

PART I

Biomechanics

INTRODUCTION

Biomechanics is the area of sport and exercise science where the laws, principles and methods of mechanics are applied to the structure and function of the human body. Mechanics can be divided into two categories: statics, which is the study of stationary objects, and dynamics, which is the study of moving objects. Examples of static analysis in sport include standing, different balances in gymnastics and acrobatics and certain resistance exercises where no movement is apparent but large forces may be exerted such as in a scrum in rugby or a closely matched tug-of-war contest. Most activities in physical activity and sport involve movement and therefore require the application of dynamics to understand that movement.

Two other subdivisions are often used to describe different levels of biomechanical analysis: **Kinematics**, which is a description of the movement in terms of time and space, and kinetics, which is concerned with an explanation of the underlying mechanics of the movement and typically involves an assessment of forces. Kinematic analyses in sport typically rely on images recorded by video and other cameras, which can be played back many times either at normal speed or frame by frame, pausing on key frames that show important aspects of the technique. Kinetic analyses in sport and exercise also employ images, but supplement these with force plates and other force transducers, that allow the forces exerted against the ground or on sports equipment to be measured. An example of kinetic analysis related to health is gait analysis, which typically combines ground reaction force data captured as an individual steps on and off a force plate synchronised with frame-by-frame images recorded by a camera. Such an analysis may help a podiatrist to diagnose the cause of problems in walking, where the data collected can assist in prescribing orthotics, which are inserts to go into shoes to help alleviate problems in walking. A typical example from sport would also combine

frame-by-frame images synchronised with force measurements, such as the video recording of a kayak paddling stroke, while simultaneously recording the magnitude and direction of the forces exerted on the shaft of the paddle.

The following entries introduce the different components of biomechanics and will help students gain a good understanding of how to analyse movement and learn how to explain how it is produced. The ability to separate good and bad elements of the mechanics of techniques and style is a requirement for all biomechanists who wish to be able to explain how movement patterns in physical activity and sport can be improved.

Projectiles

A projectile is an object that is moving through the air unassisted with only gravity and air resistance acting upon it. There are numerous examples of projectiles in sport including sports objects such as a golf ball, basketball, tennis ball, rugby ball, football, shuttlecock, discus, hammer and frisbee, and sports performers such as long jumpers, high jumpers, gymnasts, figure skaters, ski-jumpers and sky divers. Projectile motion refers to the type of motion experienced by projectiles travelling through air and, ignoring air resistance, is a special example of linear **Kinematics** where we know what changes in velocity and acceleration there will be once an object or body is released. Ignoring air resistance is okay in a number of sports examples (e.g. shot putt) where the effects are so small that they can really be ignored. In contrast, air resistance is crucial in sky-diving as the difference between hitting the ground with and without an open parachute is generally the difference between life and death! In sport-related examples of projectile motion we need to be aware of the different aims of different sports. In **Biomechanics** we refer to primary mechanical purpose as the key purpose of the sport. In long jump this is projecting the body for maximum horizontal displacement; in high jump it is projecting the body for maximum vertical displacement. These two events require different approaches to the point of projection due to the difference in primary mechanical purpose.

GRAVITY AND PARABOLIC FLIGHT

If we continue to ignore air resistance, then in projectile motion the only force acting on the object or body is due to gravity, which we experience because of the huge mass of the earth attracting our mass or the mass of objects that we throw or project in sport. Gravity is the force of attraction between two objects of different mass and the different size of the earth and our moon explains why gravity is about nine times less on the moon. The acceleration due to gravity on the surface of the earth (at sea level) is approximately 9.81 m.s^{-2} and is accelerating any projectile during the whole of its flight, meaning that the vertical velocity (gravity acts vertically down towards the centre of the earth) is increasing by 9.81 m.s^{-1} every second. Many people find this confusing because

when you throw a ball up in the air it immediately slows down, achieving zero velocity at the top of its flight before accelerating to the same speed when it drops back down to the same height at which it was released. This is an example of where the difference between vector and scalar quantities is important (acceleration is a vector quantity so has both magnitude and direction, in the case of gravity on earth 9.81 m.s^{-2} acting vertically downwards). So, ignoring air resistance we can simplify projectile motion to a consideration of constant acceleration due to gravity (9.81 m.s^{-2}) because if we ignore air resistance there is zero horizontal acceleration, which means that the horizontal velocity does not change throughout the flight of the object or body. So a shot will be travelling at the same horizontal velocity at the point of release as it is on landing as we can ignore air resistance in that event. This means that, if we know the conditions at release of the object or body (i.e. its velocity, both magnitude and direction are necessary) then ignoring air resistance we can easily assess the projectile motion of the object or body.

The flight path of a projectile is called its trajectory. In the case of either a high jumper as soon as they leave the ground, or when a cricketer throwing the ball in from the boundary lets go, this is known in both cases as the instant (referring to time) or point of release (referring to position). Once the high jumper or ball is in flight gravity is continually causing the body or object to experience the constant acceleration of 9.81 m.s^{-2} . Ignoring air resistance and given that the velocity at release was not vertical (i.e. less than 90° to the horizontal) means that the object or body will then follow a trajectory or flight path that will describe a symmetrical curve, with the line of symmetry acting vertically through the point of maximum height. This curve is known as a parabola and is why in mechanics the projectile motion of an object or body may be referred to as parabolic (Figure 1). If the object or body is projected vertically it will go straight up until it reaches zero velocity and then accelerate due to gravity until it reaches the same magnitude of velocity but in the opposite direction. It is worth remembering that we ignore the effects of air resistance both horizontally and vertically to produce the parabolic trajectory.

FACTORS AFFECTING PROJECTILE MOTION

There are three main factors that affect the trajectory of an object or body in flight: the projection angle, magnitude of projection velocity and height of projection.

