10.2 Newton's Laws of Motion

Sir Isaac Newton (1642–1727) developed *three* laws to explain the relationship between the forces acting on a body and the motion of a body.

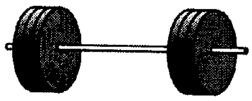
These laws form an important basis for much of the biomechanics in this unit.

A) **LAW ONE**

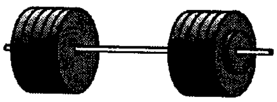
An object at rest tends to remain at rest unless acted upon by some external force.

This is also known as **law of inertia.**

Consider the two objects below. Which has more inertia? Why?



100 kg



175 kg

The 175 kg weight because it has a greater mass hence a greater resistance to a change in its state.

Basically inertia is a *resistance to motion*. It is a product of its mass.

Having a great deal of inertia can be *advantageous* in some sporting situations. Why?

A great deal of inertia can be difficult to overcome so is useful in sports such as sumo, wrestling and scrummaging.

Of course having a lot of inertia has *disadvantages* as well in some sporting situations. Why?

If you or an object, has a lot of inertia, more force or effort is required to get moving. It can also decrease agility (the ability to change direction quickly).

Once an object is moving, inertia affects the object's ability to change direction or indeed its path.

B) **LAW TWO**

When a force acts upon a mass, the result is acceleration of that mass.

A) The greater the force, **the greater the acceleration.**

B) The smaller the mass, **the greater the acceleration** when a constant force is applied.

C) The mass will accelerate in the direction **the force is applied.**

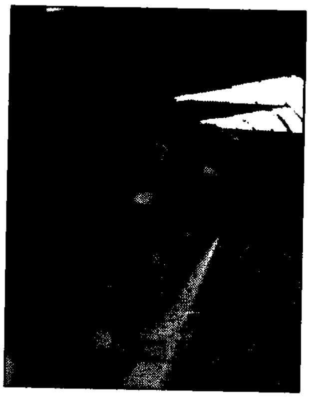
These statements can be summarised by an equation:

F	**=**	**m**	**x**	**a**
(force)	**=**	**(mass)**	**x**	**(acceleration)**

Consider the situation of a serve in tennis, a kick in soccer, a shot at goal in hockey or a pitch in softball.

How can we apply Newton's Second Law to produce a more powerful strike, throw or pitch?

The greater the initial input of force, the greater the acceleration on the object upon contact or release. The longer the lever the greater the force at the extremity, thus greater acceleration on the object on contact or release.



As we will see in later units, this law can be further manipulated by factoring in the length of the lever force arm.

C) **LAW THREE**

For every action, there is an equal and opposite reaction.

We sometimes use this law when we say 'what goes up, must come down!'

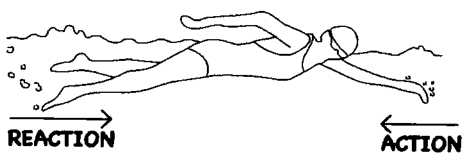
When we apply a force to something, this is known as **an action force.**

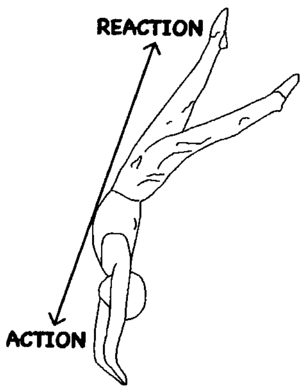
The object we apply a force to, applies a force back is a **reaction force.**

These two forces always work in pairs.

These forces are opposite in direction and equal in size.

On the illustrations below, draw in and label the two forces in action.





We can see these pairs of forces working when we run on sand. We run forward and sand is kicked up behind us in the opposite direction.

These forces are important to almost all sports activities especially in force production, balance and control of movement.

Summary Application of Newton's Law:

A gymnast is running in to complete a vault. How can we apply each of Newton's Laws of Motion to this example?

1st Law - the inertia of the body must be overcome during the run up.

2nd Law - the greater the force applied to the body, the greater the acceleration.

3rd Law - gymnast action force is into the beat-board, reaction force is the board "pushes" back.

10.3 Projectile Motion

Any object released into the air is termed a **projectile.**

All projectiles have a flight path and a flight time depending on how they are affected by the variables below.

A) **Gravity**

Gravity acts on a body to give it mass. The greater the mass of an object the greater the influence of gravity upon it.

What is the effect of gravity on a projectile?

It decreases the height a projectile can attain.

B) **Air Resistance**

Gravity acts on the vertical component of a projectile. That is, the height it is able to reach.

Air resistance acts on the horizontal component of a projectile's path.

In many sporting activities, the effect of air resistance is very small.

C) **Angle of Release**

The angle of release of a projectile determines the flight path.

If the angle of release is high, the projectile:

Has a longer flight time but decreased distance.

If the angle of release is low, the projectile:

Has a less flight time but increased distance.*

(* If angle too low, distance is poor).

Therefore:

Sports in which distance is important have a **lower** angle of release.

Sports in which height or flight time is important have a **higher** angle of release.

How is this applied in golf to club selection?

The long irons (1, 2, 3) have a shallow angle on the club face. They are designed for distance. Short irons (7, 8, 9, wedge) have steeply angled faces to give height and "stopping" ability when the ball lands.

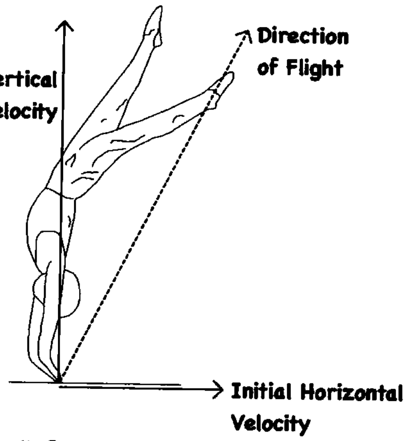
D) **Speed of Release**

Velocity of release will determine the size of the flight path.

Speed of release is divided into two components:

A) Initial Vertical Velocity
B) Initial Horizontal Velocity

(*Draw these in on the illustration*)



What are the advantages of having a high initial vertical velocity?

It results in a longer flight time due to greater height.

What are the advantages of having a high initial horizontal velocity?

Gives greater distance and good flight time.

In which sports would a high initial vertical velocity be of advantage?

Gymnastics tumbling, golf pitch shots, high jump, volleyball spike.

In which sports would a high initial horizontal velocity be of advantage?

Long jump, drive in golf, vaults in gymnastics.

For any given angle of release, speed of release makes a considerable difference to the distance a projectile will travel.

Speed of release can be maximised in order to gain distance by applying other biomechanical principles such as transfer of momentum, sequencing and lengths of levers.

Explain how these can be applied to increase the distance a projectile can be sent.

By sequencing muscle groups in a throw for example, greater velocity can be achieved by the hand, hence ball. By driving with LEGS ⟶ TORSO ⟶ SHOULDER ⟶ ARM ⟶ HAND. The body acts like a whip imparting tremendous forces to the ball. The momentum generated by the legs, torso etc is ultimately transferred to the ball. Longer levers accentuate this. Longer arms mean a longer lever so greater force is ultimately passed to the ball. Consider the force applied to a golf ball with a 1 iron compared to a pitching wedge.

E) **Height of Release**

For a given speed and angle of release, the **greater** the height of release the **greater** the distance gained.

The inter-relationship between height of release and angle of release is important to consider.

Have you ever noticed that tall basketball players shoot the ball at a lot lower angle than shorter players? The reason behind this can be summarised as follows:

1. As the height of release *increases*, the angle of release **decreases** .
2. As the height of release *decreases*, the angle of release **increases**.

Both of these cases assume a given speed of release for both.

F) **Spin**

Consider a game of volleyball. What happens to the flight path of the ball when someone applies topspin to the serve?

It travels then "dips" suddenly.

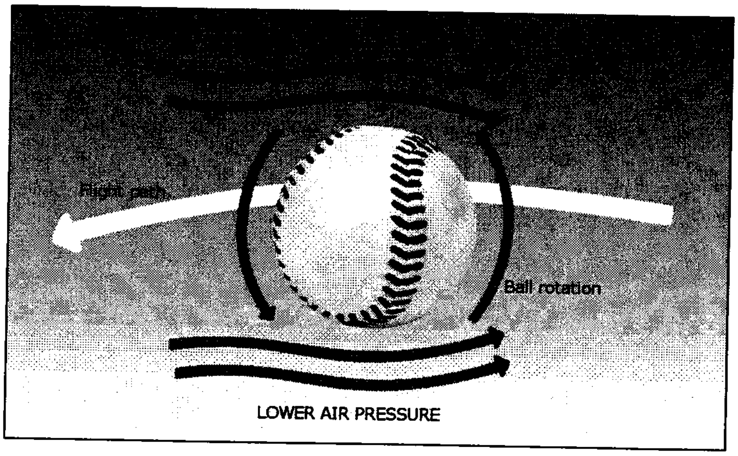
This leads us to the following two principles with respect to projectiles and spin:

1. Range is ___**decreased**___ with topspin.

2. Range is ___**increased**___ with backspin.

The reason a shot with topspin 'dips' suddenly and a backspin shot will travel a greater distance is due to **air pressure.**

A topspin shot creates a region of high pressure on top of the ball and a region of low pressure below. As a consequence, the ball will dip suddenly thereby decreasing the distance attained.

