Basic Biomechanics for Golf

Selected Topics

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Biomechanics

Biomechanics is the science that studies human motion using the principles of physics, engineering, anatomy and physiology. It provides a sound basis for the specific techniques we teach our athletes. There are two main goals of biomechanics; to improve the performance of the skill and to reduce the risk of injury. It also studies how the musculoskeletal system generates, controls and sustains forces to coordinate motion. There are two main branches of biomechanics, kinetics and kinematics. Kinetics is the study of forces that produce motion. These forces can be external or internal. Factors such as force, torque, momentum and energy involve kinetics. Kinematics is the description of the actual motion without regard to the forces producing it. Factors such as position, path, displacement, speed, velocity and acceleration involve kinematics.

The Musculoskeletal System

The musculoskeletal system provides structure and function to our bodies. It gives our bodies shape and form, provides support and stability, and enables movement.   Bones and joints provide structure. Muscles span the joints and are connected to the bones. Muscles provide stability, movement and form the underlying shape of our bodies. Ligaments hold the joints together and tendons joint the muscles to the bones. Joints act as fulcrums and bones as levers. Muscles act on these levers by contracting to produce motion. Muscles can only pull they cannot push, consequently they unusually come in pairs on either side of the bone and joint, one to flex the joint and the other to extend it. These are called agonist and antagonist muscles. Well timed actions of the muscles create forces which produce the coordinated motion of the body and limbs to propel the club into the ball during the golf swing. This well timed muscle firing is controlled by the central nervous system.

The 3D Coordinate System

All motion is measured in three spatial dimensions (3D) with respect to a reference point and three axes that are perpendicular to each other. For example, let's use the address position as shown in Figure 1. We can create our axis system by drawing the X axis parallel to the target line and just touching the back of the lead heel. The Y axis could be drawn perpendicular to that and through where the ball is placed. The Z axis is then drawn vertical from the point of intersection of the X and Y axes. The point that all three axes intersect is known as the origin or (0,0,0). This is called a 3D coordinate system. It is also known as the global reference frame for our measurement system. Some examples of what we can now measure with respect to this reference frame are:

The distance of the ball along the Y axis; this gives us how far out it is placed.

The distance along the X axis to either heel; this gives us information about our stance position with respect to the ball and plus our stance width.

The position of the golfers head; with a few extra calculations, this can give us the relationship of the ball and the head, important information especially in putting.

In fact, any point on the body or the club can be measured in this manner. These three measurements are known as the three-degrees-of-freedom (3DOF) of position.

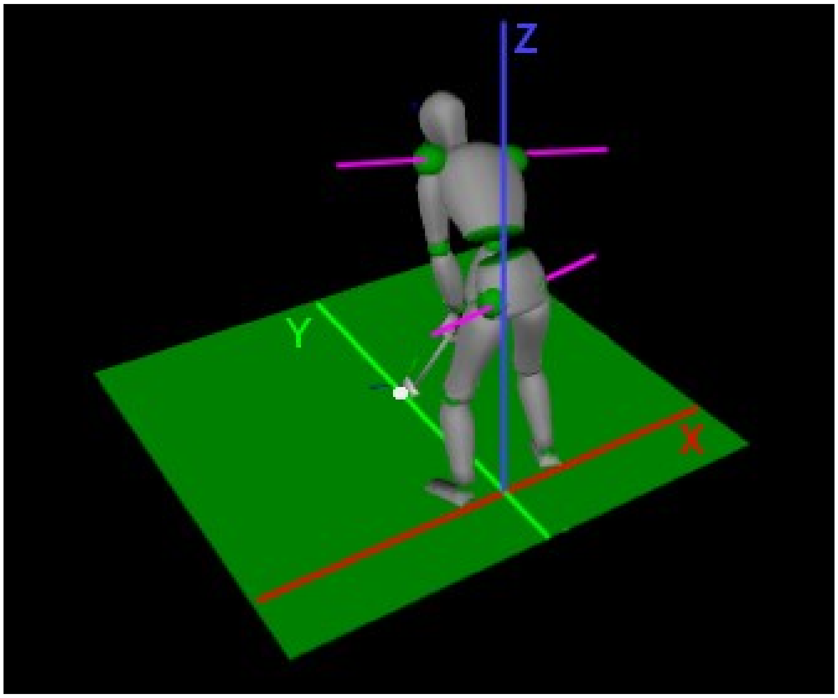

Figure 1 Three Dimensions in Space

Linear and Angular Motion in 6DOF

There is more to measuring human movement than just the three-dimensional position. For instance, every segment can also rotate. More specifically, if we were measuring the motion of your head during the swing, we could not only specify its position in inches along three axes (X, Y and Z), but also how your head is oriented. It can be rotated forward, sideways or turned, which are another three orientation possibilities or another three-degrees-of-freedom (3DOF).

The axis names, X, Y, and Z are not very descriptive, so we can rename them to make them more relevant to golf by calling them the Side-to-Side, Front-Back and Up-Down axes. It is now obvious what direction we mean when we are talking about the golfer's address position. For example, movement along the side-to-side axis is sway or slide; along the front-back axis is thrust; and along the up-down axis is lift or drop. Further, movement around the side-to-side axis is bend; around the front-back axis is side bend; and around the up-down axis is turn.

In a similar manner when we think about motion, there are two primary classifications: Linear and Angular. Linear motion, measured in feet or meters, is motion in a straight line along an axis. Angular motion is circular motion around an axis and is measured in degrees, radians or revolutions. As mentioned previously, there are three possible directions to move and three directions to rotate. So, linear motion has 3DOF and angular motion has 3DOF for a total of 6DOF. Figure 2 summarizes this discussion and adds the positive and negative direction names.

- Movement Along an Axis (3DOF)
  - Along the Side-to-Side Axis
    - Sway/Slide: Toward-Away
  - Along the Front-Back Axis
    - Thrust: Forward-Backward
  - Along the Up-Down Axis
    - Lift: Up-Down
  - POSITION: Inches, Feet, Meters
- Rotation Around an Axis (3DOF)
  - Around the Side-to-Side Axis
    - Bend: Forward-Backward
  - Around the Front-Back Axis
    - Side Bend: Trail-Lead
  - Around the Up-Down Axis
    - Turn: Open-Closed
  - ORIENTATION: Degrees, Radians, Revs

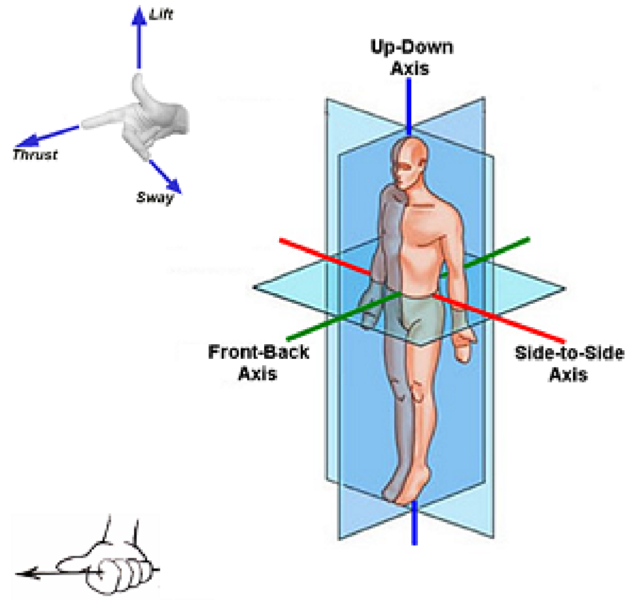

Figure 2. Six-degrees-of-freedom (6DOF), three linear and three angular.