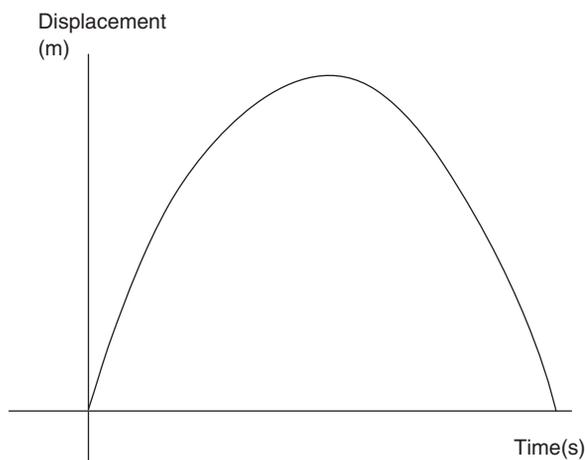


Figure 1.1 A parabolic trajectory or flight path for an object or body as it travels through the air (ignoring effects of air resistance)

Projection angle

The projection angle, i.e. the angle between the initial trajectory and the horizontal, determines the shape of the parabola described in flight by the object or body. Projection angles in some sports can be negative, such as downhill shots off cliff tops or hills in golf, in ski-jumping, or when performing a tennis serve. More generally they are between 0 and 90° to the horizontal and as a consequence will produce a parabolic shape as shown in Figure 1, but the steepness or shallowness of the curve will depend on the angle of projection, with angles greater than 45° producing steeper curves and angles less than 45° producing shallower curves.

Ignoring air resistance and with the point of release at the same height as the point of landing the optimum angle for maximum horizontal distance of flight is 45° , but there are factors in sport which mean that 45° is rarely the optimum for maximum horizontal distance. As mentioned previously, the primary mechanical purpose will affect the optimum angle of projection. In high jump the optimum angle is in the range of 40 to 48° , where the primary mechanical purpose is maximum vertical height. In contrast, in long jump, where the primary mechanical purpose is maximum horizontal distance, the take off angles are in the range of 18 – 27° .

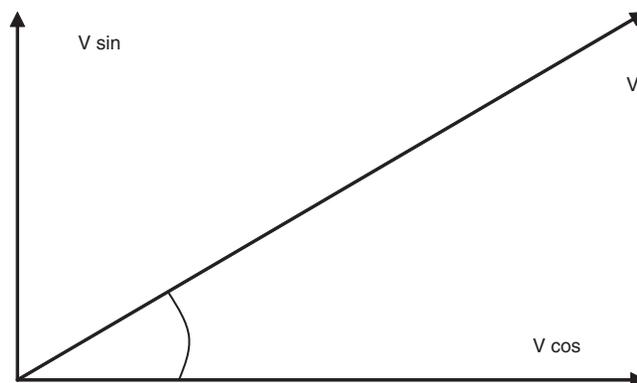


Figure 2 *Measuring projection velocity magnitude*

Magnitude of projection velocity

For a given angle of projection the magnitude of the velocity at release will determine both the height and the horizontal distance of the trajectory of the object or body. Initial conditions for projectiles are therefore normally summarised by the measurement of the angle of projection (α) and the magnitude of the velocity (V), the two components of the vector quantity which is the resultant projection velocity (Figure 2).

The initial conditions for projection defined by the projection velocity resultant vector, having magnitude V and direction specified by α . The vertical component is given by $V \sin \alpha$ and the horizontal component by $V \cos \alpha$.

The vertical and horizontal component vectors (Figure 2) derived from the resultant projection velocity vector are important and should be considered separately as they define the height and the horizontal distance of the trajectory, all other things remaining equal. After release the vertical velocity $V \sin \alpha$ is reduced by the effects of gravity by 9.81 m.s^{-1} for every second of vertical flight time. Vertical velocity will therefore reduce due to the constant acceleration due to gravity of 9.81 m.s^{-2} , which is acting vertically downwards towards the centre of the earth, causing a deceleration. This reduction will continue until zero velocity at the top of the flight trajectory, which is sometimes referred to as the apex of the trajectory, after which it will accelerate at 9.81 m.s^{-2} , gaining velocity as it now falls back towards the earth's centre.

The time it takes to get to zero vertical velocity is given by:

$$\text{Time to apex} = \text{vertical velocity/gravity} = V \sin \alpha / 9.81 \text{ m.s}^{-2}$$

If the object or body lands at the same height it was projected from then the total flight time is double the time to the apex:

$$\text{Flight time} = 2 \times (V \sin \alpha / 9.81 \text{ m.s}^{-2}) \text{ or } 2 \times (V \sin \alpha / g)$$

In contrast, because we are ignoring air resistance, the horizontal velocity $V \cos \alpha$ remains constant throughout flight. Since we know that displacement = velocity \times time, the horizontal displacement of the projectile when it lands, called the range, will be given by:

$$\text{Range} = V \cos \alpha \times (2 \times V \sin \alpha / g) = (2 V^2 \sin \alpha \cos \alpha) / g$$

$$\text{Range} = (V^2 \sin 2\alpha) / g \text{ (because } 2 \sin \alpha \cos \alpha = \sin 2\alpha)$$

$$\text{Maximum range} = \text{maximum value of } (V^2 \sin 2\alpha) / g$$

$$\text{Maximum value of } \sin 2\alpha \text{ is } \sin 90^\circ = 1, \text{ therefore} \\ \alpha = 45^\circ \text{ and}$$

Maximum range = V^2/g and the theoretical maximum range for projecting an object or body on a horizontal surface is produced by a projection angle of 45° , as mentioned before.

Because projectiles are an example of uniform acceleration due to gravity, the regular equations for uniform acceleration can be used to calculate variables in projectile motion. These equations are:

$$v = u + at, s = ut + \frac{1}{2} at^2 \text{ and } v^2 = u^2 + 2as$$

where v = final velocity (m.s^{-1}), u = initial velocity (m.s^{-1}), a = acceleration (m.s^{-2}), t = time (s).