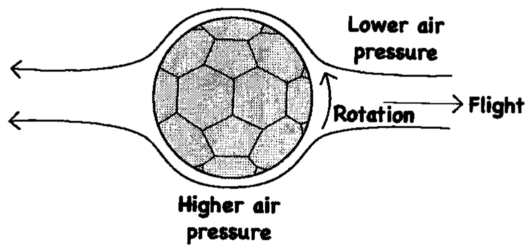


These are known as **magnus forces.**

What will happen with a backspin shot?

A region of high pressure is created under the ball with lower pressure above it. Air pressure moves from (H) to (L) causing it to "float".

Illustrate the effect of backspin on the ball below.



10.4 Stability and Balance

For the purposes of this section, we will consider **rotary stability**.

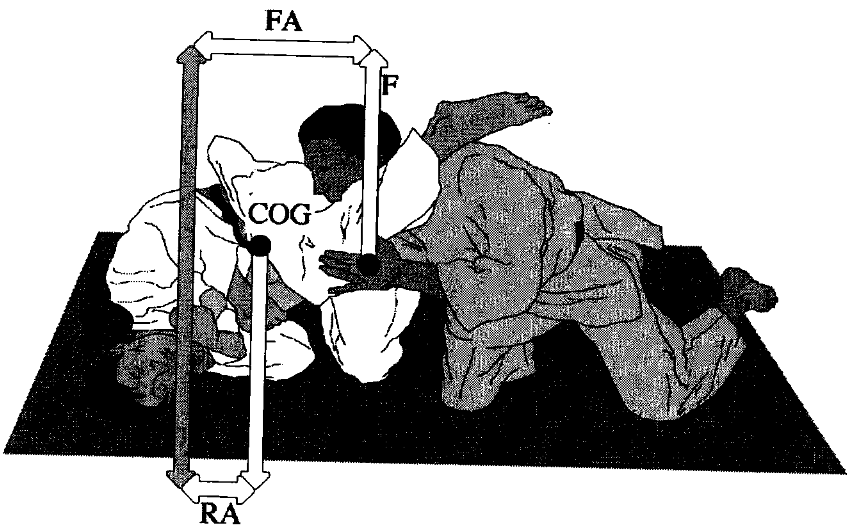
Rotary stability is the resistance an athlete has to **resistance of an object or athlete to tilt, tipping, up-ending or spinning.**

Clearly then, rotary stability is important in sports such as gymnastics, martial arts and aspects of kayaking.

Rotary stability comes back to the topic of torques. An athlete wants to keep rotary stability as high as possible in order to maintain their balance or position.

The athlete therefore is in a battle of torques either with themself, as in gymnastics or against an opponent as in wrestling and the martial arts.

Consider the wrestling example below:



Note that both the Resistance Arm (RA) and Force Arm (FA) act through the point of contact with the ground of the defender i.e. shoulder

The total torque of the aggressor (dark) is greater than the resistance torque of the defender (light).

The following factors could be applied in this instance to increasing rotary stability or balance.

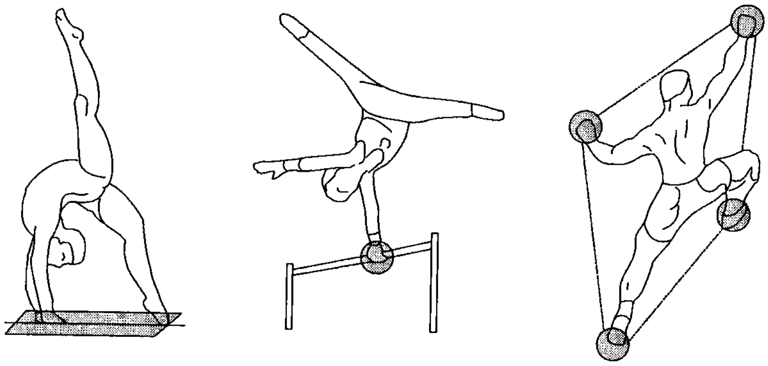
A) **Factor 1**

Athletes can increase their stability if they increase the size of their base of support.

Base of Support (BOS) is defined as:

The area on the ground defined by the athletes contact with it.

Draw in the BOS for each of the skills below.



Why is a body more stable if the base of support is larger?

Because the centre of gravity has further to travel before it approaches the margins of the BOS consequently, further to travel before stability decreases.

B) **Factor 2**

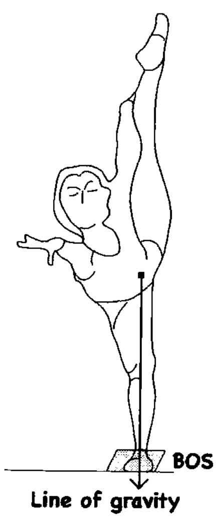
Athletes can increase their stability when the line of gravity falls within the margins of the base of support.

In some activities, the margins of the base of support are small so the COG only has to move a little before torques come into play that can upset stability.

Consider the example to the right. Draw in the line of gravity and the BOS.

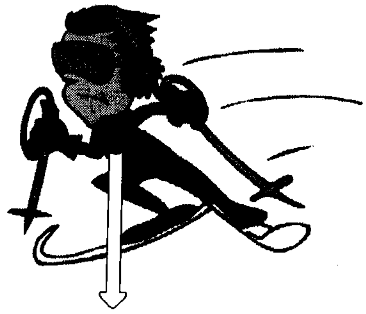
How does the gymnast keep their line of gravity inside the margins of the BOS?

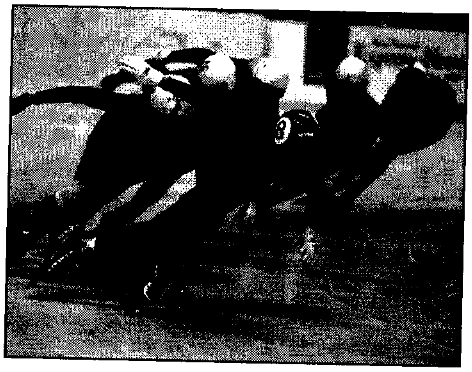
Small adjustments of the body move the line of gravity.



Of course, the COG and hence the line of gravity does not always have to stay inside the BOS to be stable.

Consider the skier and the skaters below and the turns they are required to make or the sprinter who leans into the curve in a 200 metres race.





Why is this still considered stable even though the line of gravity is clearly outside the BOS? (*Hint: Think of the factors that act on an object that is moving in a circular path*).

This is an example of dynamic equilibrium. It is a balancing act between the forces acting into the curve and those acting outward i.e. centripetal and centrifugal.

Generally, the faster an object moves around a curve or the tighter the curve is, the more they tend to lean inwards to retain stability.

C) **Factor 3**

Athletes can increase their stability when they lower their COG with respect to the base of support.

Why does this increase stability?

Because the distance the line of gravity has to travel before reaching the margins of the BOS is larger, thus stability is improved.

This is important in sports such as judo and wrestling where stability is crucial.

Tall kayakers are at a disadvantage over their shorter competitors. Why? How might this be addressed?

Because their COG with respect to the BOS (hull) is higher in taller kayakers. Solved by a wider beam kayak to increase area of BOS.

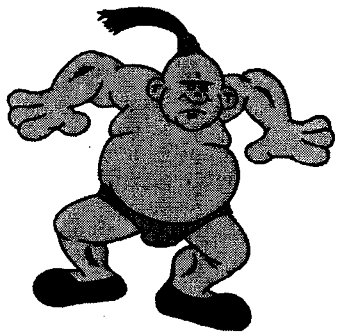
D) **Factor 4**

Athletes can increase their stability by increasing their mass.

Clearly, in many sports, an increase in body mass is either not possible or desirable. However in other sports such as sumo, judo or a rugby forward, a more massive person is advantaged over a lighter one.

Explain why.

Because their inertia is greater. This requires more force by an opponent to move the line of gravity.



E) **Factor 5**

Athletes can increase their stability when they extend their BOS in the direction of an oncoming force or direction in which a force is applied.

We might see this in cases where a rugby player steps into an oncoming tackler to try to avoid being tackled.

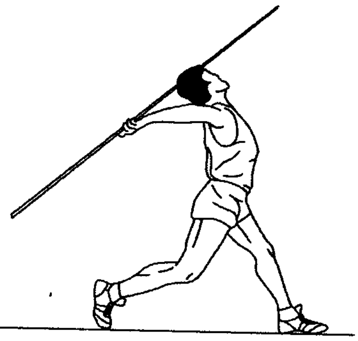
How does this work?

By stepping into the force. The size of the BOS is increased. Any shift in your COG can be accommodated.

Equally if you watch throwing events such a javelin or sports with throwing such as baseball you may notice they take a large step in the direction they are throwing. We also notice that the harder the throw, the larger the step taken.

How does this work?

Gives them a wider BOS and allows them to apply force over a considerable distance without losing balance.



F) **Factor 6**

Athletes can increase their stability when they move their line of gravity towards an oncoming force.

This is similar in rationale to Factor 5 (above). We see it when a player leans into an oncoming tackle in rugby for example.

How might this work?

So at the point of impact, the COG moves in the direction the force was applied. It moves back closer to the middle of the BOS.

How would this factor work in the case of a judo match where you are leaning into your opponent and they step back to *pull you* rather than *push you*?

Explain the action that could be taken.

If you can sense a pull might occur rather than a push, quickly shift your COG in the opposing direction and widen your BOS to become stable again.

10.5 The Biomechanics of Rotation

Rotational movements play an important part in all sports skills. Rotation does not necessarily have to refer to the whole body spinning or twisting like we are familiar with in gymnastics or diving but it is equally evident in the spinning of balls and the use of the body and equipment as levers.

This section considers many elements of Year 12 Physical Education with some more detail and greater sporting applications.

