FROM: IAAF "Introduction to Coaching Theory"

BIOMECHANICS

Expert coaches are able to analyze the techniques involved in athletics and modify them to make desired improvements with a particular athlete. The novice coach often has difficulty deciding which technique to use and what modifications to make. The simplest and most often used approach to overcome this difficulty is to copy the event techniques used by current champions. The problem that arises is top athletes frequently have different techniques and additionally, coaches and athletes copy bad, as well as good, aspects of each technique.

Every athlete has individual strengths and weaknesses. The technique of the champion is frequently built on training and practice over many years and is developed to suit his particular strengths and weaknesses. This highly developed technique is usually not suitable for a developing coach or athlete. How can coaches improve their ability to select the best techniques and identify the causes of faults they observe? To answer this question an understanding of what produces movement and an ability to analyze movement is essential for the modern coach.

FORCE

Forces produce movement and a force is simply a pull or a push. We cannot see force, but are aware of it because of the effects it produces. For example, a high jumper applies force to the ground. We do not see the force but we observe the results, the athlete leaving the ground. Biomechanics is the science concerned with understanding the internal and external forces acting on a human body and the effects produced by these forces. Internal forces are those forces created inside the athlete's body by the action of muscles pulling on bones. External forces are those acting outside the body such as gravity and friction.

In this unit we will look at the basic language and principles of biomechanics to help your analysis of movement. These principles applied in practice, combined with the development of a good "coaching eye", will make you a more effective coach.

Linear and Rotational Motion

Linear motion is movement along a straight line and rotational motion is movement about an axis of rotation. In athletics, movement is usually a combination of linear and rotational motion and is called general motion. A sprinter's body, for example, has linear motion but the movement is caused by the rotational motion of the legs. Both forms of motion take place to produce the general motion of running. A discus thrower uses rotational motion to build up speed before releasing the discus. He also moves with linear motion from the back to the front of the throwing circle. This is another example of general motion.

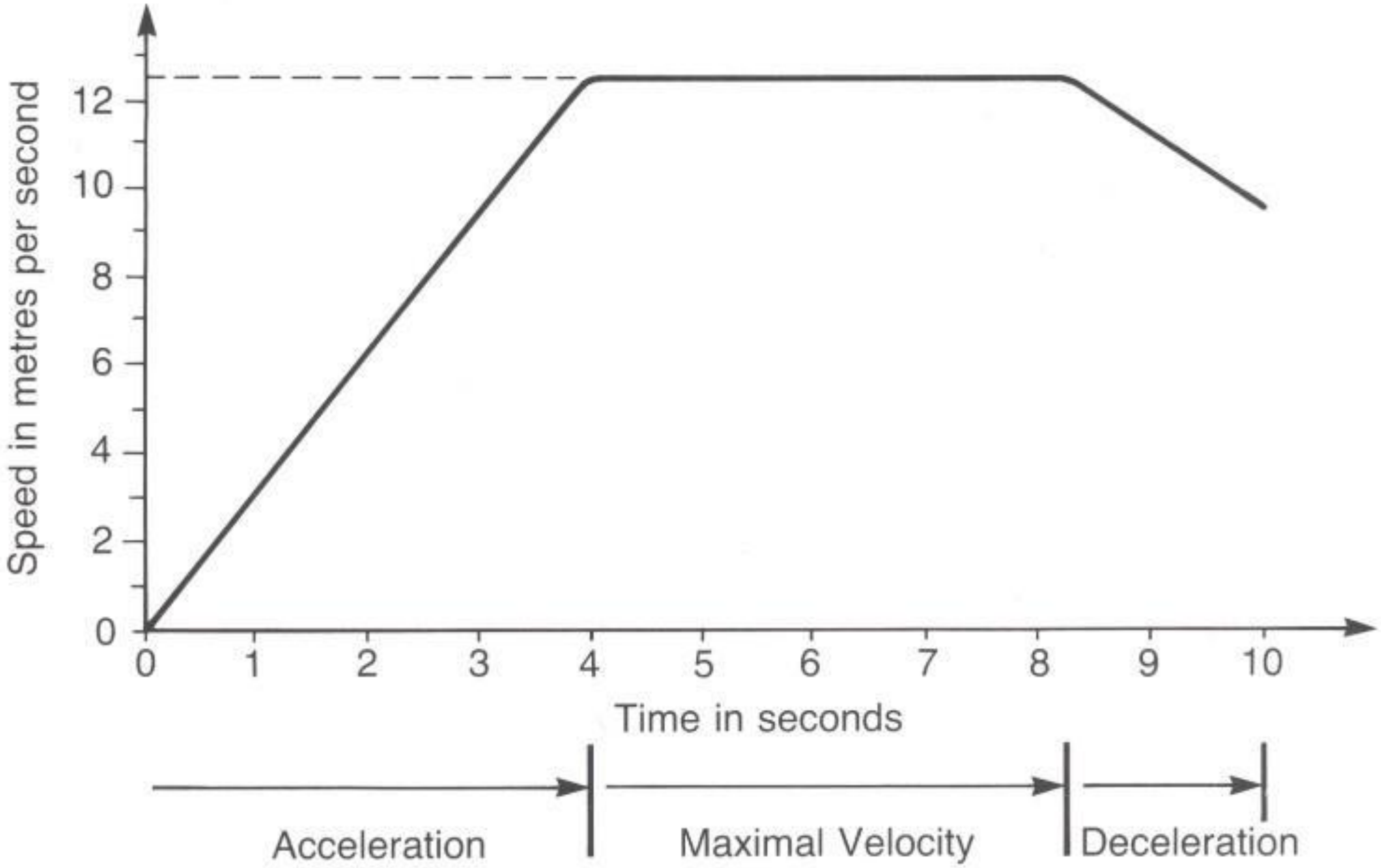
Velocity and Acceleration

Speed tells us how fast a thing is moving. This thing may be the human body or a throwing implement. Velocity tells how fast a thing is moving and in which direction. A sprinter may cover 100 metres in 10 seconds. His horizontal velocity is determined by dividing the distance covered by the time taken. In this example 100 metres divided by 10 seconds gives a velocity of 10 metres per second.