Height of projection

The third factor that affects the trajectory of a projectile in sport is the height of the point of projection or release in relation to the landing surface of the object or body. There are examples from sport where the height of projection is both above and below the landing surface. For

example in the shot putt the optimum angle is less than 45° because the point of release is well above the land surface (more than 2 m higher in senior male shot putters). In hitting a golf ball up a slope the optimum angle of projection will be greater than 45° , a ball struck at 45° will simply hit the uphill slope prematurely. In contrast, a tennis serve is hit as an attacking shot down from the point of release from the racquet head into the service court on the other side of the net, so the angle of projection here ranges typically from -3° to -15° .

AIR RESISTANCE

Everything discussed so far has ignored air resistance, but there are many examples where we use air resistance to great effect in sport when projecting objects or bodies, such as a discus and a ski-jumper (see **Fluid Mechanics**).

FURTHER READING

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Kinematics

Video analysis has become a very popular method to assess sports performance. The recording and repeated observation of motion captured by video cameras is relatively straightforward, especially now that the technology is so readily available and feedback on what has been recorded is immediate via playback through the camera.

However, there are different approaches to motion analysis, which are characterised by the principles and methodology underpinning them. Qualitative analysis (non-numerical and descriptive) is based entirely on visual observation of a movement, sequence of movements or a game performance and it draws its validity from the knowledge and experience of the person who observes and analyses the selected motion. In contrast a quantitative approach (numerical analysis) guarantees objective results as long as the correct mechanical principles and scientific methodology are used. The branch of **Biomechanics** that describes human or object motion mainly via image analysis is called kinematics. Kinematics describes motion in terms of space and time, and it provides valuable information regarding the position and the rate of movement of the human body, its segments or any implement used in a sport and exercise situation.

TYPES OF MOTION AND MECHANICAL QUANTITIES

The pathway of the motion experienced by moving bodies can be described as either straight line (rectilinear motion), or curved line (curvilinear motion) or they can rotate about an axis (*angular motion*). For example, an ice hockey player gliding straight across the ice with the same posture will result in all the segments of his body moving the same distance over the same time period (translation). In addition a discus travelling in the air following a curved path is an example of *linear motion* since its motion is translational too. In contrast, a gymnast who rotates around the high bar with a straight body position undergoes rotation about an external fixed axis where all the body segments travel through the same angle, in the same direction, in the same time, but covering different curvilinear distances with the segments further away from the axis (e.g. feet) travelling further than the segments closer to the axis (e.g. shoulders). There are also occasions where angular motion is observed with respect to an imaginary axis, which in many events could be located outside the physical boundaries of the human body (e.g. rotations in gymnastics or diving about the centre of gravity during flight). However, the most common form of motion in sport and exercise is a combination of angular and linear motion; this is called *general motion*. For instance in cycling, some body segments (e.g. thighs and legs) and parts of the bicycle (wheels) undergo rotation about joints of the body and the centre of the wheel respectively, whereas other body segments (e.g. hips and head) and bicycle parts (e.g. bicycle frame)

undergo translation with the total movement of the system (bicycle and cyclist) being linear.

Once the type of motion has been established the kinematic analysis can be performed by applying mechanical principles and formulae that provide information about the changes in the distance covered, the speed of movement and temporal pattern of the movement. In other words, by using vector quantities (magnitude and direction) instead of scalar (magnitude), the *position displacement*, *velocity* and *acceleration* of a body and/or object can be measured and expressed in S.I. units by using the same techniques and formulae for both angular and linear kinematics. The names, symbols and specific units differ between linear and angular quantities to allow inclusion of the characteristics of each type of motion. For example, the definition of velocity is the rate at which a body changes its position with respect to time and it can be obtained if the change in displacement is divided by the time taken for the change in displacement. In linear motion this velocity is denoted by the Latin letter v and it is measured in $m.s^{-1}$. In angular motion it is denoted by the Greek letter ω and it is measured in $rad.s^{-1}$ since the change in angular position is represented by the change in angle measured in radians (radians are used because they provide a means of calculating linear velocity of any point rotating around an axis by using the equation $v = \omega r$, where v is linear velocity ($m.s^{-1}$), ω is angular velocity ($rad.s^{-1}$) and r is the radius (m). There are 2π radians in 360°).

ANALYSING MOVEMENT IN PHYSICAL ACTIVITY AND SPORT

One of the main uses of biomechanics in sport and exercise science is in the analysis of patterns of human movement in either physical activity or sport. General movement patterns have common elements in terms of segment movements, axes of rotation and planes of movement and are easily recognised by most people and described as walking, running, jumping, throwing, catching, striking and kicking. When a general movement pattern is adapted for use in a particular physical activity or sport it is a skill. Taking the example of jumping, the high jump would be a particular skill within the general group of movement patterns we would all recognise as jumps. There are of course different ways of performing the high jump, with most children starting with a scissor jump and most, if not all, international high jumpers performing the Fosbury flop (named after its originator, high jumper Dick Fosbury). Different ways of performing a skill are called techniques, so that the scissor jump

and Fosbury flop represent examples of very different high jump techniques. Each of these techniques would have common elements, which make them relatively easy for us to categorise as particular forms of high jump technique. However, if you watch international high jumpers performing the Fosbury flop, you will observe that not all jumpers execute the Fosbury flop in exactly the same way. Rather, they have adapted or modified the technique; and these individual differences and adaptations are known as the style of the performer. Skill, technique and style are developed as a function of the requirements and constraints of a particular event such as the high jump (e.g. the rules of high jumping that require a one-leg take-off; the shape of the high jump area, which allows for a curved approach; the size, shape and fitness of the jumper, which are human constraints; and the coach, who may develop the Fosbury flop with an emphasis on certain aspects of the technique).