Velocity and Speed

Commonly most people use the terms speed and velocity interchangeably, but from a physics perspective they do not mean the same thing. Speed measures the rate of change of distance with respect to time of someone or something (e.g., club head speed is 92 mph), or how far something or someone has gone in a certain amount of time. It is termed a scalar because it only has magnitude. Velocity, on the other hand, is a vector quantity because it has both magnitude and direction. In our three-dimensional world we measure direction with three components, X, Y and Z as previously mentioned, and for velocity these quantities also need to be specified. For example, your club head velocity would not be 92mph, but 91mph towards the target, 2.5mph out (i.e., away from your body) and 0.5mph down. These three components not only specify the total resultant speed of the club head but also its direction at any time during the swing, including impact. Another way to specify the club head velocity would be to define the path direction as two angles, for example 4 degrees down and 7 degrees left at impact.

In summary, here are two examples of how to specify velocity, the first of which is more practical in golf:

- 92mph with 4 degrees down and 7 degrees left,
- 91mph towards the target, 2.5mph out away from the body, and 0.5mph down.

Newton's Laws of Motion

In the seventeenth century, Sir Isaac Newton developed three laws of motion that have become the basis of modern day mechanics, known as Newtonian mechanics. They involve the relationship of forces and motion.

Newton's First Law – Law of Inertia

The first law states that an object will remain at rest or continue to move with constant velocity unless acted upon by an external force. Simply put, in golf, a golf ball will remain stationary unless struck by a golf club. In putting, the ball would continue to roll forever except that the external force of friction from the grass slows it down and eventually stops it. A golf ball hit by a driver has a specific horizontal velocity at takeoff. If there were no air resistance (an opposing force) the ball would continue at that same speed forever (or at least until it hits the ground). Note that gravity acts straight up and down and so has no effect on the horizontal velocity of the ball.

Newton's Second Law – Law of Acceleration

Newton's second law defines a relationship between force, mass and acceleration. Simply put, force equals mass times acceleration or:

F = m x a (where F = Force, m = mass and a = acceleration)

This equation explains why a golf ball accelerates faster from a driver than a putter. The mass of the golf ball is the same in both cases but the force of the collision with driver is much larger than with the putter. This means that the acceleration of the ball while in contact with the club is much larger for the driver than the putter. Acceleration is the change in speed over time, so larger accelerations will cause larger changes in speed for a given period of time and as a result the ball goes much faster in the case of the driver than the putter. As you may imagine, the acceleration of the ball from the driver is enormous. In a typical skilled drive the ball goes from zero to 100mph in the matter of 500 microseconds (or one half of one thousandth of a second); almost instantaneously!

Newton's Third Law – Law of Action Reaction

Newton's third law states that for every action there is an equal and opposite reaction. Forces work in pairs. If you push on the wall, the wall will push you back. A direct golf swing example is seen in the kinematic sequence of the downswing. During the downswing your pelvis accelerates rotationally, but when your upper torso accelerates a fraction of a second later your pelvis will begin to decelerate. Try this experiment to illustrate it. Sit on an office chair that is free to spin. Lift your feet off the ground and simulate a down swing with your arms. As you throw your arms around to the left, your hips and legs will rotate to the right. The "action" is your arms swinging to the left and the "reaction" is your legs rotating to the right.

Balance, Stability and Center of Gravity

The effectiveness of the golfer's motion is enhanced when she or he can maintain good balance and stability. There are two types of balance – static balance, which is balance when the body in not moving and dynamic balance, which is balance when the body is moving. Stability can be thought of as the resistance to being moved or thrown off balance, but in a strict mechanical sense the definition is the capacity of an object to return to equilibrium after being moved.

Stability increases as the: center of gravity is lowered, size of the base of support increases and, weight of the body increases.

Center of gravity is the balance point of the body. Think of a teeter-totter. You could lie on a teeter-totter with your arms by your side and legs straight, and then slide up or down until you balance. At this point your center of gravity is directly over the fulcrum of the teeter-totter. The center of gravity point in your body changes as you change position. Using the teeter-totter example, if you raise your arms above your head, your head will begin to tip toward the ground. You have moved your center of gravity away from the fulcrum, towards your head and so you are not balanced anymore and you tip in that direction. Another example, in the address position your center of gravity point is lower than when you are standing up straight. If you move your center of gravity outside your base of support then you will begin to fall over. Walking is really just falling forward and catching yourself every time you take a step. The golfer's center of gravity does move during the swing as body is rotating, swaying, thrusting and lifting, and the arms and club are swinging. Figure 3 shows several pictures of where the center of gravity may be located with the body in different stances.

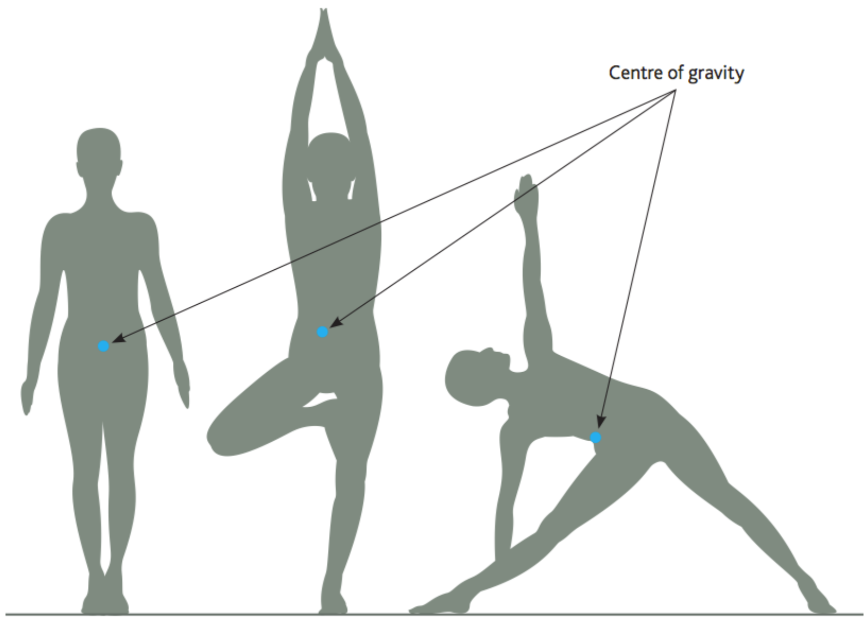

Figure 3. The Center of Gravity of the body moves as you move.