Athletics has standard distances, so we can compare times to see which athlete has greater velocity. From experience, we know that an athlete who runs 100 metres in 10 seconds is faster, or has a higher velocity, than an athlete who takes 12 seconds. An athlete who runs 1500 metres in 3:40 has a higher velocity than an athlete who runs 4:00.

When you race any distance your velocity changes. At the starting line you are not moving and have zero velocity. After the gun has fired you gain velocity or accelerate. Acceleration tells us how fast the velocity of something is changing. Running acceleration may be to a maximum velocity, as in the 100 metres or to a velocity which is optimal for the event.

An athlete who slows down, loses velocity and is said to be decelerating. If we look at the speed-time graph for a sprinter we see an initial phase of acceleration. This is followed by maximal velocity sprinting and finally a phase of deceleration as the athlete fatigues.



Speed-time graph for a sprinter

Momentum

Momentum is the quantity of motion a body has and is a product of weight and velocity. In the human body there can be a transfer of momentum from one body part to another. In the long jump, for example, the "blocking" of the free leg when the thigh is parallel to the ground transfers momentum as additional force to the take-off leg.

Angular momentum is the quantity of angular or rotational motion a body has and is the product of the moment of inertia and rotational velocity. When a body is rotating the moment of inertia is proportional to its size. If the arms are bent in sprinting, for example, their moment of inertia is less than if they are straight. A rotating body has a given quantity of motion or momentum and any reduction in the moment of inertia will cause acceleration to an increased rotational velocity. In sprinting this principle affects arm action and leg recovery. Any increase in the moment of inertia has the opposite effect of reducing rotational velocity. This increase of moment of inertia is used in the different flight techniques of the long jump to slow down forward rotation.

There can also be a transfer of angular momentum from one body part to another. This is applied in the throws when, for a right handed thrower, "blocking" the left side of the body immediately before delivery transfers angular momentum to accelerate the right, throwing side.

Implications for the Coach

There are two practical principles that apply specifically to running, jumping and throwing where the athlete is concerned with creating optimal force and speed:

- **Use all the joints that can be used**
- **Use every joint in order**

Use All the Joints That Can be Used

The forces from each joint must be combined to produce the maximum effect. This is best done when all joints that can be used are used. This will help to get the most speed or acceleration out of a movement.

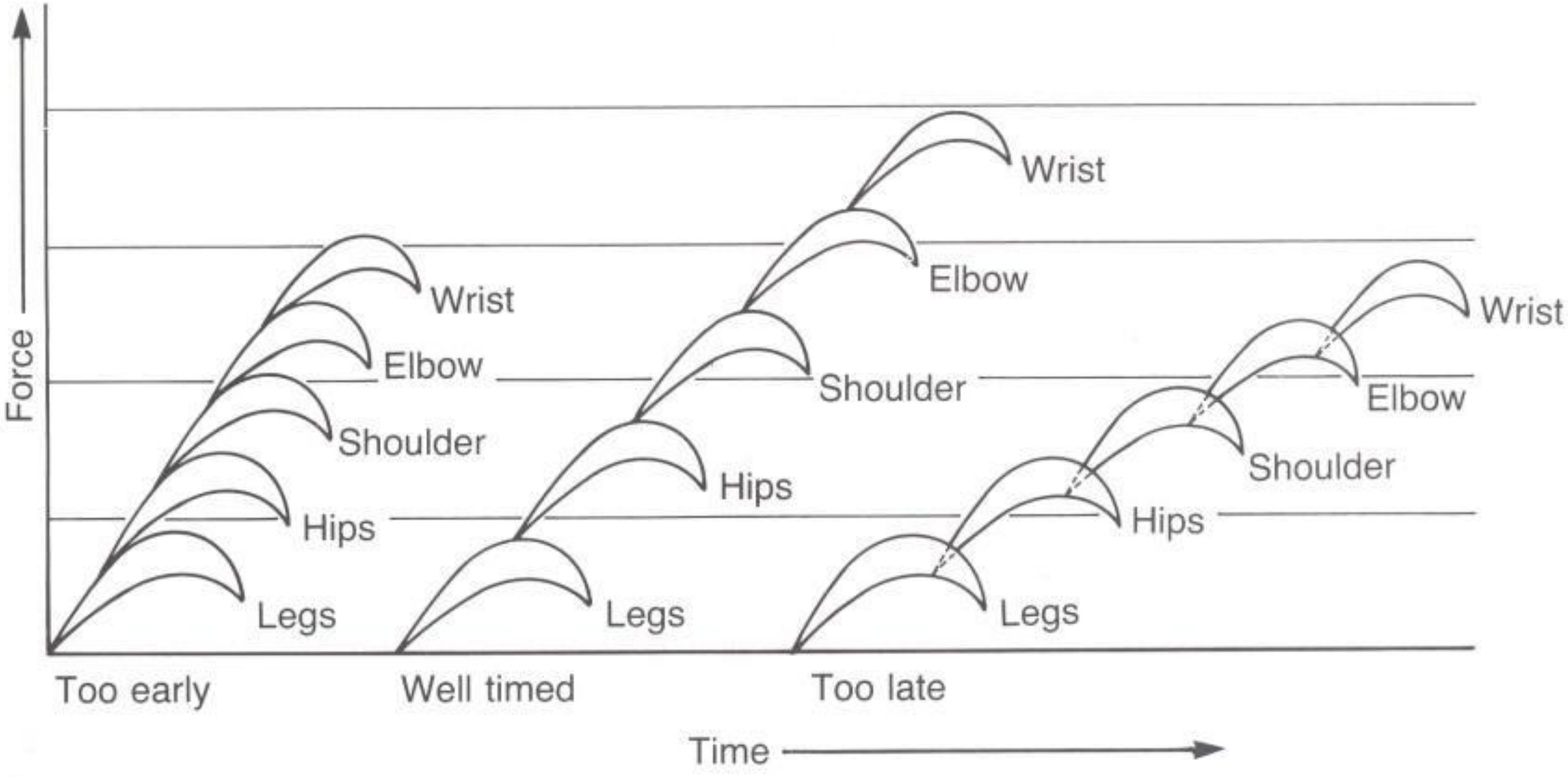
In the shot put, for example, the knee, hip, shoulder, elbow, wrist and finger joints should all be used to exert the greatest force on the shot. Beginners frequently miss out early joint movements such as the knee or hip action, or fail to complete a movement fully by not using the wrist or fingers.