This unit considers Centre of Gravity, axes of rotation, levers, torque, initiating rotation, angular velocity, angular/rotary inertia, centripetal and centrifugal forces and angular momentum.

A) **Centre of Gravity**

Centre of Gravity is defined as:

That point in the body about which all parts of the body are in balance OR the point at which gravity is centred.

The Centre of Gravity (COG) is not confined to one location. As the body moves, so the COG moves with it in the direction the movement occurs.

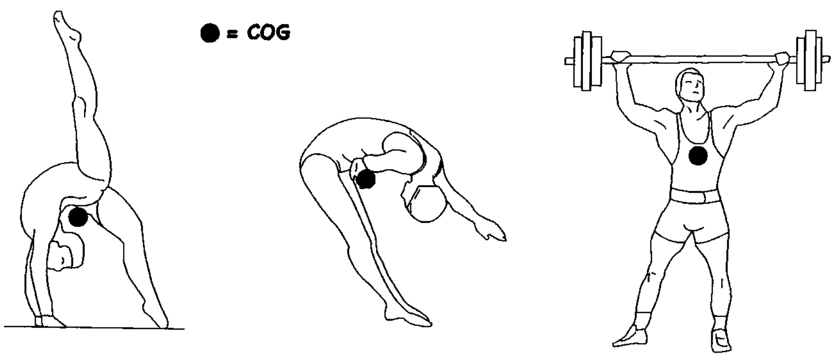
If an athlete steps forward, the COG will move forward also as the body redistributes its mass.

If the athlete moves an arm and a leg in stepping forward, how will the COG move?

It moves in the direction of the body part.

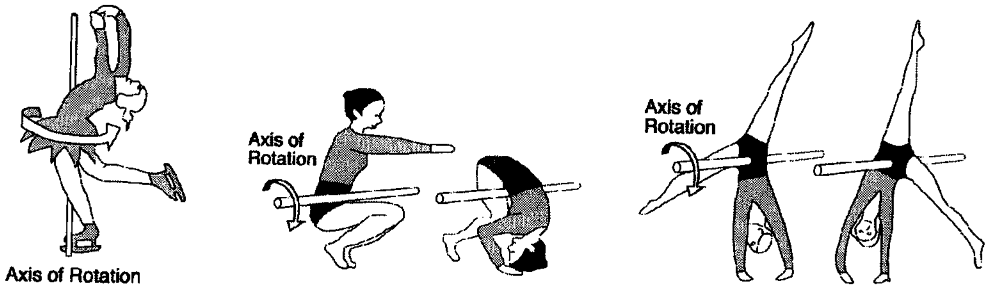
Basically the greater the mass moved, the further the COG will move in that direction.

Draw in the positions of the COG in the illustrations below:

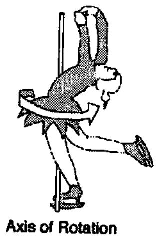
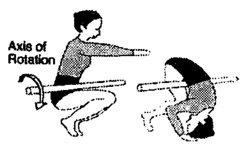
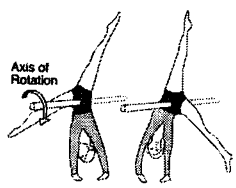


The axes of rotation of the body act through the COG also.

Consider the three movements below. They each represent one of the three axes of rotation.



Identify the axis of rotation and appropriate sporting movements for each.

AXIS OF ROTATION	SPORTING EXAMPLES
LONGITUDINAL	**Pirouette in dance.** **Twist in diving/gymnastics.** **Spinning in skating.** 
TRANSVERSE	**Forward Roll.** **Backward somersault.** **Rotation on a bar about the hips.** 
SAGITTAL	**Cartwheel.** **Cricket bowl.** 

B) **Levers**

Recall that levers are designed to allow either a greater resistance to be moved with a given force or to increase the velocity at which an object can be moved using a given force. A crowbar might be an example of the former and a golf club an example of the latter.

Levers consist of three parts:

A) **Resistance**

B) **Effort or Force**

C) **Fulcrum (Pivot)**

Importantly for levers and the actions they produce, this creates a *force arm* (FA) and a *resistance arm* (RA).

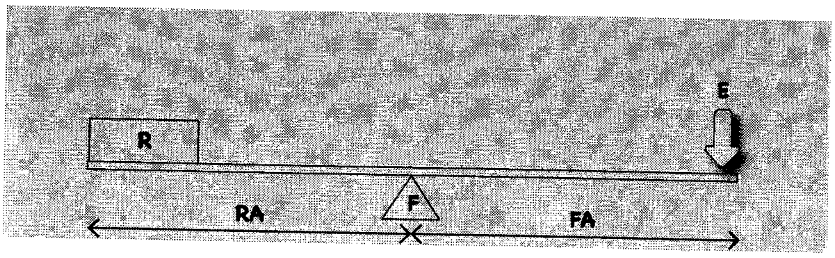
A *force arm* (FA) is defined as:

The distance from where a force is applied to the fulcrum.

A *resistance arm* (RA) is defined as:

The distance from where a resistance acts to the fulcrum.

On the simple lever below, label/draw in these five aspects of a lever.



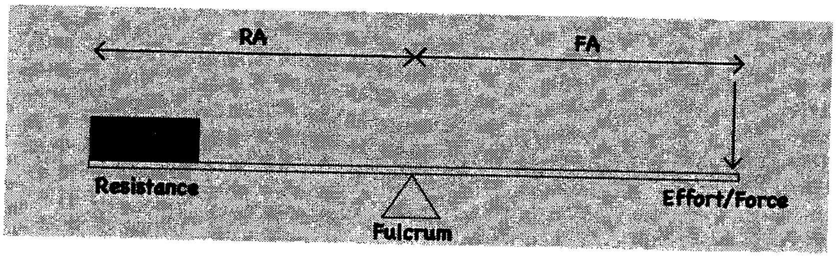
The relationship between force arm length, with respect to the resistance arm length is important when we consider what the function of the lever is. That is, are we after maximum speed with a given effort or moving a greater resistance with a given force?

Consider the three classes of lever:

A) First Class
B) Second Class
C) Third Class

1. **FIRST CLASS**

In the space below, draw a simple first class lever illustrating the pivot, resistance, force, force arm and resistance arm.



The characteristics of a first class lever are:

the fulcrum or pivot lies between the resistance and the point of effort. The FA and RA can be equal in length but not necessarily so.

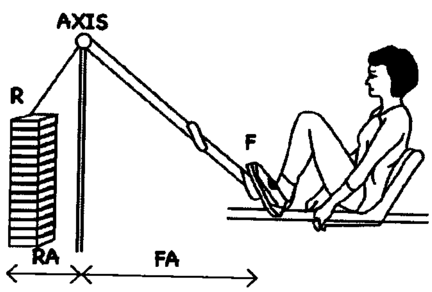
What is the purpose of the lever if the force arm is *shorter* than the resistance arm?

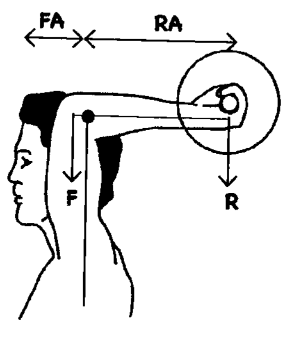
This favours speed and range of movement e.g. golf club.

What is the purpose of the lever if the force arm is *longer* than the resistance arm?

This favours force output. You get more out than you put in.

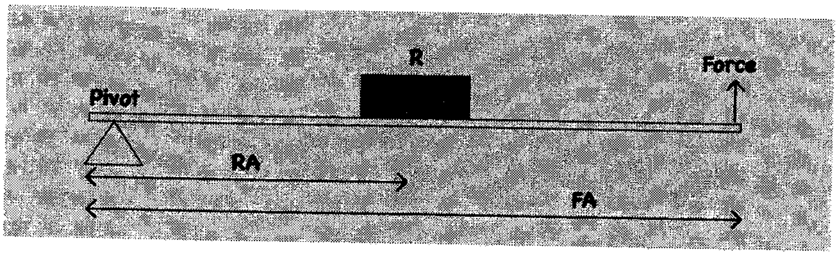
For each of the first class levers below, indicate the resistance arm and the force arm in order to determine the purpose of the lever.





2. **SECOND CLASS**

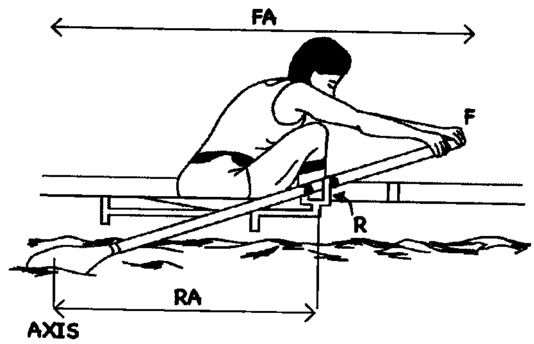
In the space below, draw a simple second class lever illustrating the pivot, resistance, force, force arm and resistance arm.



The characteristics of a second class lever are:

The resistance lies between the pivot and point of force application. Consequently, the force arm and resistance arm are on the same side of the lever. The FA is always longer than RA.