APPLICATIONS OF KINEMATICS

There is a wide spectrum of applications of linear and angular kinematics in sport and exercise. These applications are extremely valuable in motion analysis, especially now that advanced technology has improved the equipment that is used to obtain kinematic data. The employment of high-speed video systems in conjunction with sophisticated software, which converts the captured images into two- and three-dimensional coordinates, enables the sports biomechanist to obtain accurate estimates of instantaneous values of the kinematic variables critical in the performance of a movement or sequence of movements. The calculation of instantaneous rather than average values of a given quantity (e.g. velocity) distinguishes quantitative kinematic analysis from qualitative observation. In most analyses of sport it is much more informative to determine the characteristics of a performance at a particular instant in time. For instance, the linear velocities of the centre of gravity and its projection angle with respect to the horizontal at the instant of take-off in long jump will determine to a large extent the distance jumped by the athlete. There are numerous examples of the use of kinematic analyses right across the range of sport and exercise performances. On many occasions the use of kinematic analysis is significant in examining sporting movements that rely extensively on the performance of correct and effective technique, such as in a tennis serve or a javelin throw. Data from a kinematic analysis of these two movements can provide the coach and the performer with valuable information on technique, but

also inform recommendations with respect to corrections and adjustments that can lead to performance enhancement. Kinematic analysis has also proved successful in health-related applications, especially those that examine the effects of body posture and the specific movement patterns on the musculoskeletal system during different sport and recreational activities. The outcome of these applications is typically:

- 1 identification of the source of a problem affecting the performer (e.g. overpronation in running)
- 2 measures and advice on how to reduce or prevent the problem which, in running for example, might included a change of footwear or the prescription of an orthotic insert by a podiatrist.

When analysing movement a sound understanding of the laws, principles and methods of biomechanics can enable students to observe and explain which elements of technique and style are effective in optimising the movement and which need to be changed to produce a better movement pattern, either in terms of performance or prevention of injury. For example, a discus thrower who leans backwards as she makes the first turn at the back of the circle, will most probably translate that backward lean to the throwing position at the front of the circle. This will result in a loss of power and therefore velocity at the point of release. For a right-handed thrower leaning back through the delivery phase the point of release will occur too soon and the discus will land towards the right line of the sector or, worse still, hit the cage or go out of the sector, producing a foul throw. An explanation of such errors in style and technique can only be made with good observational skills coupled with the application of biomechanics.

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Work, Energy and Power

Forces are commonly applied over a certain distance. For example, a bobsleigh team will push their sleigh over a short distance in order to accelerate it. If a force is applied over a distance then a certain amount of work has been done. Work (Joules, J) is calculated by multiplying the magnitude of the force (Newtons, N) by the distance (metres, m) the body moves in the direction the force has moved it.

Power is a commonly used word whose meaning in biomechanics is the rate at which work is performed. It is often more important to be a powerful athlete, rather than just being 'strong'. The difference is that power is related to time, so if one particular weightlifter can lift 100 kg in two seconds, he is twice as powerful as another lifter who takes four seconds to lift the same mass. However, they could be considered equally strong as both have overcome the same resistance (and if both lift the bar the same distance, they will have completed the same amount of work). If we consider the equation for power constructed from above, we have:

$$\text{Power (Joules per second, } J.s^{-1}) = \text{work (J) / time taken (s)}$$

or

$$\text{Power} = \text{force} \times \text{displacement} / \text{time taken}$$

which can be rewritten as:

$$\text{Power (Watts, W)} = \text{force (N)} \times \text{velocity (m.s}^{-1})$$

From the power equation above, it follows that how quickly an athlete moves a weight will depend on the resistive force it presents. If something has a resistance that cannot be overcome by the muscles' force, no velocity occurs and no power exists. Similarly, if no resistance is present, a large velocity occurs but once again there is negligible power because of the absence of force. In order to have a power output (and therefore

to do work), force and velocity have to occur simultaneously. Individual muscles have their own optimum speed of movement to produce maximum power. As the velocity of movement increases from zero the power of the muscle increases rapidly until a plateau is reached. Further increases in the velocity will then result in a decrease in power output. If you think about pedalling on a bicycle, you will notice that using a low gear when travelling quickly has little or no effect on acceleration, because the forces applied are low and pedalling velocity is high. Likewise, pedalling in a high gear when cycling uphill is difficult because the resistive force is high in comparison to the speed of pedalling. It is therefore important in cycling that an appropriate gear is chosen to ensure maximum power output from the muscles, which is then applied through the pedals and chain to the back wheel.

Intertwined with force, work and power is the concept of energy. Energy is the capacity to do work. There are different kinds of energy and in each case they allow forces to act so that movement can occur. Similarly, in order to slow those movements (i.e. to decelerate), energy expenditure is also necessary.

Kinetic energy is the energy a body has as a result of its motion, and is dependent on both how heavy it is and how fast it's moving. A heavy rugby player running at eight metres per second has a much greater kinetic energy than a light distance runner moving at five metres per second. As a result, it is much harder to stop the rugby player because more energy (in the opposite direction of movement) is required to decelerate the player.

Potential energy is the energy a body has as a result of its height above the ground and its weight. Weight is the force due to gravity acting on a given mass, and the higher an object or person is above the ground, the longer gravity has to accelerate the body during flight. Potential energy and kinetic energy are thus interrelated when a body is in flight. For example, a tennis ball thrown high into the air will have a relatively high kinetic energy to begin with, but this will reduce as it gains height due to the slowing action of gravity. However, the potential energy of the ball is continually increasing until the peak of its flight when it is at its maximum. In this case, kinetic energy is being converted to potential energy. When the ball starts to fall back to earth, gaining speed (and therefore gaining kinetic energy), it simultaneously loses height and therefore potential energy. Potential energy is being converted back to kinetic energy, and this is one example of the physical law of the

conservation of energy, which states that energy cannot be made or destroyed but only converted from one form to another.