Use Every Joint in Order

When several joints are used in a skill, their sequence and timing are important. This principle tells us when the joints should be used. Movement should begin with the big muscle groups and move out through the progressively smaller muscles, from big to small. This pattern produces optimal forces and flowing, continuous movement.

The continuous, flowing movement produces a summation of forces, forces adding together. The force generated by one part of the body is built on by the force of subsequent joints. In the well timed shot put, the hip action commences just as the leg extension decelerates. The shoulder action commences as the hip rotation decelerates and so on.

The release velocity of an implement depends on the speed of the last part of the body at release. The correct sequence and timing allow the athlete to attain maximal release velocity.



Summation of forces in the shot put

LAWS OF MOTION

Understanding the relationship between force and motion owes much to the work of an English scientist, Sir Isaac Newton. He is best remembered for his three laws of motion.

Newton's First Law of Motion

It is important to know the definition for each of the three laws of motion and more important, know how to apply the laws in practical situations. Newton's first law of motion states:

> ***"All bodies continue in a state of rest or uniform motion in a straight line unless acted upon by some external force.***"

What are the applications of this law? A sprinter, for example, will not move from the blocks until his legs exert force against them. The high jumper will not take off from his approach run unless a force is applied to change direction.

Newton's Second Law of Motion - Law of Acceleration

> ***"The acceleration of a body is proportional to the force causing it and takes place in the direction the force acts."***

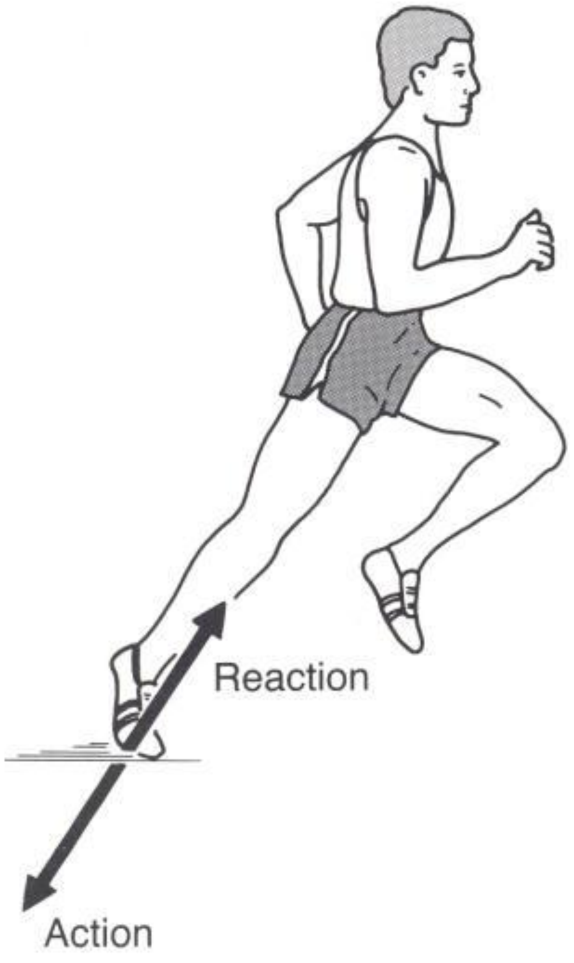
More force means more acceleration. A sprinter's acceleration from the blocks is proportional to the force exerted against the blocks. The greater the force exerted, the greater will be the acceleration away from the blocks. In the throwing events, the larger the force exerted on an implement, the greater will be the acceleration and consequently, distance thrown.

Once an implement has been released there are no forces which can act to accelerate it. The same is true in the jumping events. The greater the force the athlete exerts at take-off the greater the acceleration and height or distance achieved. Once the athlete has left the ground nothing he does will accelerate the body. When maximal forces are needed the muscles contract to generate this force and this is why injuries are more likely to occur in the acceleration or deceleration phases of a movement.