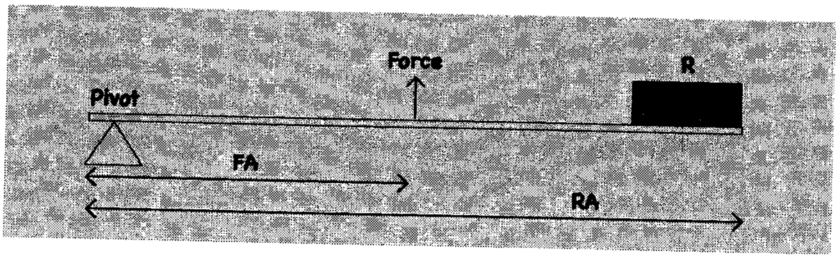
For the second class lever below, indicate the resistance arm and the force arm.



Give some more sporting examples of second class levers below. Draw in the lever components.

3. **THIRD CLASS**

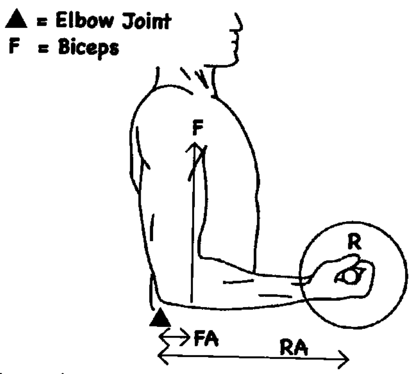
In the space below, draw a simple first class lever illustrating the pivot, resistance, force, force arm and resistance arm.

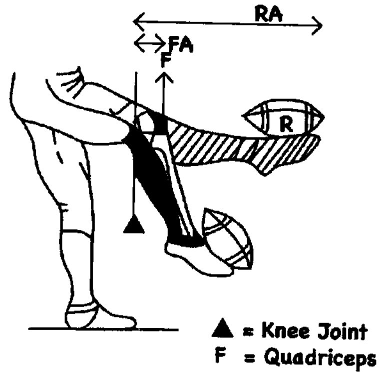


The characteristics of a third class lever are:

The force lies between the resistance and the fulcrum or pivot. The force arm is shorter than the resistance arm. In third class levers, the force applied is always greater than the resistance.

For each of the third class levers below, indicate the resistance arm and the force arm.





From these illustrations, what can we say about the function of a third class lever?

To generate speed over distance at the point of resistance for a given force.

What other examples of third class levers can you identify?

Swinging a golf club, discus throw, pitching in softball or baseball, crucifix position in rings.

What are the advantages of having long arms in a sport such as baseball, in particular pitching?

A longer limb means a longer third class lever. The resistance arm will be longer giving more speed to resistance.

How could a pitcher with long arms, become even more effective in terms of the speed of the pitch?

Increasing muscle bulk about the shoulders would increase the force applied. This coupled to the long lever means the extremity moves with grater velocity so more momentum can be passed to the ball.

Given this information, describe the physical characteristics of Olympic discus throwers and good fast bowlers in cricket.

Tall with long limbs and well developed about these long levers to generate force.

Gymnasts are usually small with relatively short arms and legs but they are extremely well muscled around the hips and shoulders. How might this prove an advantage with respect to levers?

The levers are shorter and lighter but with tremendous force capability. Of considerable benefit in static moves in gymnastics, such as rings.

C) **Torque**

Because all levers produce rotation about an axis, they also produce torque.

Torque is defined as **a turning force.**

The distance from the axis of rotation that the force is applied is given as torque and can be summarised by the following equation:

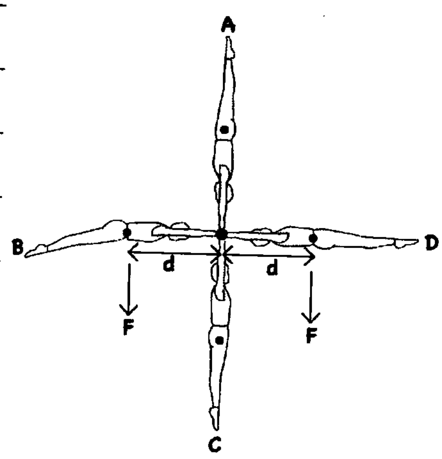
T	=	F	x	d
(Torque)	=	(Force)	x	(distance)

The greater the force applied to a given force arm, **the greater the torque.**

The longer the force arm with a given force applied, **the greater the torque.**

On the illustration below of a gymnast performing a giant circle on the high bar, indicate where torque would be at its highest and lowest and explain why.

Because gravity (force) acts vertically downward at all points, the gymnast has the greatest torque at B and D because it is the greatest distance from the point of rotation (the bar).



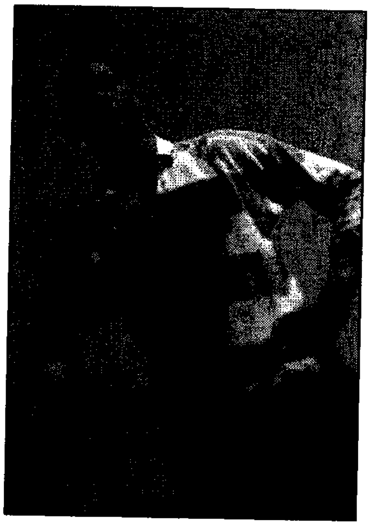
Would a taller gymnast produce more or less torque in a giant circle? Explain why.

More torque because the distance of the COG from the axis of rotation (it will be greater).

In rugby, or rugby league, there is the expression, "the bigger they are, the harder they fall".

Explain using torques how this saying is in fact true.

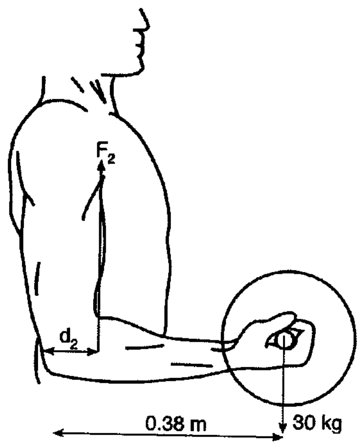
If we tackle about the ankles, the distance to the COG is greater in taller players. Their mass might also be greater meaning a greater torque.



Use your understanding of torques to explain what must occur for the 30 kilogram weight to be lifted in a biceps curl.

Note: F_2 refers to the force generated by biceps and d_2 is the distance from biceps insertion to the elbow joint.

Resistance torque = 30 kg x 0.38 m which is 11.4 kgm^{-1}. Therefore, F_2 x d_2 must be greater than 11.4 kgm^{-1}. That is, the force arm torque must be greater than the resistance arm torque.



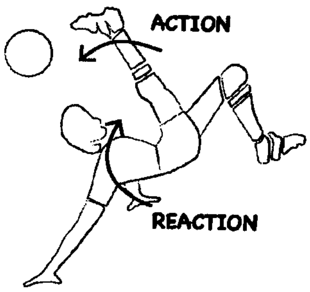
Therefore, in order to move a resistance, the torque generated by the athlete must be greater than the torque generated by the resistance to be moved.

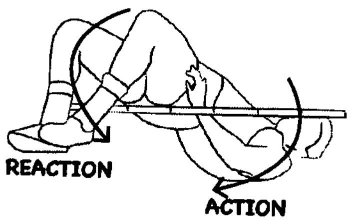
In certain sports where rotary motion occurs in the air, torques need to balance in order for control of motion to occur. These sports include heading a soccer ball, the spike in volleyball, long jump, flights on or off a box in gymnastics, or a slam dunk in basketball.

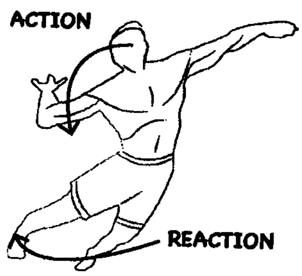
Here, we apply Newton's Law of action-reaction to torques. That is:

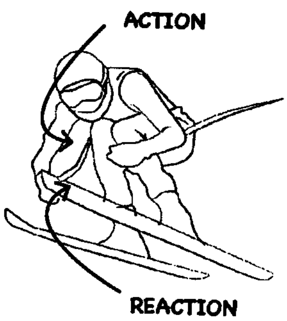
For every torque on some part of the body, there must be an equal and opposite force on another.

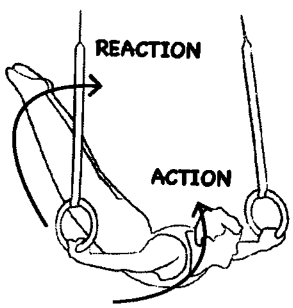
Indicate the equal and opposite torques on the following examples of rotational motion.

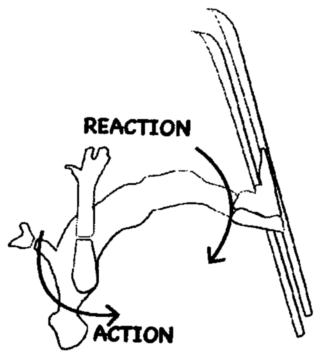


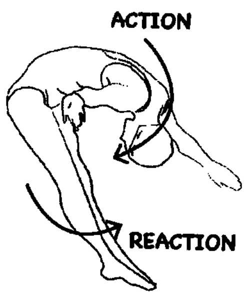










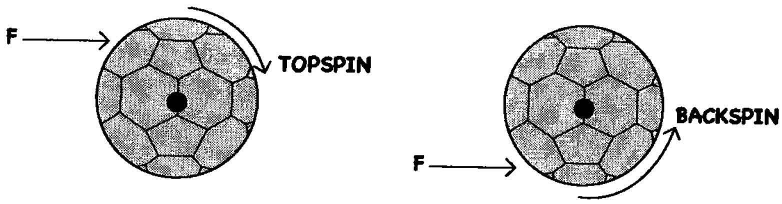


D) **Initiating Rotation**

In order to initiate rotation on any object, or the human body, an *eccentric* force must be applied.