Force

A force is simply a push or a pull. It is something that can accelerate an object. It has the ability to cause movement, change direction, speed up or slow down the object on which it is acting. As discussed in the section on Newton's Laws, forces come in pairs. When there is an action there is an equal and opposite reaction. Forces are vectors, that is, they have magnitude and direction. If I push on you, you will move in the direction of the push. If I push harder you will speed up more rapidly. Also from Newton's Laws we know that an object at rest needs a force to make it move and an object already moving needs a force in the opposite direction to slow it down.

There are two types of forces, internal and external. Internal forces are those created by the muscles and exerted on the tendons, bones, cartilage or ligaments across a joint. Internal forces cause motion of the limbs with respect to one another, but cannot cause motion of the center of gravity with respect to the outside world, unless there is also the action of an external force. The fast motion of a limb or the club can also cause forces to be exerted at the joints. These are called inertial forces. Inertial forces are important in golf because the high speed of the golf club during the swing causes large inertial forces on the arms, torso and legs. These inertial forces must be effectively controlled with good timing to facilitate correct ball contact. External forces are those that are exerted on the body from the outside. Collision with the ground or an object causes an external force to be exerted. Gravity is an external force; it is the force that is continually pulling us toward the center of the earth. It is definitely the most important external force that we deal with. It affects all aspects of how we move. To be successful in a movement we must skillfully manipulate the effects of gravity.

As we mentioned, forces act in pairs. If two forces are in alignment with each other, the resulting motion will be along the line of action of the forces. If the forces are not in alignment then they will cause rotation. This is called a force couple and is very important to the rotational motion of the golf swing. Our two feet cause a force couple on the ground, in one direction to rotate us in the backswing, in the other direction to rotate us in the downswing and then again in the opposite direction to slow us down into the finish position.

Torque

Forces that cause rotation are called torques. A torque is the combination of a force and the perpendicular distance from the axis of rotation. The equation for torque is:

T = F x r (where T = torque, F = force and r = perpendicular distance from the axis to the force)

A couple is two forces acting together in opposite directions to produce a torque as shown in Figure 4. This is the situation in the golf swing. The feet create a force couple on the ground creating the body rotation during the swing (see the section on Ground Reaction Forces for more discussion on this topic).

Figure 4. Torque created by force F and distance r. Couple produced by two forces and two distances.

Energy

Energy has many varied meanings in life, but in mechanics the definition of energy is the capacity to do work. That means the ability to produce a force and move an object through a distance. There are also many forms of energy such as light, heat, chemical and mechanical energy. We are primarily interested in mechanical energy in the golf swing. Mechanical energy comes in two forms, potential energy and kinetic energy. Potential energy is due to position, it could be gravitational potential energy, for example, an object held high has more potential energy than an object held near to the ground, or elastic potential energy, for example, a compressed spring can rebound rapidly transferring energy to the object it is pushing. Kinetic energy is related to speed and has the formula:

KE = ½ mv^2 (where KE = kinetic energy, m = mass and v = velocity)

I show this formula mainly to show that velocity is the main factor affecting kinetic energy in that the amount of kinetic energy is related to velocity squared. For instance, if the velocity is 10, then the kinetic energy goes up by a factor of 100 (10 x 10)! The kinetic energy of the golf club just before impact is at its maximum in a skilled swing because its velocity is at its maximum.

Energy can be transferred from one form to another. If you hold a golf ball in your hand, it has potential energy which is related to the mass of the ball, the height above the ground and gravity, but it is not moving so it has no kinetic energy and it is not deformed so it also has no elastic potential energy. Once dropped however it gains speed and the potential energy is converted to kinetic energy. At the moment before it hits the ground it has its maximum kinetic energy, but no gravitational potential energy or elastic potential energy. At this point, the speed of the ball is at its maximum and its height is at its minimum. On collision with the ground the ball deforms and slows down. Kinetic energy is converted into elastic energy and the ball rebounds, converting the elastic energy back into kinetic energy and eventually back again to gravitational potential energy at the top of the bounce. Note that the ball doesn't bounce back to the same height because some of the energy is converted to heat and sound energy while in contact with the ground.

The Stretch Shorten Cycle

A principle of producing maximal muscular force during a muscular contraction is known as the Stretch Shorten Cycle (SSC) of muscle. It is defined as a rapid active stretch (eccentric contraction) followed quickly by a rapid active shortening (concentric contraction) of a muscle. This cycle of action allows the muscle to contract more strongly than if it was just contracted. There are several possible reasons:

- The initial eccentric contraction builds up the initial force in the muscle to a higher level and so sets up a higher force to begin with,
- Stretching the muscle may store elastic energy in the elastic fibers of the muscle and connective tissue which can be returned during contraction, and
- The stretch reflex may be stimulated causing a reflex contraction that will also help increase muscle contraction force.

This SSC principle of increasing force of contraction is used by expert golfers at several points in the swing to help generate high club head speeds. In a good transition sequence the pelvis rotates into the downswing before the upper body, causing an SSC on the muscles of the stomach and lower back. This is known as the X-Factor Stretch. The ribcage (thorax) turns into the downswing before the lead arm causing an SSC on the shoulder muscles. The club lags the lead arm in the transition causing an SSC on the lead forearm and wrist muscles. Using three-dimensional motion analysis and the kinematic sequence graph these actions can be clearly seen in the best tour pros as shown in Figure 5.

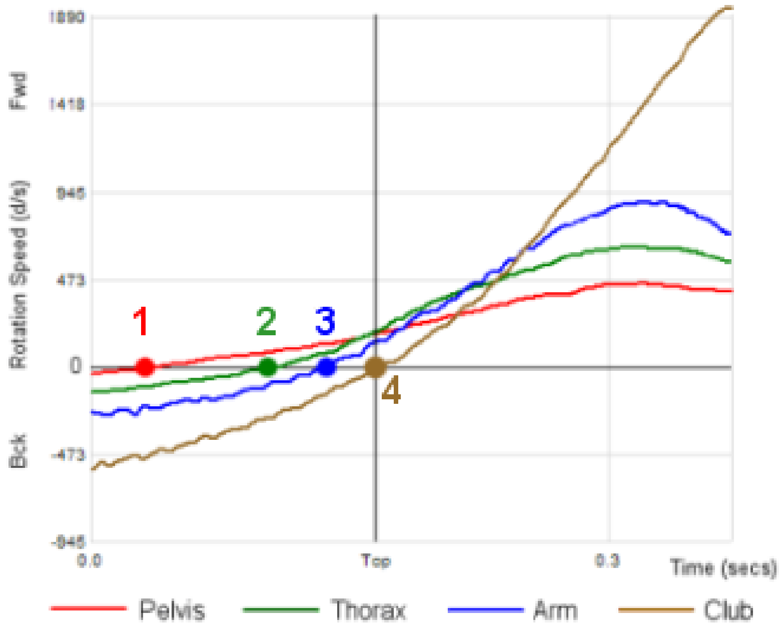

Figure 5. This graph shows the transition phase of a typical tour pro. The vertical axis is rotation speed and the horizontal axis is time. Each curve represents the rotation speed of a segment during the transition phase. The pelvis is red, thorax (ribcage) is green, lead arm is blue and club shaft is brown. When a curve crosses the horizontal zero line that segment has transitioned from backswing to downswing. Notice that the pelvis transitions first (1), thorax second (2), lead arm third (3), and club shaft fourth (4).