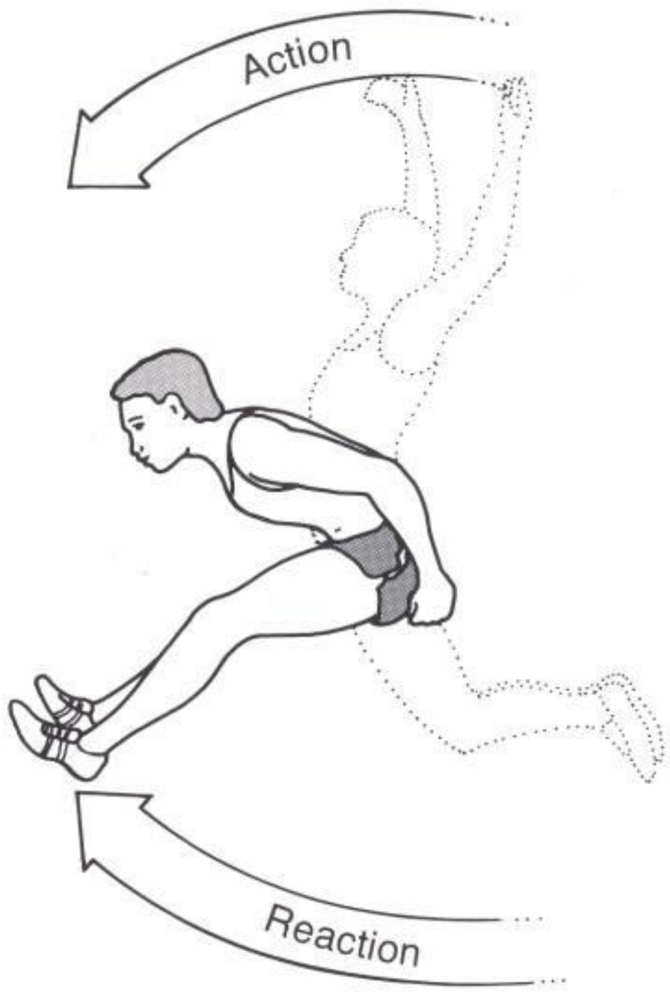
Newton's Third Law of Motion - Law of Reaction

> ***"To every action there is an equal and opposite reaction."***

A runner exerts a force against the ground. This creates an equal and opposite reaction force which moves the body over the ground.



A runner creating an
equal and opposite reaction



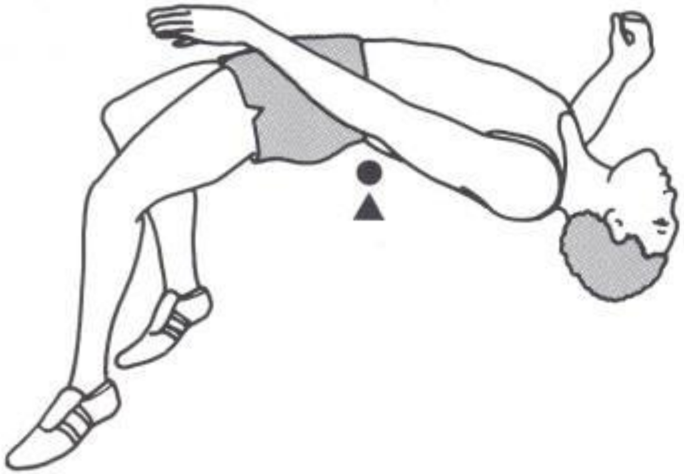
Action and reaction
in long jump landing

The law of reaction also applies to movements that occur in the air. In these situations the equal and opposite reaction is shown in movements of other parts of the body. A long jumper, for example, will bring the arms and trunk forward in preparation for landing. The equal and opposite reaction is movement of the legs into a good position for landing.

Center of Gravity

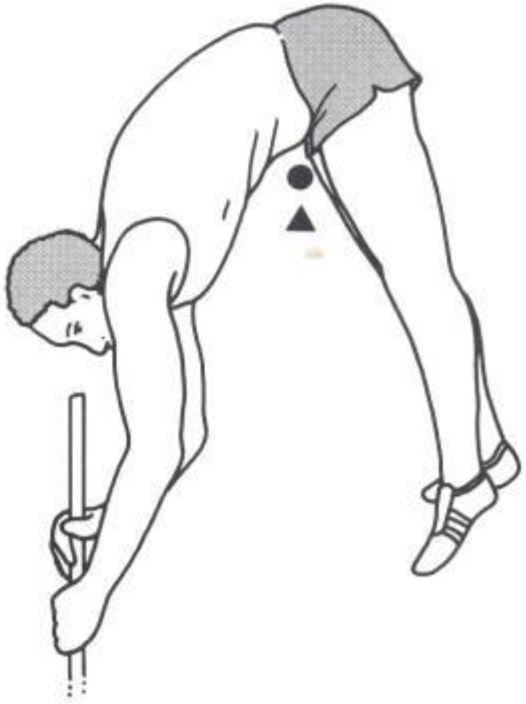
Gravity is a force which is always present and is a pulling force in the direction of the centre of the earth. This force acts on every body through an imaginary point called the centre of gravity (GG). A solid object like a shot or discus has its CG in the centre and this is a fixed point.

The human body is a complex and constantly changing shape. The centre of gravity now moves according to the positioning of the body and limbs. The CG may be inside the body, for example, when standing or it may be outside the body as in the pole vault and flop high jump bar clearances.