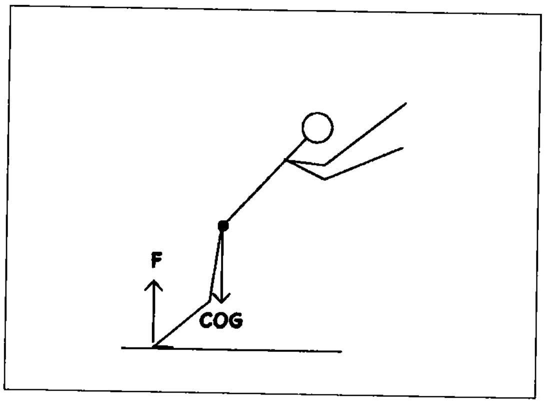
An *eccentric force* is **a force applied away from the COG.**

On the illustrations below, draw in the position of the force that needs to be applied in order to generate topspin and backspin on the balls below.



Draw in the body position of the athlete in order to initiate a dive roll in gymnastics.
Explain this position.

The force applied acts behind the COG causing forward rotation to be initiated.



How can an athlete initiate more rotation to the body, or object?

By applying the force a greater distance from the COG or by increasing the input of force when it is applied.

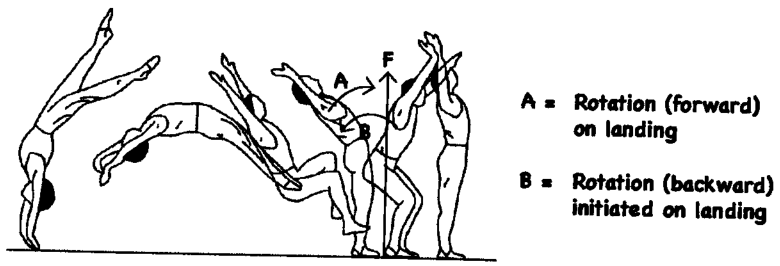
In sports such as golf, the club face aids in the amount of spin given to the ball. Nine irons and pitching wedges help with backspin by applying the force further away from the COG of the ball than other clubs.

Eccentric forces are also used to help cancel out rotation when the body lands in sports such as gymnastics and long jump.

How does this happen?

By landing in such a way that force is applied in front of the COG, backward rotation is initiated thereby "cancelling out" some of the forward rotation.

On the illustration below, draw in the eccentric force required to cancel out rotational force still present at landing.



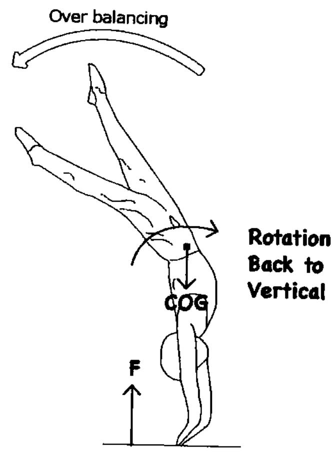
Note that the eccentric force is applied in front of the COG in order to generate rotation in the direction opposite to the handspring.

This is of course very important in sports such as gymnastics where landing is an important part of the overall aesthetic of the skill.

Consider the gymnast in the handstand position below. Maintenance of this position is very important in execution of some skills. If the gymnast feels that they may overbalance, how can they apply eccentric forces to counter this?

Draw in these forces on the illustration and explain your answer.

By pushing against the floor with their fingers they can generate small eccentric forces about the COG rotating the body back to vertical. Because the COG is high, these forces only need to be small. The greater the overbalancing forces, the greater the forces about the wrists to counteract it.



E) **Angular Velocity and Speed of Rotation**

Angular velocity is defined as:

The rate of spin of an athlete or object as they move in a particular direction.

Speed of rotation is defined as:

How quickly parts of an object or athlete move in a rotational movement.

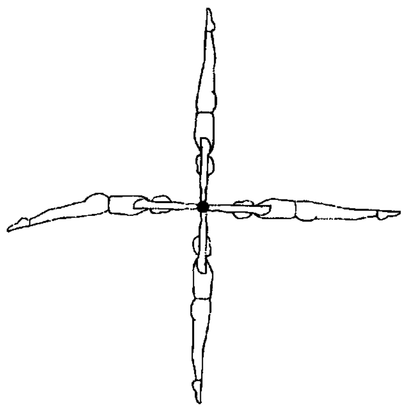
Speed of rotation of an object increases the further it is away from the axis of rotation.

Speed of rotation of an object increases the greater the angular velocity.

Consider the gymnast on the high bar once more. What is the angular velocity of the hands, hips and feet with respect to each other? Explain why.

What is the speed of rotation of the hands, hips and feet with respect to each other? Explain why.

Angular velocity of hands, hip and feet remains the same (assuming the gymnast is rigid). He moves through the same angles in the same time. The speed of rotation of his feet is greater than his hips, which in turn is greater than his hands. His feet "look" to be moving faster.



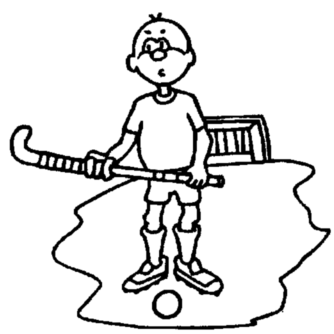
Speed of rotation of an object, or part of an object is a product of angular velocity and the radius of the object, or part of the object from the axis of rotation.

How can we apply this to a serve in tennis if we want to hit the ball as hard as possible? Explain why.

The higher up we can hit the ball in our serve the better. The lever is longer meaning the extremity will travel faster. Gripping the racquet low down increases its length. Swinging the racquet as fast as possible increases angular velocity.

A hockey player wants to hit the ball as far as possible. They have a choice between a 35, 36 and 37.5 inch stick. Which would generate the greatest head speed (assuming the angular velocity is constant)? Explain why.

The 37.5 inch stick because the head is further from the point of rotation so speed of rotation will be greater.



How could the hockey player maximise the stick head speed still further?

Swing the stick harder to increase angular velocity. Take a long grip, not a choke grip. This gives a longer lever radius.

Of course with increasing speeds and radius come problems of control.

This is best illustrated through the concepts of inertia, centrifugal and centripetal forces in the next section.

F) **Inertia, Centrifugal and Centripetal Forces**

When an object rotates, be it a body or a piece of equipment such as a softball bat, it has inertia.

Inertia is defined as:

The tendency of object or athlete to either stay at rest or to move continuously in a straight line at a uniform velocity.

However, when an object rotates about an axis, it has a tendency to want to break away from this curved path and return to its linear one. Consequently, an equal and opposite force must be applied to keep it on its curved path. These are centrifugal and centripetal forces.

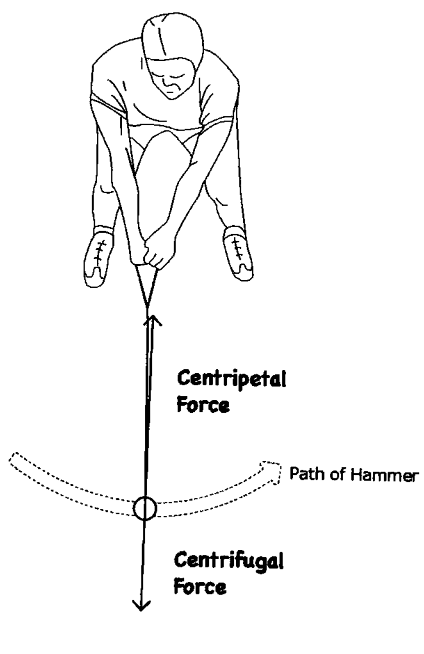
Centrifugal force is defined as:

The force that tries to move an object in a straight line rather than around a circular path. It acts outward.

Centripetal force is defined as:

A force acting inwards towards the axis of rotation which keeps it on its rotary path.

Draw these forces on the hammer thrower below.



Centrifugal and centripetal forces need to be equal and opposite to each other.

Consider the athlete swinging a softball bat. If centrifugal force were greater than centripetal force, what would happen?

The bat would fly out of their hand.

Often we find softball, or baseball batters using pine resin which is sticky to increase the grip on the bat. Bats also have a knob on the end that the hand can work up against to decrease the probability of the bat flying out of the hands.

There is an inter-relationship between rotary inertia, centrifugal force and centripetal force.

The equation for calculating the inertia of a rotating body is:

$$I = mr^2$$

Inertia (rotary) = mass x (radius of rotation)²

Clearly, this rotary inertia helps produce the centrifugal force that tries to turn the curved path of the object into a straight line path. Sufficient centripetal force must be generated by the athlete to resist this.

Consider the hammer thrower previously. Initially they use a 20 kg hammer then move up to a 25 kg hammer. If the length of the hammer from handle to shot is 1.2 metres, calculate the inertia of each hammer.

20 kg HAMMER

$$I = mr^2 = 20 \text{ kg} \times (1.2)^2 = 28.8 \text{ kgm}^2$$

25 kg HAMMER

$$I = mr^2 = 25 \text{ kg} \times (1.2)^2 = 36 \text{ kgm}^2$$

This requires the athlete to produce sufficient centripetal force to help keep the hammer on its circular path.

Equally, if an athlete increases their angular velocity, i.e. rotates faster then centripetal force increases by the square of the angular velocity.

Therefore, centripetal force (generated by the athlete) needs to increase if:

A) **the mass increases.**

B) **angular velocity increases.**

C) **the radial distribution of mass increases.**

We can apply all these factors to any sport that involves an object rotating about an axis. Centripetal force will need to be generated by the athlete to hold on to racquets, clubs, sticks, or bars.