Linear Momentum

Momentum can be thought of as the "quantity" of motion that a body possesses. It is the product of the body's inertia and velocity. Remember that mass is a description of a body's inertia. So this means that linear momentum is the product of mass and linear velocity. Its formula is:

L = m x v (where L = linear momentum, m = mass and v = linear velocity)

An object that is more massive or is moving faster has more momentum.

Linear momentum can be transferred from one object to another and in a closed system, linear momentum is conserved. If we consider the golf ball and the club head as a system and we look at their momentum before and after impact we will see that their total momentum is conserved. Just before impact the ball has no momentum because it has zero velocity, so regardless of its mass, something times zero is always zero. Before we can do the math on this equation we need one other value, the Smash Factor. It is the ratio of the club head speed before impact to the ball speed after impact, a measurement of the quality of impact. An excellent smash factor with a driver is 1.5. This occurs with an almost perfect center hit. That means that if the club head speed is 100mph, the ball speed will be 150 mph. The mass of a typical drive head is 200gm and the mass of a golf ball is about 50gm. Using this information we can calculate the speed of the club head after impact, using the conservation of linear momentum principle.

The equation is:

Momentum of Club Head & Ball Before Impact = Momentum of Club Head & Ball After Impact

$\mathbf{m_b.v_b + m_c.v_c}$ **(Before) =** $\mathbf{m_b.v_b + m_c.v_c}$ **(After)**

50gm x 0mph + 200gm x 100mph = 50gm x 150mph + 200gm x $\mathbf{v_c}$

$\mathbf{v_c}$ **(After) = (20000 – 7500)/200 = 62.5 mph**

That means that the club slows down from 100mph before impact to 62.5mph after impact, losing 37.5mph because of the collision. On the other hand the ball speeds up from 0mph to 150mph. This all occurs because of the conservation of linear momentum.

Angular Momentum

Angular momentum is similar in principle to linear momentum but in a rotational sense. Angular momentum is proportional to the angular velocity and the rotational inertia of the object. The rotational inertial of a body is also known as the moment of inertia, but unlike linear inertia (i.e. mass), it is not constant.

$\mathbf{H = I \times \omega}$ (H = angular momentum, I = moment of inertia and ω = angular velocity)

The moment of inertia is dependent on the distribution of the mass with respect to the axis of rotation. Rotational inertia can change if you bring all the mass closer to the center of rotation.

$\mathbf{I = \sum (mr^2)}$ (m = mass “elements”, r = radius from axis of rotation, ∑ means “add them all up”)

If we put these two equations together we can easily see what angular momentum is dependent on.

$\mathbf{H = \sum (mr^2) \times \omega}$

From this equation we can see that angular momentum (H) is dependent on mass (m), angular velocity (ω) and the distance of each mass element away from the axis of rotation, but squared (r^2). The squared part means that the distance of the mass from the center greatly affects the angular momentum.

The best example of this is a figure skater in a spin. With arms out she spins slowly, with arms in she spins fast. This is due to the conservation of angular momentum. Angular momentum is conserved only if there are no outside net turning forces (torques). Since the skater is on the point of her skate there are no external torques acting on her to slow her down and angular momentum is conserved.

Unfortunately conservation of angular momentum does not relate directly to the golf swing; although many articles have professed that it does. Conservation of angular momentum requires that there are no external torques applied to the system during the motion. The golfer is solidly in contact with the ground, in contrast to the skater; forces and torques are generated from the ground to create the motion, so external forces are acting. In fact if conservation of angular momentum did apply then the golfer would not be able to swing at all since at address she is stationary so there is zero angular momentum and no angular momentum means no motion.

However, the moment of inertia of the body and the club certainly does have an effect on the speed of the swing. A large moment of inertia makes it harder to rotate and a low moment of inertial makes it easier to rotate. So when a novice golfer casts the club from the top the moment of inertia increases and the resistance to rotation increase meaning that try as she might the golfer will not be able to make the club swing very fast. In contrast, a skilled player, will maintain the wrist set angle until late in the downswing meaning that the club is close to the body for much of the downswing, keeping the moment of inertia low and allowing the golfer to rapidly increase the turning speed, which allows for a more rapid club speed when the wrist angle is rapidly released.

Ground Reaction Forces

As previously discussed there are two types of motion; linear and rotational. The same applies to forces. There are linear forces that push in a straight line and there are rotational forces that cause rotation. Forces that cause rotation are called torques. And again just like motion linear forces have three components, X, Y and Z, and torques also have three directions and act around the X, Y and Z axes. Just like motion, forces have six-degrees-of-freedom also (6DOF)

During the swing, the only parts of our body that are in contact with the ground are our feet. Consequently that is the only way that we can generate forces to begin the swing. We push on the ground with our feet, and due to Newton's Third Law of Action-Reaction, the ground pushes back on us. These are called ground reaction forces and there is always an action and reaction. For example, to jump up, we push down; to move right, we push left; to move forward we push back. With the appropriate combination of forces and good timing of those forces we learn to run, jump and swing a golf club.

Because we live in a three-dimensional world, we can push on the ground in three different directions; the vertical direction, the side-to-side direction and the forward-back direction. We use all these forces in combination during the swing. We can also push forward with one foot and backward with the other creating a force couple that causes us to turn.

Firstly, linear body motion in the swing is mostly side-to-side. There is some forward backward motion toward and away from the ball, but in a skilled swing this would be minimal compared to the side-to-side motion. That should make intuitive sense because our base of support is wider than it is deep, so we can move more side-to-side. If we move too much forward and back we would lose balance. In the backswing, we move slightly away from the target, putting more weight on to our trail leg. In the downswing as well as in the follow through we move toward the target and onto our lead leg. We use shear forces and weight shift to create this motion. Shear forces are forces parallel to the ground (horizontal forces). These forces can be exerted due to the presence of friction. If we were standing on ice we couldn't exert these side-to-side forces because there would be no friction. That is why good shoes are so important in golf. They produce the correct amount of friction to allow us to move appropriately. If we are right handed, on the backswing we push to the left with our lead foot to move our body to the right. On the downswing and follow through we move to our left by pushing to the right with our trail foot and shifting our weight to the lead foot during the downswing and follow through.

However the golf swing is mostly rotational, so in addition to the side-to-side forces we have to generate rotational forces on the ground. We do this by pushing forward with one foot and backward with the other causing a "force couple" and creating a torque that causes us to turn. In a right handed swing, the right foot pushes forward on the ground causing the right hip to move backward. The left foot pushes backward on the ground causing the left hip to move forward as illustrated in Figure 6. The result is the turn into the backswing. Before the club reaches the top the golfer reverses the direction of the foot push and causes a torque in the opposite direction to stop the backswing turning motion and transform it into powerful forward turning motion for the downswing.