● Crossbar
▲ Centre of gravity

The Fosbury flop technique in the high jump



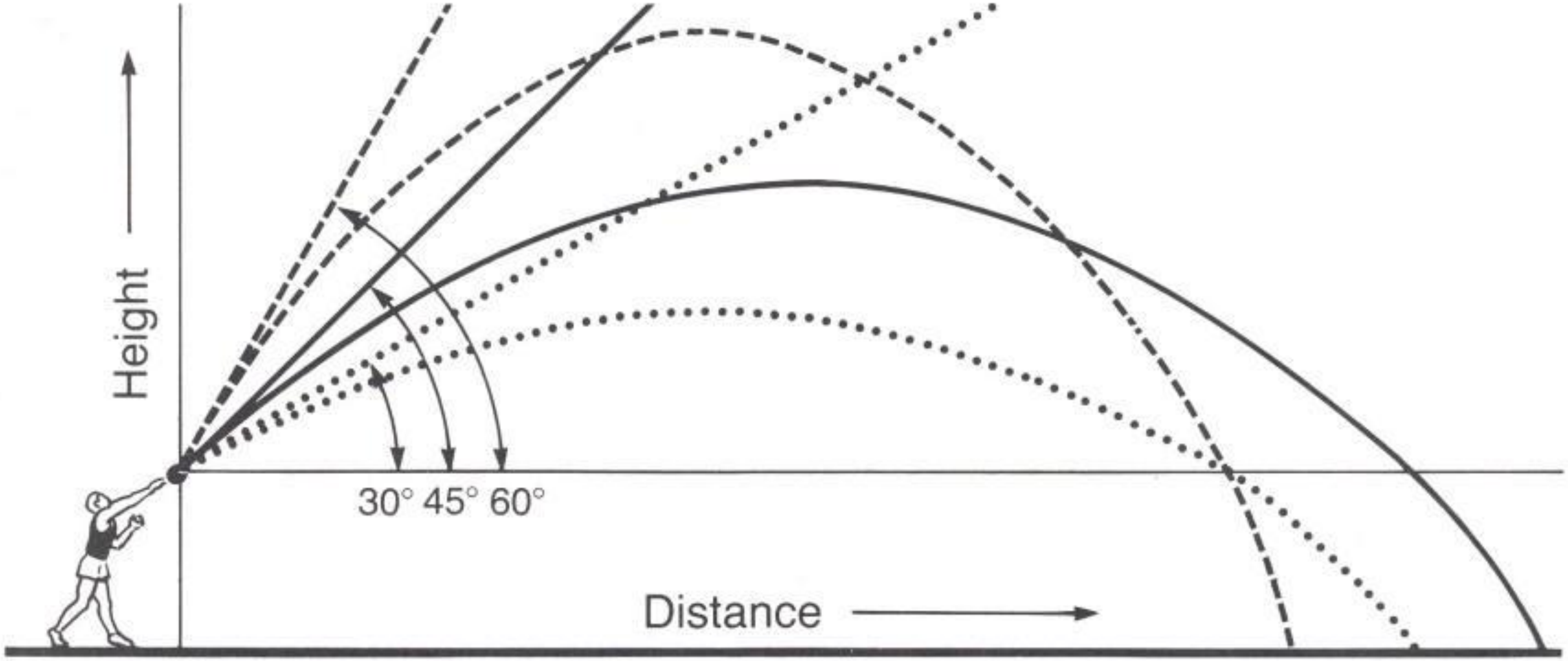
The piked bar clearance in the pole vault

The athlete passes over the bar while his centre of gravity passes through or beneath it.

When an athlete launches himself or an object into flight gravity will act as a force pulling the athlete or object towards the ground. The flight path of the centre of gravity of a body is a curve called a parabola. The parabolic flight path depends on three factors:

- **Speed of take off or release**
- **Angle of take off or release**
- **Height of the athlete's CG at take off, or CG of implement at release**

Of these, the speed of an athlete at take off, or of an implement at release, is the most important factor. Greater speed means greater distance achieved. Air resistance can also affect the distance travelled by an athlete or implement.



The parabolic flight path for various release angles

All the principles of movement are based on how forces are made by the athlete or how they act on the athlete's body. They may appear complex at first but, as you learn the basics for each event, biomechanics and an analysis of movement will become an understandable and usable part of your coaching knowledge helping to make you a better coach.

Basic principles for understanding sport mechanics

Before we begin, we need to brush up on the mechanical principles that are fundamental to understanding sport mechanics. The following reference section provides an overview of the mechanical terms mass, weight, and inertia; linear and angular motion; and speed, velocity, and acceleration.

Mass

Mass simply means substance, or matter, and is typically measured with the units of pounds (lb) or kilograms (kg). People often interchange mass with weight, but scientifically these terms mean two different things. If an object has substance and occupies space, it has mass. Mass is the quantity of matter that the object takes up. Weight, on the other hand, is this quantity of matter plus the influence of gravity or, more precisely, gravitational force. So for all our studies on Earth, where the acceleration (measured in meters per second squared, m/s2) due to gravity is pretty constant (at 10 m/s2), weight is simply mass multiplied by the gravitational force, 10. For example, someone with a mass of 100 kg will have a force of weight (measured in newtons, N) of 1,000 N. So for coaches, athletes, and sport scientists, mass is the most common term we should use, and weight is the force this mass generates.