The main forms of chemical energy for fuelling sports movement in humans come from glycogen stored in the muscles and liver and fat stored in the muscle and elsewhere in the body. These fuels are sources of chemical energy that are converted to kinetic energy (movement of muscles) and heat energy. In fact, the majority of chemical energy provided from food is heat energy and relatively little is used mechanically by the muscles during contraction to produce movement. The body can therefore be described as being relatively inefficient. Efficiency is a measure of how much energy is wasted by a particular process (% Efficiency = Output Energy/Input Energy \times 100). For the purposes of movement, much heat energy is wasted energy because it does not help sports performance beyond a certain point. In fact, the body has to then work hard to dissipate this heat, which can have a severe detrimental effect on performance; this is achieved through various methods, but the main mechanism is sweating.

In motor sport, the engineers and designers continually strive to maximise the efficiency of the vehicle. Formula One cars are especially designed to reduce slowing forces such as air resistance because the more forces needing to be overcome, the more energy is required. Energy requirements need to be kept down so that the car can carry less fuel (which adds weight) and require less refuelling stops. Be careful not to confuse efficiency with economy, as economy refers to how well the system uses the fuels it draws on. In a car this might mean how well the petrol or diesel is burned in the engine, in the human body it refers to how much oxygen is utilised to produce a certain exercise intensity (e.g. run at a given speed).

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Impacts

Impacts are common in the world of sport. Many impacts are desirable because, for instance, of the need to move the human body (e.g. impact between the feet and ground in running), to score points (e.g. impact between the board and the ball in basketball), or just to continue a game by passing the ball (e.g. impact between the foot and the ball in football). The list with examples that demonstrate the critical and essential role of impacts in sports can be extended to include almost every single sport played today. Most sports have been designed and developed by using impacts as the means by which the execution of the sport-specific movements are achieved. In many sports there are different types of impact taking place, which are affected by a variety of factors.

For example in tennis, the impact between the tennis racquet and the ball is influenced by factors such as the mass and elasticity of the two impacting bodies, the ball velocity, the angle of impact and the type of ball spin. The impact between the tennis player's feet and the ground is influenced by the elasticity of both bodies, the impact angle, the frictional characteristics of the tennis surface used (i.e. grass, clay or synthetic). In addition a third type of impact occurs in tennis when the ball contacts the ground and this is affected by all the factors mentioned above for the other two impacts.

MECHANICS OF IMPACT

Impacts between two bodies can be divided into direct and oblique impacts. Direct ones are those that occur when *a*) one moving body strikes one stationary body after it has travelled along a path that forms a right angle with the second body's surface (a volleyball lands on the ground) or *b*) the two bodies are in motion and they have travelled along the same straight line prior to the impact (a defender's header against an oncoming ball in football). Oblique impacts are those which occur when *a*) a moving body impacts a stationary body after it has travelled along a path that forms an oblique angle with the second body's point of impact or surface (e.g. squash ball hits the wall from an oblique angle) or *b*) the impact angle is oblique but both bodies are in motion prior to impact (e.g. cricket bat strikes the ball). Many of the impacts in sport involve

different types of balls and implements and belong to the oblique category, but there are also impacts, which are not discussed here, involving more than two bodies coming into contact simultaneously (e.g. snooker balls).

To understand the mechanics of impacts and to be able to predict the post-impact events is very useful since these events dramatically affect the performance outcomes of many sporting situations. Some factors that influence the outcome of an impact were mentioned earlier but below there is a comprehensive list of factors that should be taken into account by sport scientists, coaches and athletes when attempting to understand and determine the outcome of a specific impact:

- the coefficient of restitution (e) of the impact, which depends on the degree of elasticity of both impacting bodies;
- the masses of the two impacting bodies;
- the velocity (ies) of the body(ies) before impact;
- the approach angle before impact;
- the type and the amount of spin (e.g. when one of the bodies is a spinning ball).

IMPACTS AND PERFORMANCE

The coefficient of restitution (e) is the ratio of the speed before impact to the speed after impact and is often expressed as a percentage. (A 100 per cent would indicate a perfect rebound, e.g. where a ball returns to the height from which it was dropped. Try this with a range of different sports balls and see what happens; you should see that even with really bouncy balls they do not return to the height they were dropped from.) The coefficient of restitution describes the elasticity of an impact (and not the elasticity of a body) and can be changed by altering the materials used to make the impacting bodies (e.g. different rubber compounds used in different grades of squash balls from beginner up to match balls). Other factors such as temperature will also affect the coefficient of restitution, which explains why squash balls get bouncier after they have been played with for a period of time. Scientific developments, especially with the introduction of new materials, have led to large performance improvements in sports that involve impacts (e.g. artificial surfaces in athletics and new tennis racquets).

Velocity, approach angle and spin are determined during the sports performance and are largely dependent on the performer's physical abilities and skills. However, factors related to the performer will also

interact with environmental factors (e.g. temperature, humidity, wind direction and strength). The manipulation of performance variables within the constraints of the environmental factors to produce impacts that result in favourable outcomes is often what separates the performance of the more skilled individual from that of the less skilled.

IMPACTS AND INJURY

Many injuries that occur throughout sport are the result of different kinds of impacts. Single powerful impacts (e.g. head impacts from a fast delivery in cricket or from a stick in ice hockey) or repeated sizeable impacts (e.g. in running and jumping or in tennis) can lead to acute (e.g. head trauma) and chronic injuries (e.g. shin splints or tennis elbow) to the performer's body. The size of the forces experienced by the tissues during an impact is dependent on the product of the mass and deceleration of the striking object as it hits the body. Therefore, there is a tension between performance enhancement and the prevalence and incidence of injury related to impacts in sport. Both codes of rugby involve very large impacts between players which are quite legitimate within the rules of the game. However, in order to play rugby at the highest level, players need to be both highly skilled and well conditioned to both initiate successful impacts and withstand impacts initiated by other players, thereby affecting both their performance and the likelihood of becoming injured. The prevention and reduction of injuries due to impacts has received significant research attention over the recent decades and new technology has been engaged to control and improve outcomes of impacts. Protective equipment has been introduced or improved in many sports in an attempt to decrease the probability of certain injuries through impacts (e.g. helmets in cricket, gum shields, head guards and shoulder pads in rugby). In terms of single impacts the main purpose of the protective equipment, which is achieved by its unique shape and the elastic materials of its construction, is to absorb the energy of the impact and to spread the impact force over a larger area (e.g. cricket helmets, protective pads and gloves). With regard to repeated impacts, and especially those produced during running, jumping and landing, the focus has tended to be on modifying the impact-absorbing properties of the footwear rather than the compliance of the surfaces involved, since low compliance (high stiffness) of a surface can produce better performance in jumps and sprints due to the substantial amount of energy returned to the performer during the propulsive part of the ground contact. Running