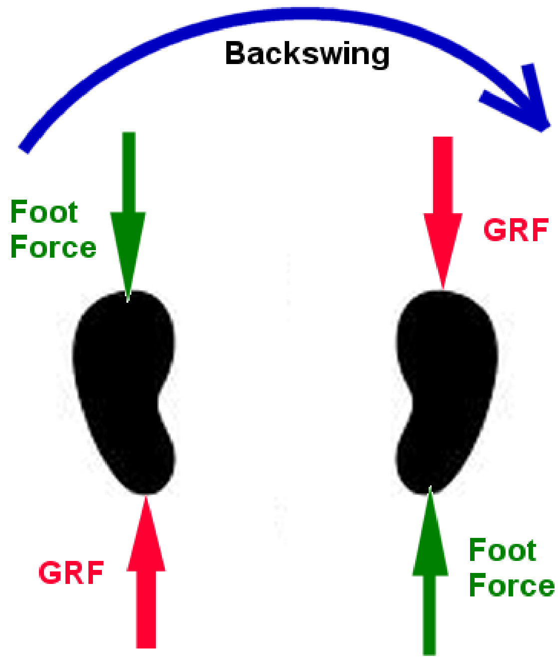

Figure 6. Forces in the backswing. Overhead view of the feet beginning the backswing. The right foot pushes forward and the left foot pushes backward (green). This causes ground reaction forces (GRF) in the opposite direct turning the golfer into the backswing.

Skillful golfers combine both the side-to-side and the forward-back forces on the ground to produce a fluid weight shift to the trail leg then to the lead leg with a simultaneous backward turn to a forward turn. Note that the weight shift in the swing is a result of these forces not the cause of these forces.

True scientific force platforms measure all these force directions (up-down, left-right and forward-back) plus the torques around each axis as well. They measure in six-degrees-of-freedom (6DOF). Unfortunately these force platforms are very expensive and are usually only found in the biomechanics labs at universities and hospitals. Less expensive plates, usually called pressure plates, are available but they only measure the vertical force component; just like a weighing scale in your bathroom. This type of plate can show you the weight shift during the swing by plotting the motion of your center of pressure, but it doesn't show you what is really causing the center of pressure to move in the first place, only a 6DOF force plate can do that.

Center of Pressure

Center of pressure is the single point of application of all the forces your feet are producing on the ground. It is the weighted average of where all your forces could be substituted by one equivalent force. When you are standing still it is a point directly below your center of gravity. If you move slowly it follows under your center of gravity pretty closely, especially if you just sway but stay on balance. It is very interesting to note however that center of pressure is calculated only from the vertical forces. Its calculation is not affected at all by the horizontal shear forces. That's why weight shift plates are less expensive. They only need to measure your weight under each foot.

When you move fast, your center of pressure is no longer under your center of gravity. Think of this example, stand with your legs apart and your weight evenly distributed. Your center of pressure will be a point on the ground about in the middle between your feet. Now quickly just lift your left foot off the ground without moving toward your right foot. You have to do it quickly and put it down again otherwise you will fall over. For the instant that your foot was in the air, where was your center of pressure? It must have been under your right foot because that's the only point that was in contact with the ground! So does your center of pressure always move in the same direction that you move? No. When you lifted your left foot you fell to the left side but your center of pressure moved from the center of your stance immediately to your right foot.

In general, when you are moving slowly you can think of your center of pressure moving with you; move to the right, center of pressure moves to the right. But when you move fast, especially if you lift a foot, the center of pressure can move in the opposite direction to your motion. If you use a pressure plate to analyze a golf swing, always look at the video of the motion as well as the graph otherwise your interpretation of the motion may be incorrect.

The Kinematic Sequence

In the golf swing our muscles convert stored elastic and chemical energy into muscular force which allows us to generate a well-timed golf swing. An efficient swing requires us to convert or transfer these various types of energy into motion. An efficient swing requires that each muscle fire and generate force with precise timing to generate and transfer energy to each subsequent body segment in the chain. The energy starts from the ground up. The stronger, larger muscles of the legs and core accelerate themselves and the segments above them by pushing on the ground, then in sequence the smaller, fast muscles of the shoulders, arms and wrists fire next to propel the club at maximum speed into the ball. This process has several descriptive names. It is known as, proximal-to-distal sequencing or the kinetic link or the kinematic sequence. We will refer to it as the kinematic sequence. It is a basic principle of human motion when the goal is to speed up a distal segment such as the foot, hand or club.

In golf where the need is to create maximal speed of the club, we find through motion analysis techniques, strong evidence of the kinematic sequence. There is a precisely timed sequence of body segment motions progressing from the proximal (inner), large segments to the distal (outer), smaller segments. During the downswing all body segments must accelerate and decelerate in the correct sequence with precise and specific timing so that the club arrives at impact accurately and with maximal speed. The most efficient sequence of motion for the major segments is: pelvis, thorax (upper body), arms and finally club. This motion must occur sequentially with each peak speed being faster but later than the previous one. This sequence reflects an efficient transfer of energy across each joint and facilitates an increase in energy from the proximal segment to the distal one. The muscles of each joint produce this increase in energy. On the other hand, if the timing of energy transfer is wrong, energy can be lost and hence speed will be lost; also if one body part has to compensation because another is not acting correctly then injury may result.

During the downswing, the larger, inner segments such as the pelvis and thorax move slower with the speed building as the energy progresses to the smaller distal segments such as the arms and club. Note that the pelvis does not continue accelerating through impact, but decelerates before impact.

In order to quantify the differences in the kinematic sequence between golfers we compare specific values from the segmental rotational speed curves. For example, we can look at the maximum rotation speeds of each segment; progressive speed gains between segments; sequence of maximum speeds; timing of maximum speeds; and average accelerations and decelerations before impact. Using these values we can quickly tell which segment of the body is not performing optimally.