We frequently talk of National Football League (NFL) linemen as being massive or having tremendous body mass, indicating that the athletes are enormous and have plenty of muscle, bones, fat, tissue, fluids, and other substances that make up their bodies. Athletes who want to perform well in their chosen events carefully monitor their body mass. They know that too much or too little mass can seriously affect their performance. For all of us, checking our body mass is a means of assessing our general health and fitness. When we get on a scale, the dial gives us a reading that we associate with the amount of body mass that we carry around. A common assumption is that an athlete’s body mass compresses the springs in the scale, and that the readout on the dial represents the amount by which the springs are squeezed together. This is true, but what actually happens is a little more complex, as discussed next.

Weight

In mechanical terms, an athlete’s weight represents the earth’s gravity pulling on the athlete’s body. The readout on the scale represents how much pull or attraction exists between the two. The earth pulls the athlete downward. So an athlete with more body mass compresses the springs to a greater extent than an athlete who has less body mass. As a result the needle on the scale moves farther around the dial.

Inertia

We use the word inertia in everyday life to characterize the behavior of people who are slow to commit themselves to action. So you could say that there’s a relationship between inertia and laziness. In mechanical terms, inertia means more than just laziness because it refers to the “desire” of an object (or an athlete) to continue doing whatever it’s doing. Inertia means resistance to change. If an object is motionless it will “want” to remain motionless. If it’s moving slowly it will want to continue moving slowly, and if it’s moving fast it will want to continue moving fast. If we are looking at something moving, then the mass of the object will directly relate to the inertia. Which is harder to throw, or get moving, a men’s shot put (16 lb or 7.3 kg) or a tennis ball (2 oz or 56 g)? Naturally, the shot put is harder to get moving; so the greater the mass an object has, the more inertia it has too. We must also consider one more important characteristic of inertia. Once on the move, objects always want to move in a straight line. They will not willingly travel around circular pathways; it’s necessary to pull or push on them to produce a curved pathway. A ball thrown by an outfielder would travel in a straight line following its release trajectory were it not for air resistance slowing it down and gravity curving its flight path toward the earth’s surface.

The more massive an athlete, the more the athlete’s body mass resists change. A giant 300 lb (136 kg) athlete needs to exert great muscular force to get his body mass moving. Once moving in a particular direction, the athlete must again produce an immense amount of muscular force to stop or change direction. Athletes with less body mass have less inertia and therefore need to apply less force to get themselves going. Likewise, they need less force than a more massive athlete to maneuver or stop themselves once they’re on the move. There are many examples in everyday life of inertia at work. Oil tankers that cross our oceans have tremendous mass and inertia. They need powerful engines to get them going and huge distances to stop and to turn around. Consider Japanese sumo wrestlers or defensive and offensive linemen in American football. Just like the oil tanker, these athletes must apply tremendous force to get their body mass moving and then apply a huge amount of force to change direction or to maneuver the great masses of their opponents.

In sports like squash or badminton, it’s possible for the immense mass and inertia of huge athletes to work against them. It’s no good being massive when sudden and varied movement changes are required unless you have the power to move your mass quickly and to control it once it’s moving. Massive athletes tend to have a poorer strength-to-mass ratio than do smaller, less massive athletes; so they have a tougher time stopping, starting, and changing direction. That’s why badminton and squash players are lean, lightweight, and anything but massive. If you’re a small, lightweight squash player, you can get a lot of pleasure from making your massive opponent crash into the side walls. You have a friend helping you in the court—your opponent’s inertia!

An interesting example of inertia at work occurs when athletes are in flight. Consider two athletes who decide to bungee jump from a bridge. One athlete is twice as massive as the other. They step off the bridge at the same instant. Surprisingly, they accelerate toward the earth at approximately the same rate. Because the earth attracts the more massive bungee jumper twice as much, you might think that this athlete would accelerate downward twice as fast. But this same athlete has twice the inertia of the other thrill seeker and so resists being accelerated by gravity twice as much. In this situation, air resistance plays a negligible role, and the two athletes accelerate downward at approximately the same rate.

Think of inertia as an enemy when an athlete wants to get moving. To defeat this enemy, it’s good if the athlete’s mass is made up of powerful muscles that are able to generate the required amount of force. Once the athlete is on the move, inertia can become a friend because the second characteristic of inertia is that it wants to keep the athlete going. The difference between resting inertia and moving inertia causes athletes to expend much more energy at the start of a 100 m dash than when sprinting in the middle of the race. The two characteristics of inertia, resistance to motion and then persistence in motion, are seen not only in linear situations in which objects and athletes move in a straight line, but also in rotary situations when objects such as bats and clubs are made to follow a circular pathway. As long as the athlete makes a baseball bat travel around in an arc, the bat will try to continue moving along this circular pathway. If the bat slips out of the athlete’s hands, it will immediately go back to its initial preference, which is to move at a constant speed along a straight line.

In linear movement, mass is synonymous with inertia. The more mass, the more inertia. The characteristics of inertia are described in the first of Isaac Newton’s three famous laws of motion. We commonly call it Newton’s first law, Newton’s law of inertia, or simply Newton I. This law also applies to rotary situations. But rotary inertia (also called rotary resistance or moment of inertia) involves more than just the mass of the object. We also need to know how the mass is distributed (i.e., spread out or compressed) relative to the axis around which the object is spinning. Chapter 4 will cover rotational movement.

Figure 2.1 A wheelchair athlete exhibits a combination of angular and linear motion.

Linear and Angular Motion

The movement of an object can be classified in three different ways. Movement can be linear (in a straight line), angular (in a circular or rotary fashion), or a mix of linear and angular, which we simply call general motion. In sport, a mix of linear and angular movement is most common.