We note that many gymnasts are quite short in stature and light weight. Taller and/or heavier gymnasts generate problems when it comes to rotary motion.

Consider a gymnast rotating on the high bar.

Gymnast A is 45 kg and has the COG rotating 1.2 metres from the bar.

Gymnast B is 45 kg but has grown and now has the COG rotating 1.3 metres from the bar.

Gymnast C keeps the COG 1.3 metres from the bar but has increased body mass to 50 kg.

In each case, calculate the inertia of each athlete and indicate which needs to generate the most centripetal force to stay on the high bar.

GYMNAST A	**GYMNAST B**	**GYMNAST C**
$I = mr^2$	$I = mr^2$	$I = mr^2$
$= 45\ kg \times (1.2m)^2$	$= 45\ kg \times (1.3m)^2$	$= 50\ kg \times (1.3m)^2$
$= 64.8\ kgm^2$	$= 76.1\ kgm^2$	$= 84.5\ kgm^2$

Clearly, GYMNAST C has the most work to do. Sudden changes in weight or height for a gymnast often requires a lot of re-training of skills.

G) **Controlling Rotation**

Once the body is rotating, control of the rotation is achieved through the redistribution of mass about the centre of gravity or axis of rotation.

When the mass is distributed *closer* to the axis of rotation, or the COG:

A) Angular velocity **increases**

B) Rotary Inertia **decreases**

When the mass is distributed *further away from* the axis of rotation, or the COG:

A) Angular velocity **decreases**

B) Rotary Inertia **increases**

We see this illustrated in gymnastics tumbling where the degree of "openness" or "tuck" determines how quickly the body will somersault.

In diving, if an athlete wishes to complete more somersaults on the descent, what should they do?

Tuck tighter and/or increase initial eccentric force.

If an gymnast performing a somersault dismount off the high bar remains tucked for too long, what may happen?

Over rotation causing a missed landing or stepping on landing.

Why do good tennis players bring the non-striking arm in closer to the body when looking to return the ball on the forehand side?

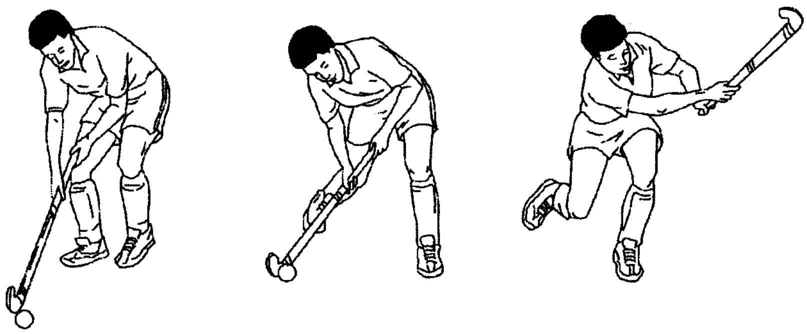
This brings the mass closer to the axis of rotation (shoulders) causing inertia to decrease and angular velocity to increase. Provides more power.

10.6 Force Summation

In order to generate momentum, a force must be applied to the object, be it a ball to throw, a ball to strike with a hockey stick or a body to rotate as in gymnastics.

When we are trying to give an object momentum, the amount of momentum we can give to it is determined by the sum of all the forces generated by different body parts.

Consider the hockey player below. How do they give maximum momentum to the ball when it is flicked? What are they doing?



There are five basic guidelines for giving an object as much linear momentum as possible.

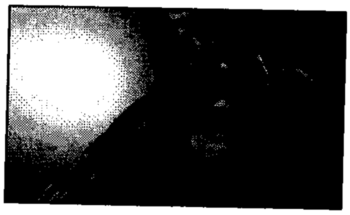
1. **Using Body Segments:**
   We should use as many body segments as possible when trying to give an object maximum momentum. Why?

   Because we can maximise the muscular force that each muscle group associated with each segment can generate.

   In the hockey illustration, what body segments are being used?

   LEGS ⟶ HIPS ⟶ TRUNK ⟶ SHOULDERS ⟶ ARMS ⟶ WRIST

2. **Stretch Out:**



Before we begin the sequence of movements, such as the throwing action, we should stretch muscles out to their optimal length. Why?

It allows the muscle to be contracted with optimal force. We do not want to over-stretch or over-reach. This decreases the force.

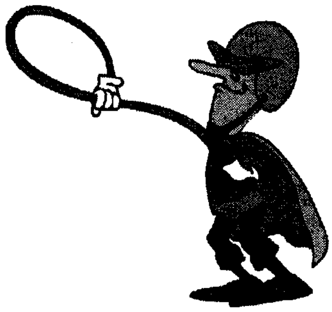
In the hockey illustration, how do we see this principle being applied?

Large step forward. Extension of arms about the stick.

3. **Sequencing of Body Segments:**

Generally, to give maximum momentum to an object in throwing, kicking, or striking, we move larger muscle groups *first* and the smaller muscle groups closer to the object *last*.

In effect we use the body like a giant whip.



What is the benefit of this?

The momentum generated by larger muscles about larger segments can be passed on to smaller ones until we make contact/release etc.

In the hockey illustration, how do we see this principle being applied?

Look at the order of execution sequence,

i.e. LEGS ⟶ TRUNK ⟶ ARMS ⟶ WRIST ⟶ STICK ⟶ BALL

4. **Timing of Body Segments:**

Generally, to give maximum momentum to an object in throwing, kicking, or striking, we need to make sure that the right body segment is adding to the overall momentum at the right time.

What could happen if the timing of body segments is "out of order"?

Not only does it lack co-ordination but maximum force generation is lessened or lost.

How does correct timing ensure maximum momentum?

It means we use those larger muscle groups first and the smaller muscle groups last.

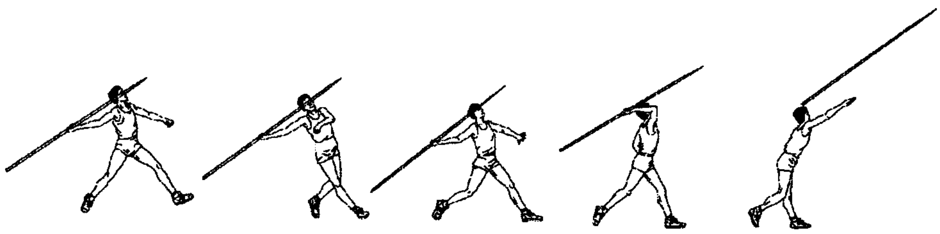
5. **Full Range of Motion:**

Generally, to give maximum momentum to an object in throwing, kicking, or striking, we need to move the segments through the greatest range of motion that we possibly can.

What are the benefits of this?

The greater the range of motion, the higher the speed of the extremities on release/contact.

We can apply all this information to the example of the javelin throw below:



Using your knowledge of generating momentum, explain how the athlete generates maximum momentum to the javelin upon release.

1. They use the large muscle groups of the legs and trunk to overcome inertia and generate force.
Due to conservation of momentum, this force is passed onto the shoulder, arms and finally the hand.
Forces are getting increasingly larger up to release.

2. They fully extend the arm (at shoulder) prior to the throwing action.

3. Timing is LEGS ⟶ TRUNK ⟶ SHOULDER ⟶ ARMS ⟶ HAND

4. The arm moves through its full range of motion to maximise lever length and force summation.

10.7 Analysing Skills Using Biomechanics

Coming to understand how a skill is to be performed is important in being able to better perform that skill.

When watching other people and giving advice, we can move away from saying, "Do this", towards, "If you do this it could be better because ...", or "That happened because you ..."

There are many different ways of analysing a skill, but we will consider an initial task analysis to identify the key biomechanical ideas, then two sample analyses.

Throughout the next two sections, we will use the example of the handstand forward roll in gymnastics as a skill for analysis.

Part I: Task Analysis

Using the illustration above, complete the boxes on the chart below that answer the question, "What biomechanical factors are important in the execution of the handstand forward roll?"