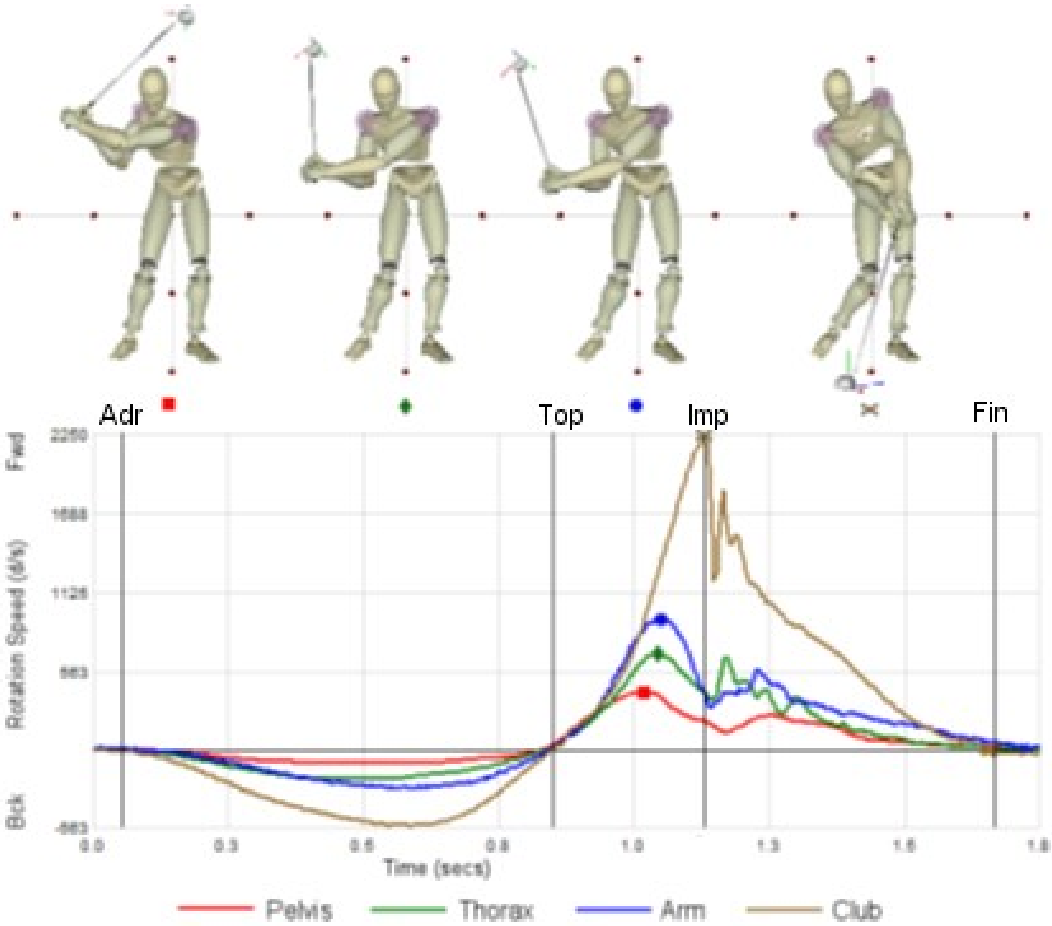

Figure 7. The kinematic sequence of a male tour pro.

In summary, and looking at the graph in Figure 7, in the downswing phase; between Top (of the backswing) and Imp (impact) the Kinematic Sequence proceeds as follows:

1. Pelvis (red) accelerates and peaks at a lower speed than the other segments, and then decelerates rapidly.
2. Thorax (green) accelerates to a higher speed than the pelvis, and then decelerates rapidly.
3. Lead Upper Arm (blue) accelerates to a higher speed than the thorax, and then decelerates rapidly.
4. Club (brown) continues accelerating reaching maximum speed at impact.

Notice also that each segment speed peaks slightly later than the previous highest speed, that is, each peak is more to the right of the previous one. The pictures of the golfer show the body position at each of the peak rotational speeds; from left to right, pelvis peak, thorax peak, lead arm peak, and club peak. The pictures should clearly show (looking at the position of the golf club) that the pelvis peaked first, then the thorax, then the arm and then the club. The peak for the thorax and arm will be very close so these two pictures should show the club at almost the same location. There should be a larger time between the pelvis peak and thorax peak; and again between the arm peak and the club peak. The club rotational speed should peak at impact; notice in fact that it is still going up at impact. This means that the club is still accelerating at impact.

Important Features of the Kinematic Sequence

So far we have mentioned two key areas in the kinematic sequence graph, the transition sequence and the downswing sequence. The takeaway sequence is also of importance, and we will also discuss the follow through for completeness.

The Takeaway Sequence

It is common for most good ball strikers to begin their takeaway sequence with the club first, followed by the arms, chest and then hips. This is not always the case, but the key point is not to let the hips start the motion. Having the correct takeaway sequence will aid the golfer to create a good transition as shown in Figure 8.

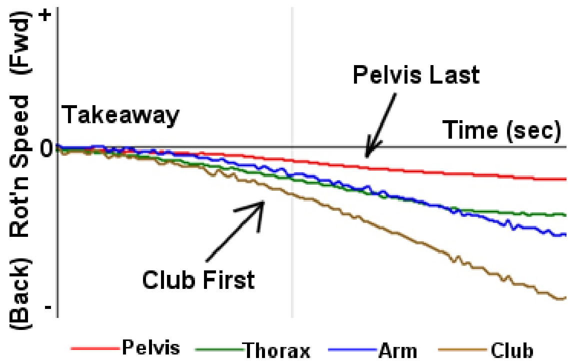

Figure 8. Takeaway Sequence. The graph shows that the club moves first because it has the fastest initial backswing velocity and pelvis last because it has slowest backswing velocity.

Transition Sequence

The majority of tour players don't transition simultaneously from backswing to downswing with all body segments. In fact, there is a specific order of transition as shown in Figure 9, which is the pelvis first (1), thorax (ribcage) second (2), lead arm third (3) and club last (4). This order sets up an additional stretch at each joint (remember the stretch shorten cycle discussed earlier) allowing the muscles to fire stronger in the downswing, facilitating higher body rotation speeds. The average time of transition, from pelvis to club transition, for male tour players is about 0.05 seconds and about 0.07 seconds female tour players. Even though these times are faster than the blink of an eye, they are still important to the power the muscles can generate in the downswing.

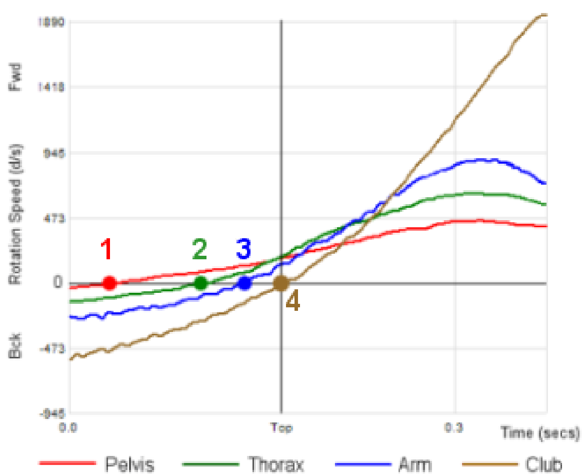

Figure 9. Transition Sequence.

Downswing Sequence

The takeaway and transition sequences, if done correctly, have set the golfer up for the downswing, but what happens in the one quarter second of the downswing is important to the speed and accuracy of impact. With modern three-dimensional motion analysis systems we can see within a millisecond what happens in this critical phase of the swing.

Male tour players take about 0.25 seconds and female tour players about 0.30 seconds to complete the downswing. In addition to the time of the downswing, there are several factors that we extract from the kinematic sequence curves.

Accelerations and Decelerations - Acceleration is how fast each segment speeds up and deceleration is how fast each segment slows down. Remember that we are talking rotational (turning) not linear accelerations and decelerations. The key to a powerful swing is fast, sequential rotational accelerations and decelerations. Notice from the graphs in Figure 10 that each body segment accelerates, reaches peak speed, then decelerates **before** impact in order to efficiently transfer speed to the following segment. The only thing that accelerates all the way to impact is the club. This is a critical feature of the downswing kinematic sequence.