on more compliant surfaces would result in slower sprinting speeds, but there has been a compromise in the specification of modern athletic track surfaces, which have to conform to strict requirements in terms of mechanical properties such as compliance.

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Angular Kinetics

Angular kinetics has similar concepts to those of linear kinetics, such as force, **Work, Energy and Power**, although they are somewhat more complicated. The important concepts in angular kinetics are levers, torque and angular momentum.

LEVERS

A lever is defined as a rigid body that rotates about an axis, which is also sometimes called a fulcrum or a pivot. Levers rotate about an axis due to a force being applied, generally to overcome a resistance. In the human body, the bones are the main levers, the joints are the axes, the muscles provide the force by contracting, and the weight of the body segment (with or without an extra implement or weight) is the resistance.

First-class levers are useful if a large resistance has to be overcome with a small force. First-class levers occur when the axis is placed between the force and the resistance (it is easiest to picture this as a see-saw). Opening a tin of paint with a screwdriver is a common

application of this type of lever. First-class levers are also helpful for moving small resistances quickly. An example in the human body is the triceps brachii in the upper arm. The force of the muscle causes rotation around the elbow axis so that the resistance of the forearm is overcome.

Second-class levers are useful to move large resistances with little force. Second-class levers have the resistance located between the force and the axis. A good example of this type of lever is a wheelbarrow. There are very few meaningful examples of this type of lever in the human body, because it is mostly built for speed of movement. One example is standing up on your toes, where the fulcrum is your metatarsal-phalanges joints (ball of the foot), the resistance is the weight of the body and the force is supplied by the calf muscles. The human body mainly consists of third-class levers, which occur when the force is placed between the resistance and the axis. One example is elbow flexion. The force is provided predominantly by the biceps brachii, the axis is the elbow joint, and the resistance is provided by the forearm. Note how the biceps brachii is a third-class lever while the triceps brachii is a first-class lever because of the different positioning of their tendinous insertions.

How well a lever works depends on the length of the lever and the positions of the force and resistance from its axis. The distance from the axis to the point of force application is called the force arm, while the distance from the axis to the point of resistance application is called the resistance arm. Multiplying the force arm length (m) by the force (N) applied gives a turning moment (Nm), sometimes known as a torque. In order for the lever to be effective, the 'effort' torque has to be greater than the resistive torque (calculated in the same manner as the 'effort' torque).

The longer the force arm, the less force is required to overcome the resistance; and the shorter the resistance arm, the less force is required also. It is rare in the human body to have long force arms and short resistance arms. It is usually the opposite in that the resistances are a much greater distance from the joints than where the forces are applied (i.e. muscular insertions). This situation is known as a mechanical disadvantage. A mechanical advantage occurs when the effort force arm is longer than the resistance arm and this occurs in some first-class levers and all second-class levers.

TORQUE, MOMENT OF INERTIA AND RADIUS OF GYRATION

Torque is the angular version of force. Similarly to force, a torque is something that causes angular acceleration. A rotating object will rotate more quickly, more slowly or change direction if a torque is applied. How

effective the torque is does not just depend on how heavy the rotating object is but also on how that weight is distributed with respect to the axis of rotation. This resistive property of rotating bodies is known as the moment of inertia, and the distance from the axis to where the moment of inertia is said to act is known as the radius of gyration. It is worth pointing out that the point where the moment of inertia is said to act is not always the centre of mass. For example, a discus in flight will rotate around its centre of mass but will still have a certain resistance to rotation because its moment of inertia is slightly further out on the discus.

The radius of gyration is of great importance in altering how fast rotation occurs. This is because changing the radius of gyration changes the moment of inertia and hence the resistance to rotation. So if the radius of gyration is shortened, the resistance to rotation is decreased and positive angular acceleration occurs. In effect, the rotating body's angular velocity increases. For example, a baseball bat swings faster if it is held further up the bat than normal – this technique is often adopted by children for whom the bat is often too long and heavy to swing successfully. A sprinter's leg during the swing phase of running is also a rotating body, and can be made to complete the running step more quickly by reducing the leg's radius of gyration. This is achieved through maximal flexing at the knee, bringing all the leg's mass closer to the hip joint. In some sporting situations, it is preferable to reduce angular velocity and this is achieved through increasing the radius of gyration. One example is the sail technique in long jumping, where the athlete spreads out their arms to prevent forward rotation. Among other things, this prevents the athlete from somersaulting, a technique forbidden in the event.

CONSERVATION OF ANGULAR MOMENTUM

We have seen that there is a relationship between angular velocity and moment of inertia. If we multiply the moment of inertia by angular velocity, we can calculate angular momentum, which is defined as the quantity of angular motion. By decreasing the moment of inertia, angular velocity increases, and vice versa. This is the principle of conservation of angular momentum, and applies to all bodies rotating in the air (it is normally assumed that in this situation there is negligible air resistance). It is this principle that allows gymnasts and divers to control the speed of their rotations when tucking or piking. A diver might tuck during flight to spin quickly during forward somersaults and then open out again towards the bottom of flight in order to enter the water with a straight body.