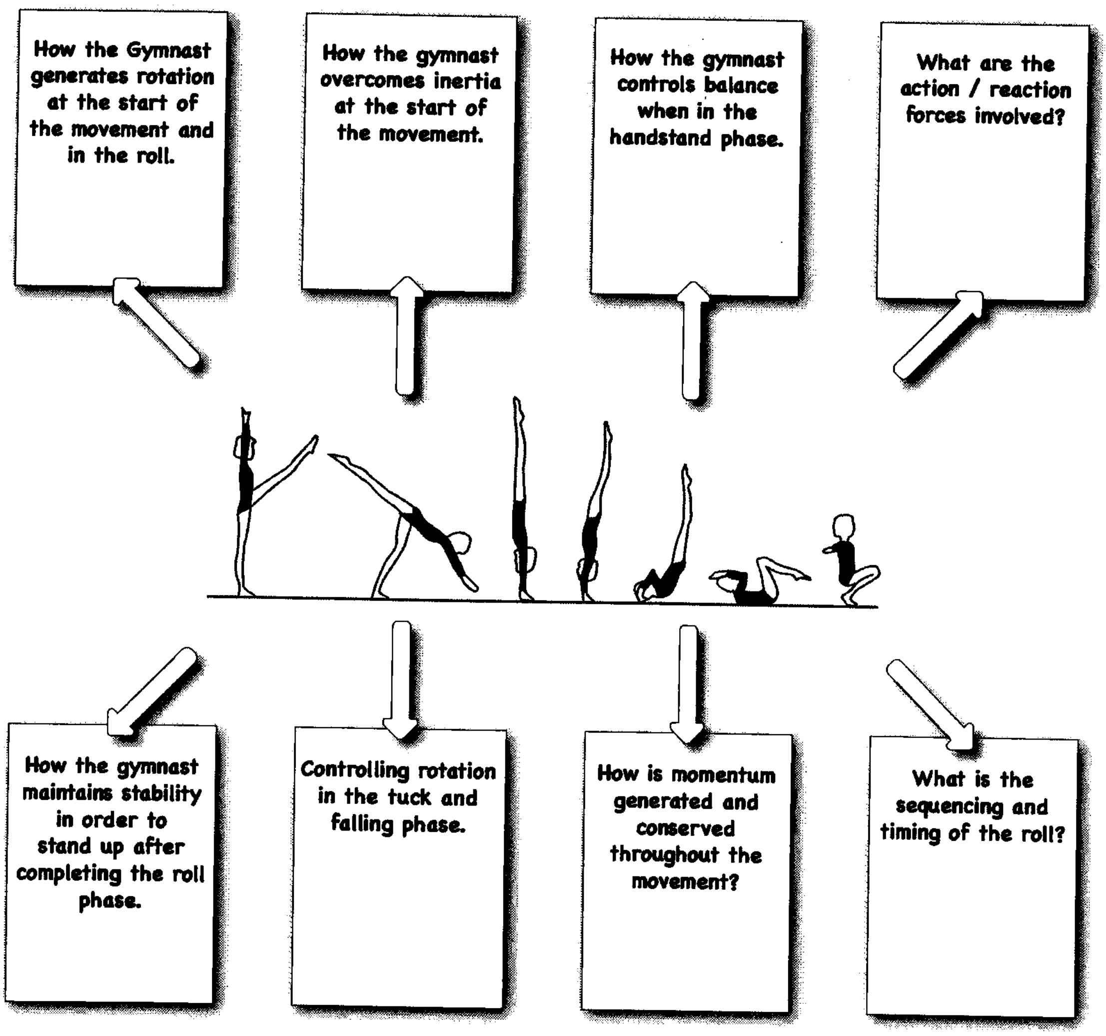
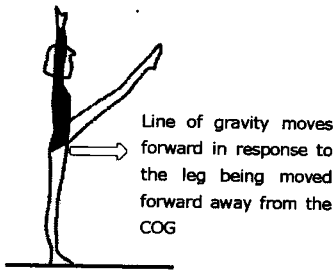


Illustration reproduced courtesy of Gymnastics Canada Gymnastique.

We can now use these biomechanical factors to explain how the skill is performed.

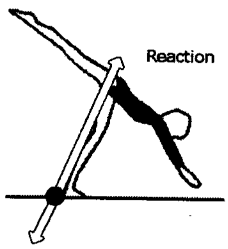
Key Element 1: The raising of the front leg (Frame 1)

Raising the front leg moves the COG of the gymnast outside the margins of the base of support allowing for the generation of a torque (small turning force) in the direction the skill will be performed. The 'unstable' nature of this position is enhanced by raising both arms above the head. This raises the COG with respect to the base of support making the system even more unstable.



Key Element 2: Kicking up of the rear leg (Frame 2)

The gymnast steps forward and places their hand on the mat. This creates a new pivot about which the body will rotate. The rear leg swings upward and backward. This generates angular momentum. When the leg approaches the limit of its swing, some of this momentum is transferred to the body to help in rotating it through to the vertical. Equally, the remaining foot on the mat pushes off producing a reaction force from the floor to aid in rotating the body upward.

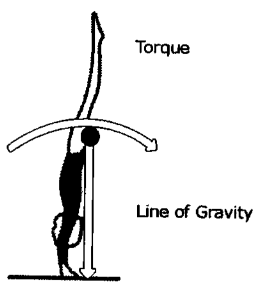


Key Element 3: Handstand position (Frame 3)

The gymnast has to generate enough angular momentum in the previous two stages to overcome the resistance of the body weight acting through the COG. That is, the forces generated have to be more than can be resisted by body weight. Balance is maintained by small eccentric forces acting about the wrists (generated by the fingers on the mat). This will generate a turning force in the direction opposite the initial rotation to allow the gymnast to show a clear balancing phase to the skill. The line of gravity of all body segments should lie inside the margins of the base of support to increase the probability of stability. The gymnast may also splay the fingers slightly to increase the size of the base of support. A straight back handstand (as shown) is biomechanically more efficient and aesthetically more pleasing than a curved back handstand.

Key Element 4: Initiating the roll (Frame 4)

Because the base of support is small and the COG is high, stability is low. The gymnast then moves the feet forward of the BOS. This will move the COG of the body in front of the BOS initiating a torque in the direction of the forward roll. This torque is not resisted. The gymnast must be careful not allow the COG to move too far from the point of rotation (hands) in case a torque is generated of such a size that it cannot be controlled in the rolling phase. Equally, they have to generate just enough to see them through the roll phase to the final standing phase.



Key Element 5: Control of the rolling motion (Frame 5 & 6)

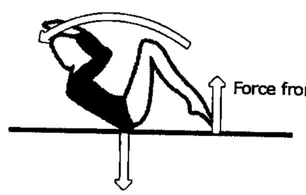
The size of the tuck is dependent on the angular momentum generated when the body began its rolling motion from the handstand. If the gymnast feels that they do not have enough angular momentum to roll to their feet (final frame) then they will tuck tighter. This will decrease the rotary inertia of the body and increases their angular velocity, i.e. they will roll faster. If they feel they have too much angular momentum (so will over rotate when trying to stand), they should open the roll position out. This increases rotary inertia and decreases the angular velocity, i.e. they will roll slower.

Key Element 6: Stop and stand (Frame 7)

The final phase to standing relies on the fact that sufficient momentum has been generated through the rolling phase so that when the feet touch the floor, momentum is conserved to help right the body to allow the gymnast to stand. The gymnast now has to cancel out forces generated by translation (moving forward) and rotation about the transverse axis. When the feet contact the floor, eccentric forces are generated (and controlled by muscles) to create a torque in the direction opposite the rotation and translation. Both rotation and translation need to be reduced to zero in order to stand without overbalancing, or struggling to do so. When the feet touch the floor, there is an action/reaction force pairing helping to reduce rotation and translation. In order to remain stable following the stand, the translation of the COG must stop inside the margins of the base of support.

Line of gravity falls inside the margins of the base of support.

Rotation in opposite direction to roll to help cancel out rotational forces

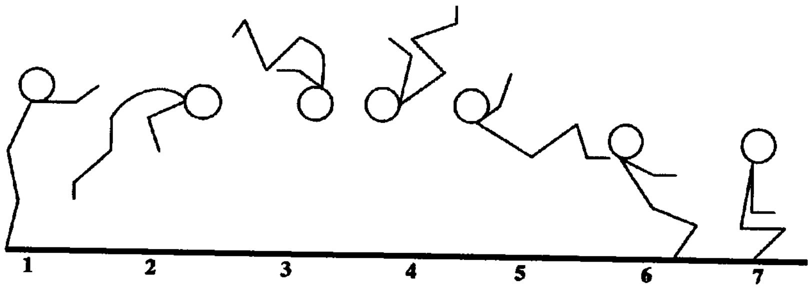


Summary

Remember, these steps may be used to identify what makes a skill so good but also to identify why aspects of a skill performance are not so good. This should help considerably in not only analysing skill performance but also appraisal of performance and developing motor learning plans for practising the skill.

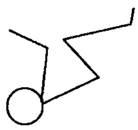
Alternatively we could use sheets below that identify the key biomechanical principles we have already identified in this unit and apply them to the performance of the skill by asking ourselves, *"Where (if necessary) is this biomechanical principle applied to the skill and how does it contribute to the execution of it?"*

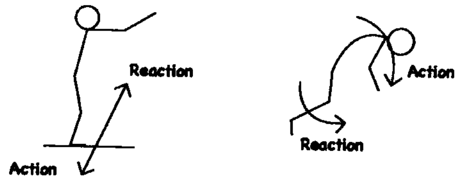
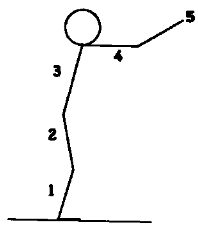
A Year 13 Physical Education student films themselves doing a standing front somersault. They convert the film footage to a seven frame animated sequence.

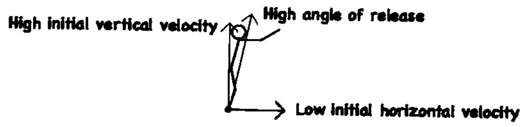
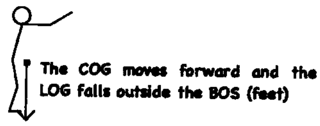
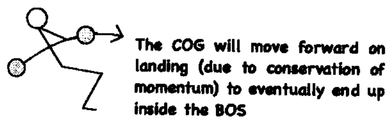


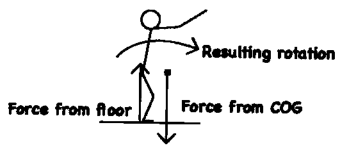
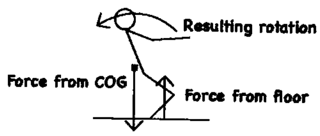
Try using the templates on the next few pages to explain how the biomechanical principles contribute to the execution of the standing forward somersault.

Make sure you identify where that principle(s) are being applied.