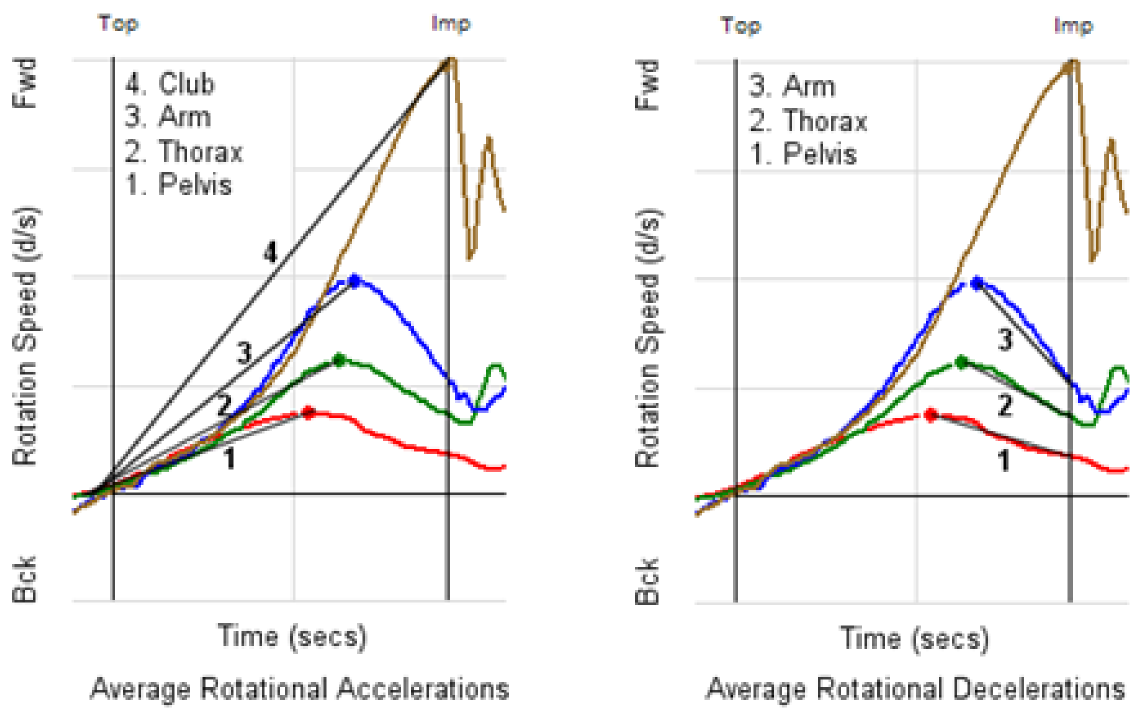

Figure 10. Downswing rotational accelerations and decelerations of pelvis, thorax, lead arm and club.

One particular point of interest can be seen in the pelvis curve and the model of the golfer in Figure 7 earlier in this section, and that is the time at which the pelvis reaches peak speed and begins to decelerate. Looking at the time line in the graph it appears to be approximately half way down, but that is slightly misleading. Indeed, it is approximately half way from a time perspective but not from a body position point of view. Notice the model, his arm is parallel to the ground, club is still pointing back towards the target and pelvis is about parallel to the target line. From this point on the pelvis is decelerating and the core is stabilizing the upper body allowing the chest and arms to accelerate through.

Peak Rotational Speeds and Speed Gains – Each segment speed peaks sequentially and faster than the previous segment. The higher the peak speed of each segment the higher the potential speed of the club at impact. Also the speed gain or increase from segment to segment, across each joint, is indicative of how much energy that joint contributes to the final speed of the club. If one particular joint speed gain is found to be lacking, then that may be an indication of weakness in that muscle group. Pros have been found to have significantly higher peak segmental speeds and speed gains in the downswing than amateurs. Figure 11 shows definitions of peak speeds and speed gains.

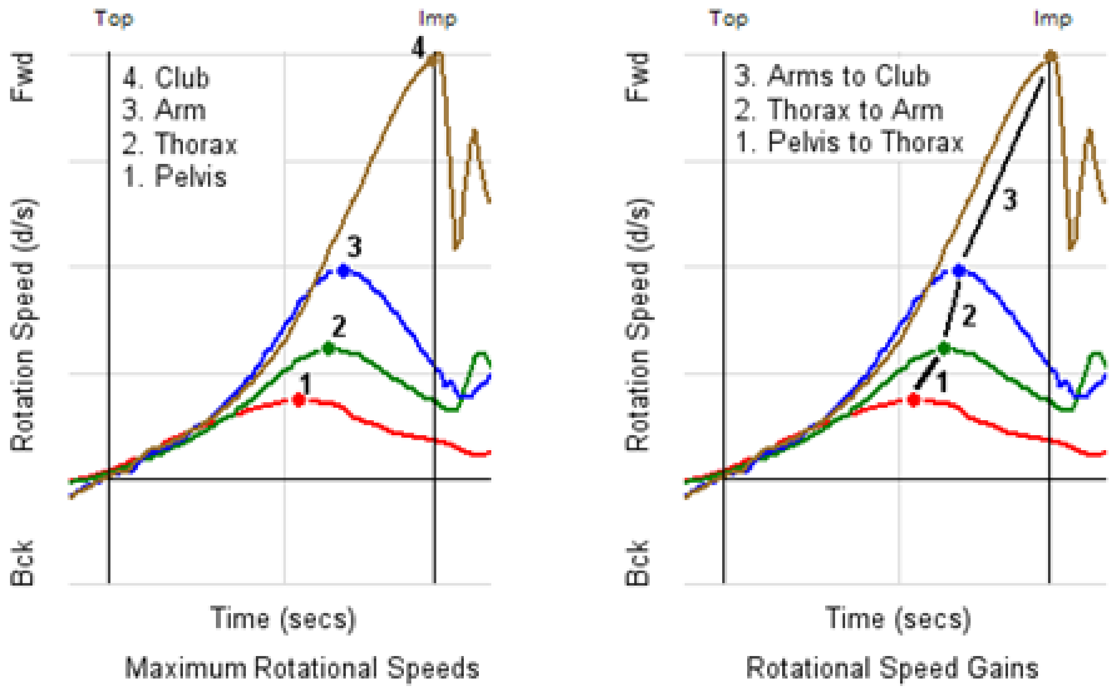

Figure 11. Downswing peak rotational speeds and speed gains of pelvis, thorax, lead arm and club.

Follow Through Sequence

After the ball has left the club face the golfer must now slow the club down to a stop while still maintaining balance and avoiding injury. Interestingly we see a second speed up in each of the three body segment curves. This is due to the club being decelerated and passing its remaining energy back through the chain from the club, to the arms, the upper body, and finally to the pelvis and the legs. The follow through phase takes about 0.7 seconds for both male and female tour pros. Note again though, the re-accelaration of each major body part is **after** impact, which is shown in Figure 12.

