the object being hit, struck or kicked.
- Angular velocity is increased through the coordinated summation of velocity of each individual body segment or through an increase in the length of the radius of rotation.
- Any object or body that is propelled into the air can be considered a projectile.
- Projectiles have both a vertical and a horizontal component to their motion.
- Air resistance and gravity are the only forces affecting projectiles and often the effect of air resistance is negligible.
- The flight path of a projectile depends on the velocity and height of release and the angle of projection.
- The optimal angle of projection for the greatest horizontal distance a projectile can travel is 45°, when the height of release is zero.
- When the height of release is greater than zero (above the landing height) the optimal angle of projection is less than 45°.
- When the height of release is less than zero (below the landing height), the optimal angle of projection is more than 45°.

Multiple-choice questions

1 When batting, a baseball player could increase the linear velocity of the baseball by:

   A decreasing the radius of rotation by sliding their hands down the handle of the bat, 'choking' it.

   B swinging the bat faster by increasing the angular velocities of the individual body segments.

   C increasing the length of the bat.

   D both B and C

2 A golf club is 0.90 metres long and the angular velocity of the club head at impact is 55°/s. Which is the linear velocity imparted to the ball?

   A 49.5 m/s

   B 495 m/s

   C 61 m/s

   D 610 m/s

3 Which of the following statements about the vertical component of projectile motion is correct?

   A The vertical component of projectile motion is affected by gravity and air resistance only.

   B Vertical velocity is zero at the highest point of the projectile's motion.

   C The force of gravity determines the vertical component of a projectile.

   D All of the above.

Short-answer questions

4 List three different sports in which the linear motion of the body is a result of angular motion. Outline the rotational movement of the body segment/s and any equipment that contributes to the linear motion of the body.

5 A student completes 5½ laps of a 400-metre running track in a 12-minute run test. Calculate the following:

   a the distance the runner covered

   b the displacement of the runner after 12 minutes

   c the runner's average speed for the 12 minutes (Hint: Don't forget to show the time in seconds.)

   d the runner's average velocity.

6 In terms of the race distance, the swimmers' velocity and acceleration, contrast a sprint event in swimming such as the 100-metre freestyle with an endurance event such as the 1500-metre freestyle.

7 In Australian Rules football a ball kicked using a drop punt will spin end over end, and a torpedo punt will spin in a spiral motion. Use these two different skills to explain how eccentric forces cause rotation.

8 Refer back to the diagram on page 74 to answer the following questions.

   a Redraw the diagram and label each position with the correct angular distance: 0°, 60°, 120°, 180°, 240° and 300°.

   b Determine the angular displacement of the gymnast in position C compared to position A.

   c Determine the angular displacement of the gymnast after completing 1½ rotations.

   d If the time taken to rotate from position B to F is 0.6 seconds, calculate the angular velocity of the gymnast.

9 Taking into account the height of release and the landing heights, predict the optimal angle of release for the flowing athletic events and justify your decision:

- triple jump
- discus
- javelin

10 Draw a diagram of an athlete putting a shot into flight. Include the flight path, angle of projection, direction of the force of gravity and air resistance and the vertical and horizontal components of the motion.