BIOMECHANICAL PRINCIPLE	FACTORS	EXPLANATION OF HOW AND WHERE THIS PRINCIPLE IS APPLIED TO SKILL EXECUTION
NEWTON'S LAWS OF MOTION	Inertia (1st Law)	**The body has inertia that must be overcome. This inertia is a product of the gymnast's mass. This inertia must be overcome to move from a stationary position to moving. The force generated to overcome this inertia must be greater than the inertia of the body.** **We also see this applied in the tuck phase where as the gymnast brings their mass closer to the transverse axis (axis of rotation), their rotary inertia will decrease allowing angular velocity to increase i.e. they will spin faster.** 
	Acceleration and Force (2nd Law)	**The greater the force generated in the first frame, the greater the acceleration of the body. By using principles of force summation (see later), the gymnast can generate sufficient forces to see them through the entire performance.**

BIOMECHANICAL PRINCIPLE	FACTORS	EXPLANATION OF HOW AND WHERE THIS PRINCIPLE IS APPLIED TO SKILL EXECUTION
NEWTON'S LAWS OF MOTION	Action & Reaction (3rd Law)	**At the point of takeoff, the gymnast exerts an action force into the group, the ground exerts a reaction force back and they take off. The greater the action force, the greater the reaction force.** **This also applies as the gymnast tucks. As the upper body moves down, the lower body moves up to balance the forces as a reaction.** 
GENERATING MOMENTUM & FORCE SUMMATION	Body Segments Stretching Out Sequencing Timing Range of Motion	**The sequence and timing of body segments is legs ⟶ hips ⟶ shoulders ⟶ arms. The forces generated from the legs are passed onto the rest of the body. The momentum that is generated is conserved so the arms can be driven downwards powerfully. This all helps overcome the inertia of the body.** **The gymnast stretches out as they begin the movement to ensure optimum force can be generated from the legs and arms.** **The timing must follow the sequencing so the forces generated by the larger muscle groups can be passed onto the smaller ones.**  **If the timing and sequencing of the movement are "out" the gymnast risks reducing those factors that aid in the generating of enough force to make the body as a projectile "fly" i.e. height of release, speed of release and angle of release (see later).**

BIOMECHANICAL PRINCIPLE	FACTORS	EXPLANATION OF HOW AND WHERE THIS PRINCIPLE IS APPLIED TO SKILL EXECUTION
PROJECTILE MOTION	Angle of release Height of release Speed of release Spin	The body must be positioned in such a way that the height of release can be maximised. A greater height of release will help the projectile fly higher at take-off. The gymnast does this by stretching out at the start and raising the arms above shoulder height. Speed of release is maximised by ensuring there is enough reaction force from the floor to propel the body upward. The gymnast must ensure that initial vertical velocity is greater than initial horizontal velocity. This will give greater height and flight time allowing the movement to be completed. Driving the arms downward just before take-off increases the reaction force from the floor.  The angle of release needs to be such that they gain maximum height at the expense of greater distance. A high angle of release ensures greater height and longer flight time. The gymnast's flight is set at take-off and cannot be altered in flight. All these factors combine to give height and a long enough flight time to rotate the body fully through the somersault.
STABILITY & BALANCE	Centre of Gravity Base of Support Line of Gravity	At take-off, the body is deliberately placed in a slightly unstable position by moving the line of gravity closer to or slightly outside of the margins of the base of support. The COG is raised by lifting the arms. As the arms are lifted they are moved forward adding to the unstable nature of the initial position.  This allows for the generation of an eccentric force (see later). When the gymnast lands, they want to allow some rotation and translation so the body's COG moves forward inside the new base of support (the feet on landing). 

BIOMECHANICAL PRINCIPLE	FACTORS	EXPLANATION OF HOW AND WHERE THIS PRINCIPLE IS APPLIED TO SKILL EXECUTION
TRANSFER & CONSERVATION OF MOMENTUM		On landing, momentum is conserved, allowing the body to continue rotating to a standing position. This means some of the momentum generated at take-off is passed to the floor. Because a new pivot point has been established, the body will continue to rotate in the direction of the movement i.e. forward direction. Momentum is conserved through the flight and cannot be added to or taken away. It must be controlled in flight and in landing.
GENERATING & CONTROLLING ROTATION	Eccentric forces Inertia v angular velocity Axis of rotation	At takeoff, an eccentric force initiates rotation. The further the gymnast moves their COG from the point of force application (feet), he greater the eccentric force. Equally, the greater the force from the floor, the greater the eccentric force. This will generate a turning force on the body that should be enough to complete the somersault.  Once in the air, distributing the mass closer to the axis of rotation (transverse) will decrease rotary inertial and increase angular velocity. This allows the gymnast to control the rate at which they spin depending on how the skill is progressing. That is, if the gymnast recognises that they will not spin enough for the feet to find the floor, they can tuck tighter and spin quicker. If, on the other hand, they sense they are over rotating, they can open out earlier or slightly more to decrease angular velocity. When the gymnast lands, they will generate an eccentric force that will rotate the body backwards slightly. This has the effect of cancelling out some of the forward rotation generated in the execution of the skill. 

10.8 Appraising Performance

Another important use of biomechanics is to allow us to appraise performance.

By *appraise*, we mean:

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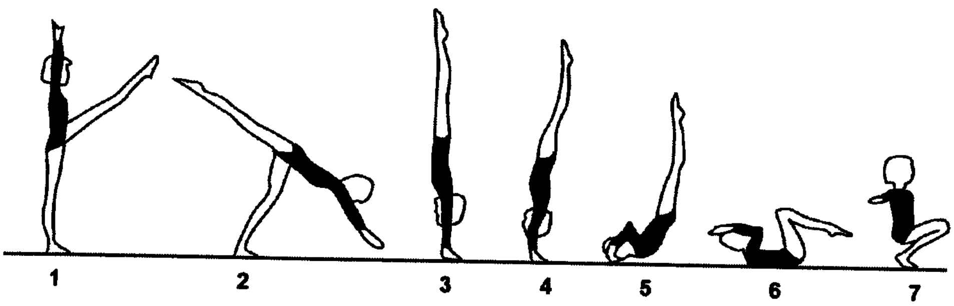
It is important to understand the biomechanics of the ideal in order to make accurate comparisons.

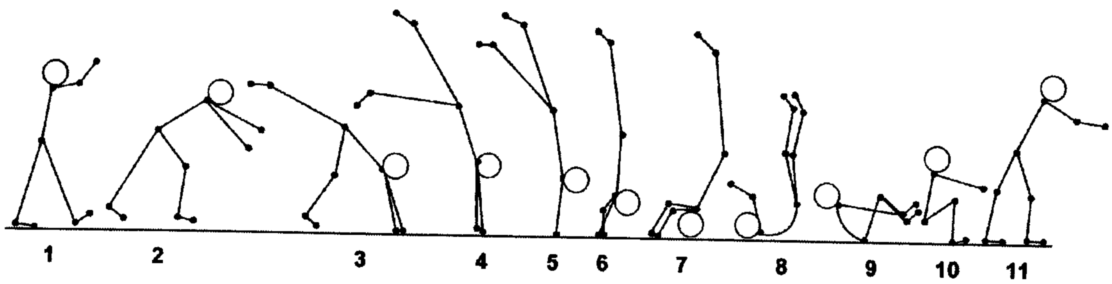
We can identify points of error, and explain them in terms of biomechanics, and functional anatomy. Since biomechanics is a science of cause and effect, we can identify errors and suggest reasons for them.

Earlier, we analysed biomechanically the performance of the handstand forward roll in gymnastics. Below this is a stick figure animation taken from a video sequence of the same skill.

Ideal Performance:



Student Performance:



The table over the page identifies relevant points of difference and explains some of them with respect to biomechanics and functional anatomy.

In the illustration of the student performance above, there are points of difference at 1→3, 5→6, and 9→11.

Complete the missing parts of the table.

POINT OF DIFFERENCE	DESCRIPTION OF DIFFERENCE	EXPLANATION OF DIFFERENCE USING BIOMECHANICAL AND FUNCTIONAL ANATOMY
1→3	• The amplitude of movement compared to the ideal is smaller i.e. the student is more tucked compared to the ideal.	From 1 → 3 the student is flexed at the knee joint to a greater extent than in the ideal. Consequently, the body will rotate faster since when the mass is distributed closer to the axis of rotation, angular velocity increases since rotary inertia decreases. This will provide a greater degree of momentum to the movement than would normally be required. Equally, the COG has been lowered with respect to the BOS (which is larger than the ideal) thereby increasing stability. A greater force is now required to move the body outside the BOS. This "greater force" could lead to over rotation manifested through an inability to maintain a handstand position before moving into the forward roll. To correct the error, the student needs to increase the degree of extension at the legs (about the knee) as they move into the handstand position. This will require contraction of the quadriceps to a greater extent. This will increase rotary inertia thereby decreasing angular velocity. The student will need to make some adjustments to the force required to initiate rotation. This can be achieved through force summation coupled to the increased forces that can be generated through longer levers. It will also look aesthetically more pleasing.
5→6	• A handstand position has not been maintained (as in the ideal – Frame 3). • The head is not tucked in line with the body.	Too much momentum was generated initially which could not be controlled by muscles when the body reached vertical. To correct the error, less force must be generated initially. If the head is not in line this brings the toes more forward off the body accentuating the inability to maintain a handstand position.
9→11	• The tuck is tighter during the roll compared to the ideal • The student takes a step forward after completing the roll.	Because the tuck is tighter than the ideal the body has decreased inertia and increased angular velocity so it will roll faster. This spills over into standing. There is too much rotation to control as they stand so they have to step to create a large enough eccentric force in the opposite direction to cancel out rotation.