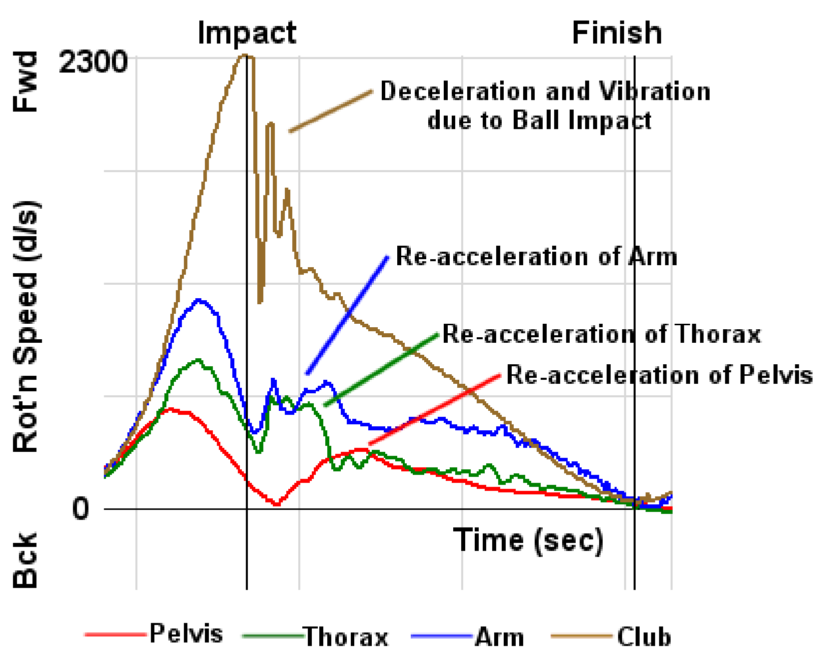

Figure 12. Follow through sequence of the pelvis, thorax, lead arm and club.

AMM Systems for Measuring Motion in the Golf Swing

All of the graphs discussed in this document were generated using electromagnetic motion analysis systems by Advanced Motion Measurement Inc., Phoenix, Arizona. Here is a brief explanation of two of AMM's systems.

AMM Walkabout 6D Golf

This system uses three six-degree-of-freedom (6DOF) electromagnetic sensors to capture the position and orientation of the pelvis, thorax and club, 120 times per second during a swing. It uses the TPI 3D biomechanics and reporting software (Titleist Performance Institute, Oceanside, California) to produce the biomechanics report. It measures sway, thrust and lift of the pelvis and thorax; release angle of the wrist, X-Factor and X-Factor Stretch, to name a few. It is easily configured to measure many more important variables. These values can be compared to the tour databases so the golfer and instructor will know what is in or out of range. The system also measures the Kinematic Sequence of the pelvis, thorax, arms and club shaft. These measurements allow the instructor to check most of the typical faults in the swing such as, address posture, C or S posture, sway on the backswing, slide on the downswing, hanging back, reverse spine angle, hip and shoulder over or under rotation, early extension in the downswing, flat shoulders, coming out of posture, over the top. In fact all of the "Big 12" faults that are taught at the TPI seminars can be measured, plus many others as well.

An added benefit of the system, and some say its most important feature, is its biofeedback mode. Tones can be set on each of the motions and positions to indicate to the golfer when he/she is doing the motion correctly or incorrectly. Am I in the right position or the wrong position? The tone and the real-time numbers on the screen show and give the golfer the feel of what is right or wrong. This method when applied correctly speeds up learning.

The AMM Walkabout system is quick and easy to set up yet very accurate in its measurements. It is teatherless allowing the golfer to "walkabout" without the hindrance of wires. During setup, offsets measured from the golfer are used to electronically move the sensors "inside the body" so the segment centers are measured instead of the segment's surface. Figure 13 shows the system.

Figure 13. AMM Walkabout 6D System. Self-contained and quick to setup.

AMM3D 12 Sensor Full-Body System

This is AMM's flagship product and it captures the full body of the golfer plus the club in six-degrees-of-freedom (6DOF) at high speed; 240 samples per second. It is the most accurate of the systems but takes the longest to setup. The instructor must digitize body landmarks with a sensor pen. This is the most accurate method because it aligns the sensors to the body segments and scales them as well. Once digitizing is complete a full-body 3D robot can be seen emulating the entire golfer's motions in real-time. In addition to the kinematic sequence and pelvis and upper body 6DOF you also can get the motion of the legs and arms; plus all the release angles of the wrist and forearm; flexion/extension, radial/ulnar deviation and pronation/supination. If you want to know everything about the swing's biomechanics and have research quality data, this is the system to use. It is illustrated in Figure 14.

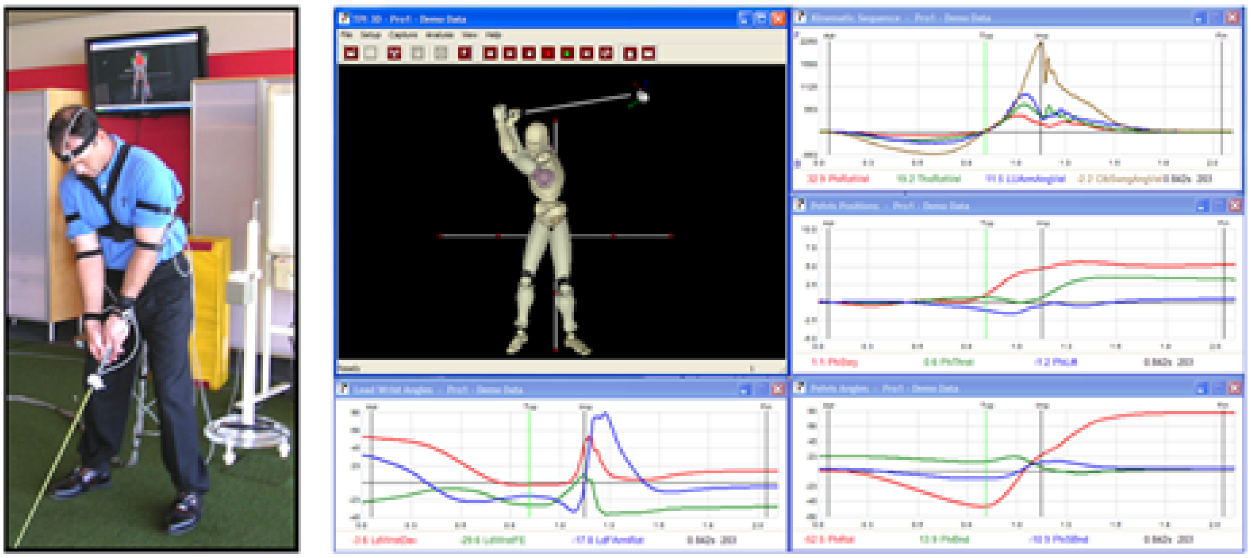

Figure 14. AMM3D 12 Sensor System. The system is shown with an example graph layout including the kinematic sequence, pelvis angles and positions, plus wrist angles.