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Fluid Mechanics

Fluid mechanics is the area of sport and exercise biomechanics that helps us understand the forces exerted on objects or bodies by interactions with the fluid they are travelling through. These are often studied separately where the fluid is air (aerodynamics) or water (hydrodynamics). However, the two main concepts and mechanical principles are the same for both:

- drag forces, which are forces that are parallel and opposite to the motion of the object or body as it moves through a fluid, and
- lift forces, which always act perpendicular (at a right angle (90°)) to the direction of flow of the fluid.

To understand drag and lift forces we must focus on the relative motion between the object or body and the fluid that it is moving through. The importance of this principle is illustrated by ski-jumpers, who in optimum conditions when jumping into an oncoming breeze, can generate lift forces that carry them considerably further than they would jump without the oncoming wind. However, cross-winds interfere with the technique of ski-jumping and often mean that competitions have to be postponed until there are more favourable wind conditions. In the case of the relative motion of air flow and the ski-jumper:

- in still conditions the ski-jumper will only experience air flow past their skis and body in the direction opposite to their travel;
- jumping into an oncoming wind will increase the flow of air past their skis and body, due to their velocity added to the velocity of the wind which is blowing towards them;
- in across-wind the ski-jumper will experience a flow of air that will be the combination (resultant vector) of the velocity of the cross-wind and the velocity of their movement through the air as a result of their jump, making it impossible to jump straight down the fall line of the hill.

DRAG FORCES

A drag force is a fluid resistance force that opposes the motion of an object or body moving through it and is called either aerodynamic or hydrodynamic drag respectively. A good example of a large difference in drag force when moving in air is given by a comparison of cycling with dropped handle bars in a crouched racing position and straight handle bars with the rider in an upright position. The same cyclist going at the same speed will experience very different drag forces in the two different body positions. Similarly, in swimming the position of the body in the water will have a large effect on the drag forces. A streamlined position with the whole body on or close to the surface of the water will create much less drag than in a swimmer who allows their legs to sink, which increases the drag forces. Both these examples of different drag forces in air and water are explained almost completely by body position in relation to the oncoming fluid, be it air or water. However, there are several other important variables that contribute to drag forces.

Skin friction and profile drag are common to both air and water and a third form of drag that is important in water sports is wave drag. Skin friction or surface drag is caused by the fluid in contact with the body or object moving with the surface of the object against the flow, which drags along the fluid next to it, but this effect decreases with increasing distance away from the body or object. This rubbing of layers of fluid causes friction and is known as the boundary layer. Skin friction, which is the interaction between the body or object and the fluid layers, depends on the roughness of the surface and the viscosity of the fluid. Profile, pressure or form drag refer to the drag caused by the pressure difference between the zone of high pressure on the front of the body or object as it moves through the air and the low pressure zone behind the object. These

different pressure zones are caused where the boundary layer of fluid flowing around the body or object breaks away from it, as the fluid cannot flow smoothly all the way around the surface of the object, which causes a low pressure turbulent zone behind the object. The pressure difference between the high and low pressure zones causes a net profile drag force on the body or object, which is the largest air resistance variable that affects athletes moving quickly, such as runners and speed skaters and all projectiles in sport, such as balls or javelins. Both skin friction and profile drag depend on shape, size and position of the object or body, the density of the fluid (water is denser than air) and the velocity of the fluid flow relative to the object or body. Wave drag is the resistance force caused by a body moving along, through or under the surface of the water that produces waves. At low speeds wave drag is not that significant, but it can become the largest resistance force at high speeds. Front-crawl swimmers do make use of the trough of the bow wave to make breathing easier. Wave drag in rowing boats, kayaks and canoes is related to boat length, with a longer boat length facilitating higher possible boat speeds.

Drag force is based on the following equation:

$$\text{Drag force} = \frac{1}{2} \text{ coefficient of drag} \times \text{frontal area} \times \text{fluid density} \times \text{relative flow velocity}^2$$

$$F_D = \frac{1}{2} C_D A \rho v^2$$

Where F_D is the drag force, C_D is the coefficient of drag, A is the frontal area perpendicular to the flow, ρ is the fluid density and v is the velocity.

The coefficient of drag, which tells us how streamlined a body or object is, changes with the position of the body or object relative to the flow and is determined experimentally. Streamlining depends not only on shape but also on orientation to the direction of fluid flow, so you can have a streamlined shape, such as a javelin, which stalls because it is not correctly orientated to the flow of oncoming air. Frontal area is the area of the body or object facing the flow of fluid, as illustrated above in the example of body position in cycling. Fluid density (mass/volume) represents how closely the atoms of the fluid are arranged, with air being almost 1,000 times less dense than water. The density of air will vary with humidity, temperature and pressure and changes in the density of air from the height of a delivery from the hand of a bowler in cricket to the level of the pitch contribute to how much the ball will move in the air. Such effects will vary depending

on the environmental conditions, which is why a swing bowler's performance will vary with the weather conditions. As shown by the equation, drag force increases with the square of the velocity, so the effects of a given coefficient of drag and frontal area on the drag forces are magnified by an increase in the relative flow velocity.

Drag forces as propulsion

Although drag forces oppose the motion of an object or body, they are not always negative in their contribution to the sport or exercise. This is well illustrated by the example of a skydiver who opens their parachute, which dramatically increases the drag force, slowing them down sufficiently so they can execute a safe landing. Another example is the drag force exerted on the blade of an oar in rowing as it is pulled backwards through the water, which is responsible for propelling the boat forward.

LIFT FORCES

Lift forces are most commonly explained with reference to the pressure differences created by different speeds of air travelling either side of an aerofoil or hydrofoil. Figure 3 shows a cross-section of an aerofoil, which could be an aircraft wing. The explanation is that air dividing at the front edge of the aerofoil travels faster over the longer curved surface of the top of the aerofoil compared with the air flowing underneath the straight surface of the bottom of the aerofoil. These different speeds of air flow relative to the surface of the aerofoil develop different pressures, with high pressure developed underneath the aerofoil, where the flow velocity is slow and low pressure above the aerofoil where the flow velocity is fast. The lift force is therefore the result of the pressure difference between the top and bottom of the aerofoil, which results in the aerofoil experiencing a lift force in the direction from high to low pressure perpendicular to the relative flow of the fluid and directly proportional to the magnitude of pressure difference.