Angular movement plays the dominant role because most of an athlete’s movements result from the swinging, turning action of the athlete’s limbs as they rotate around the joints.

Linear motion describes a situation in which movement occurs in a straight line. Linear motion can also be called translation, but only if all parts of the object or the athlete move the same distance, in the same direction, and in the same time frame. As you can imagine, translation rarely occurs in an athlete’s movement because some parts of an athlete’s body can be moving faster than other parts and not always exactly in the same direction. For example, an athlete in the 100 m sprint wants to travel the shortest distance from the start to the finish. The shortest distance is a straight line. Yet sprinting is produced by a rotary motion of the limbs as they pivot at the athlete’s joints, and the athlete’s center of gravity rises and falls during each stride.

Many terms are used to refer to angular motion. Coaches talk of athletes rotating, spinning, swinging, circling, turning, rolling, pirouetting, somersaulting, and twisting. All of these terms indicate that an object or an athlete is turning through an angle, or number of degrees. In sports such as gymnastics, skateboarding, basketball, diving, figure skating, and ballet, the movements used by athletes include quarter turns (90 degrees); half turns (180 degrees); and full turns, or “revs” (revolutions), which are multiples of 360 degrees. Slam dunk competitions are a great example of basketball players showing off their “360s.”

To produce angular motion, movement has to occur around an axis. You can think of an axis as the axle of a wheel or the hinge on a door. An athlete’s body has many joints, and they all act as axes. The most visible rotary motion occurs in the arms and legs. The upper arm rotates at the shoulder joint, the lower arm at the elbow joint, and the hand at the wrist. The hip joint acts as an axis for the leg, the knee for the lower leg, and the ankle for the foot. Movements like walking and running depend on the rotary motion of each segment (e.g., foot, lower leg, and thigh) of an athlete’s limbs as they rotate around the joints.

All human motion is best described as general motion, a combination of linear and angular motion. Even those sport skills that require an athlete to hold a set position involve various amounts of linear and angular motion. A gymnast balancing on a beam and the aerodynamic crouch position during the acceleration prior to takeoff in ski jumping are good examples. In maintaining balance on the beam, the gymnast still moves, however slightly. This movement may contain some linear motion but will be made up primarily of angular motion occurring around the axes of the gymnast's joints and where the gymnast's feet contact the beam. The ski jumper holding a crouched position attempts to reduce air resistance to a minimum and accelerate as much as possible prior to takeoff. Sliding down the inrun holding a crouched position is a good example of linear motion. But the athlete never fully maintains the same body position throughout, and the inrun is not straight throughout, so any motion that the ski jumper makes will be angular in character.

Perhaps the most visible combination of angular and linear motion occurs in a wheelchair race. The swinging, repetitive angular motion of the athlete's arms rotates the wheels. The motion of the wheels carries both the athlete and the chair along the track. Down the straightaway, the athlete and chair can be moving in a linear fashion. At the same time the wheels and the athlete's arms exhibit angular motion (see figure 2.1). This combination of angular and linear motion is an example of general motion.

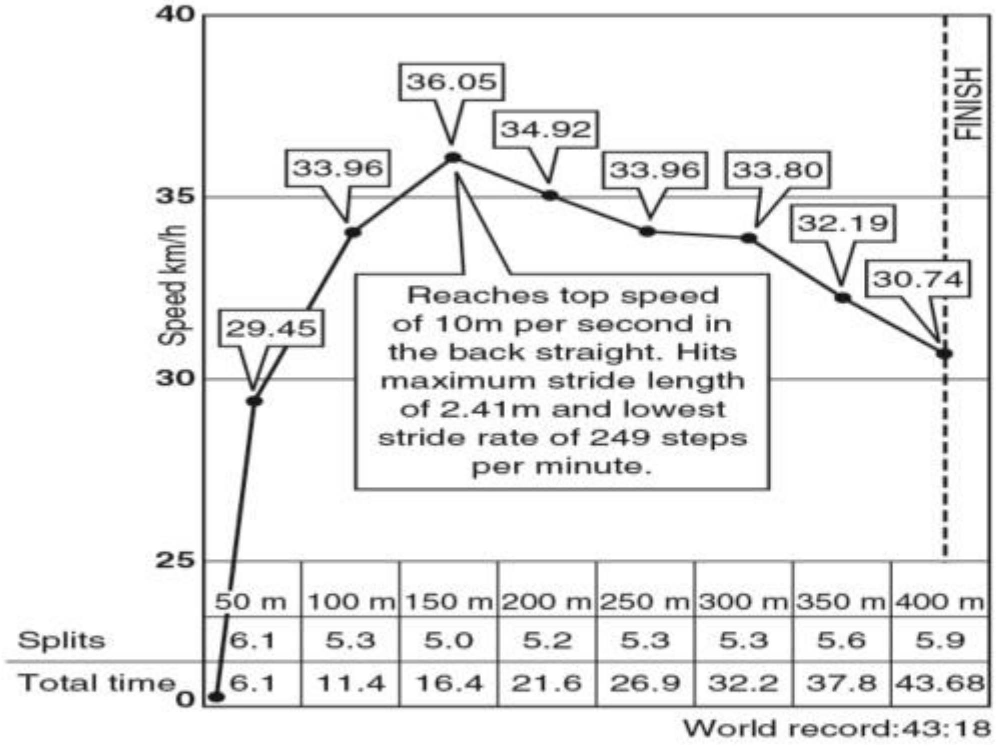
Speed, Velocity, and Acceleration

Just as the terms mass and weight are interchanged (sometimes incorrectly), a similar situation occurs with speed and velocity. While both terms indicate how fast an object is traveling, with respect to time, they have subtle differences. Speed is a scalar measure indicating how fast an object is traveling, measured by dividing the length or distance traveled by the time; but speed does not quantify the direction of travel. Velocity, on the other hand, is the change in position divided by the time.

If an elite sprinter runs 100 m in 10 s, we know that the athlete has run a certain distance (100 m, or 109.4 yd) in a certain time (10 s). From this information you can work out the sprinter's average speed, which is 10 m/s (10.9 yd/s), or 36 km/h (22.4 mph). And in running 100 m on a straight track, since the direction of travel is in a straight and consistent line, the change in position is also 100 m, so there is really no difference in calculating speed and calculating velocity in this instance. However, sometimes we need to know in which direction, as well as how fast, the object is traveling (i.e., north or south or positive or negative). In these situations, velocity is the better term to use. For example, when kicking a ball, as the ball takes off we can look at how fast the ball is traveling in the horizontal direction, in the vertical direction, and the resultant of these two components. To measure how fast the ball travels in these planes, we measure velocity, not speed.

The velocity that the sprinter averaged over a distance of 100 m is 22.4 mph (36 km/h)—nothing more. These numbers don't tell you the sprinter's top velocity, which could be as high as 26 mph (42 km/h), and they don't tell you anything about the sprinter's acceleration or deceleration, which is the rate at which velocity (or speed) changes. A sprinter who averages 22.4 mph over 100 m runs faster and slower than 22.4 mph during different phases of the race. Why? Because immediately after the starter's gun goes off, the athlete is gaining velocity and for a while runs much slower than 22.4 mph. The athlete then has to run faster somewhere else in the race to average 22.4 mph over the whole distance.

Rates of acceleration vary dramatically from one athlete to another. Some athletes rocket out of the blocks and have tremendous acceleration over the first 40 m of a 100 m race. Thereafter their rate of acceleration drops off, and close to the tape they may even decelerate. Athletes who raced against multiple Olympic champion Carl Lewis were well aware that he could still be accelerating at the 70 m mark in the 100 m dash. His rate of acceleration may have been less than that of his opponents at the start of the race, but his acceleration continued longer. Over the last 30 m, Lewis frequently caught and passed athletes who were "tying up" (i.e., breaking proper form because of fatigue) and decelerating. In the 400 m event, the 50 m velocity measures for Michael Johnson as he broke the 400 m world record in the time of 43.18 s in 1999 are shown in figure 2.2 (note that this world-record time was not broken at the 2008 Beijing Olympic Games). Johnson's maximum velocity was at the 150 m mark, and the key difference between Johnson and the opposition was also the smaller amount of drop-off between each 50 m interval.



	50 m	100 m	150 m	200 m	250 m	300 m	350 m	400 m
Splits	6.1	5.3	5.0	5.2	5.3	5.3	5.6	5.9
Total time	6.1	11.4	16.4	21.6	26.9	32.2	37.8	43.68

Figure 2.2 The velocity profile of Michael Johnson's 400 m world record set in 1999.

It is possible for athletes to reduce their rate of acceleration and still increase velocity. As long as acceleration exists, even if it's minimal, velocity will increase. If deceleration occurs, velocity will be reduced. How much an athlete's velocity increases or decreases depends on the rate of acceleration and deceleration.

Uniform acceleration and uniform deceleration mean that an athlete or an object speeds up or slows down at a regular rate. An example of uniform acceleration occurs when a four-man bobsled slides down the track in the Winter Olympics and accelerates to a speed of 15 ft/s (4.6 m/s) by the first second, 30 ft/s (9.1 m/s) by the second, and 45 ft/s (13.7 m/s) by the third. For every second that the bobsled is moving, it is increasing speed at a uniform rate of 15 ft/s. You write this acceleration as 15 ft/s/s, or 15 ft/s2 (4.6 m/s/s, or 4.6 m/s2). Notice that there is one distance unit (i.e., 15 ft) and there are two time units (i.e., s/s) whenever you refer to acceleration. This indicates the rate of change of velocity, or the amount of velocity added (i.e., 15 ft/s), with each successive time unit (i.e., 1 s) that passes. If the bobsled decelerates at a uniform rate, then the reverse occurs. In this case it is slowing, or losing velocity, at a uniform rate.

Uniform acceleration and deceleration do not happen that often in sport. When athletes (or objects such as balls or javelins) are on the move, varying oppositional forces, ranging from opponents to air resistance, cause their acceleration (or deceleration) to be varied or, in other words, nonuniform. However, one of the best examples of uniform acceleration and deceleration occurs in flights of short duration such as in high jump, long jump, diving, trampoline, and gymnastics. In these situations, air resistance is so minimal as to be considered negligible. Gravity uniformly slows, or decelerates, the athletes as they rise in flight by a speed of 32 ft/s for every 1 s of flight (i.e., 32 ft/s2) and then accelerates them at a uniform rate of 32 ft/s2 on the way down (in the metric system, approximately 32 ft/s2 = 9.8 m/s2). Sometimes you’ll see deceleration described as negative acceleration and acceleration as positive acceleration. A minus sign in front of 32 ft/s2 (i.e., −32 ft/s2) indicates that the diver is decelerating at a rate of 32 ft/s for each second that he is rising in the air.