The relationship between pressure and flow velocity is summarised by Bernoulli's principle, which states the inverse relationship, when the flow of fluid is fast the pressure is low and when the flow velocity is slow the pressure is high. You can demonstrate this principle easily by taking two sheets of A4 paper, one in each hand and holding them in front of your mouth about 10 cm apart, supporting each in the middle

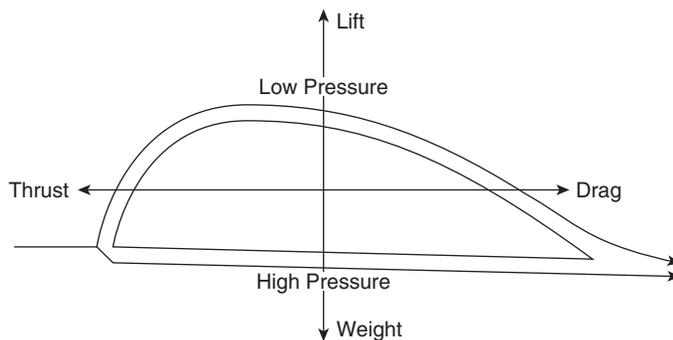


Figure 3 Forces acting on an aerofoil (this way up it could be the wing of an aircraft, upside down it could be an aerofoil on a racing car with the 'lift' force pushing the car into the track).

of the long side so that they hang down parallel making a channel in front of your mouth. Blow air down the channel between the two pieces of paper and observe what happens. The two pieces move together because the flow velocity in the channel is relatively fast as you blow the air through compared to the air on the outside of the paper, which is still. This generates a low pressure zone in the channel with a lift force acting horizontally forcing the two pieces of paper together in the channel. Another two important observations to make are that you do not need an aerofoil shape to generate pressure differences and lift forces, and that lift forces can act in any direction (not just up!) according to where the different pressure zones are. The aerofoil shown in Figure 3 illustrates how lift forces are generated to help keep planes in the air, or the hulls of hydrofoils out of the water (although you need a lot of forward speed to generate big enough lift forces in both cases). However, if you turn the aerofoil over (or turn the book upside down) you will be looking at how an aerofoil helps keeps a Formula One racing car on the track (again the faster it goes the faster the relative air flow, the greater the pressure difference and the more lift force is generated).

Angle of Attack

If a body or object does not have an aerofoil shape, a difference in flow velocity can be created to generate a lift force resulting from differences in pressure by tilting the body or object relative to the oncoming fluid

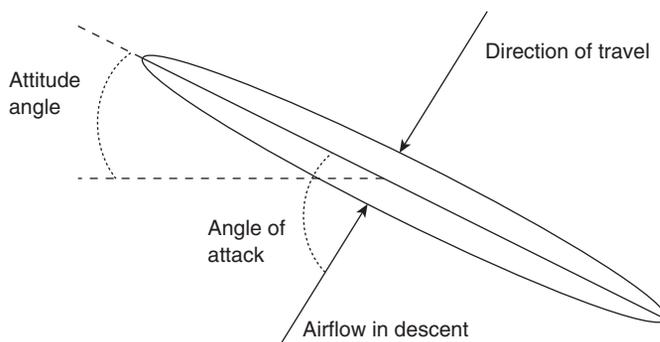


Figure 4 *Angle of attack of a discus during the descent phase of the throw.*

flow. This angle of tilt between the oncoming fluid and the body or object is called the angle of attack. A good example from sport is the discus throw, where at the point of release the thrower releases the discus with a negative angle of attack in order to benefit from relatively large lift forces in the descending part of the flight path of the discus (Figure 4). This is achieved because the discus tends to maintain the same angle between its axis and the ground (attitude angle) throughout its flight, which is helped by the gyroscopic stability generated by the spinning of the discus at release. Good discus throwers therefore throw better into a light wind because they can generate greater lift forces. Poor discus throwers often get the angle of attack wrong at release, which means it will be wrong throughout the throw and stall, falling steeply for a shorter throw in the descent part of flight. Some biomechanists adopt an alternative approach to explaining the use of angle of attack through Newton's laws of motion.

Factors that cause lift

The magnitude of lift force that can be generated is dependent on a number of factors, which can be summarised by the following equation:

$$\text{Lift force} = \frac{1}{2} \text{ coefficient of lift} \times \text{pressure area} \times \text{fluid density} \times \text{relative flow velocity}^2$$

$$F_D = \frac{1}{2} C_L A v^2$$

where F_L is the lift force, C_L is the coefficient of lift, A is the pressure area which is the surface area of the body where the pressure acts, ρ is the fluid density and v is the velocity.

The coefficient of lift is the index of how well an object can generate lift force, but will be different depending on its orientation to the flow of fluid (i.e. dependent on angle of attack). Using the discus throw as an example, an angle of attack of approximately 26° will produce a higher coefficient of lift than for larger or smaller angles of attack, but this angle will vary throughout the flight of the discus.

The size of the surface area that is angled to the flow, which generates the pressure differences, is positively related to the generation of lift forces. Design features of objects used in sport are often manipulated in order to generate lift in this way, which is why rules are often introduced to control such factors. For example, single design sailing boats will focus on testing the skill of the sailors when they race, although how the sails are rigged and set for the prevailing conditions will affect how well the boat performs.

The density of fluid is also positively related to the generation of lift forces, with water generating more lift than air. This is similar to the effect of density on drag forces.

Also similar to the effects on drag, lift forces will increase with the square of the relative velocity between the fluid and the object. This means that if the velocity doubles the lift force generated will increase by a factor of four.

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