Of all the techniques used to play sport, the golf swing has perhaps been scrutinized more than any other. There are now literally hundreds of instructional books describing the golf swing, but many of these are based on anecdotal insights provided by elite players and their coaches. In this chapter, various aspects of the golf swing are considered from an evidence-based scientific perspective. Integrating theoretical and empirical research from the sub-disciplines of sports biomechanics and motor control, Paul Glazier and Peter Lamb tackle a series of important questions about the sequencing and timing of body segment rotations, the magnitude and variability of grip forces, and the transference of weight during the swing, among others.
What is the “summation of speed” principle?

In recent years, the sequencing and timing of body segment motions in the golf swing have been popular topics for study by golf scientists, in part because of the more widespread use of automated 3D motion-capture technology. An important finding to emerge from this line of research is that the generation of clubhead speed in golf is governed by the “summation of speed” principle.1 This principle states that to maximize velocity at the end of a series of linked body segments (known as a “kinematic chain”), the series should commence with the larger, heavier, inner (or proximal) body segments and proceed to the smaller, lighter, outer (or distal) body segments.2

Another study, by Cheetham and colleagues,4 has compared the kinematic chains of professional and amateur golfers. It was reported that the professional golfers exhibited significantly greater values than amateurs for the following variables: all average rotational accelerations and decelerations (except pelvis); all peak rotational speeds; all rotational speed gains (i.e. pelvis to thorax, thorax to arm, and arm to club); and peak linear clubhead speed.4 It was suggested that, in general, these results indicated that amateurs had poorer coordination, weaker power production, and less efficient energy transfer between segments than professional golfers.

Based on these findings, it would appear that analyzing the motions of body segments in the kinematic chain could provide invaluable information for identifying faults and prescribing modifications to technique. With the increased availability and affordability of 3D motion-capture technology and its growing capacity to more accurately measure body segment motion in realtime, this line of research could help professionals and amateurs alike to improve the efficiency of their swings and maximize clubhead speed.

How can I coordinate my movements to maximize clubhead speed?

A number of biomechanical studies examining proximal-to-distal sequencing in the golf swing have generally confirmed that, following the preparatory (backswing) phase, the action (downswing) phase starts with a rapid rotation of the pelvis (498 degree/s), followed by progressively faster rotations of the thorax (723 degree/s), lead arm (1165 degree/s), and club (2090 degree/s) as impact nears, before slowing during the recovery (follow-through) phase (representative data taken from Geisler3 for professional golfers).

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Does head movement hinder swing performance?

Head movement is a good marker for body movement in the golf swing, specifically the lateral thorax shift. Although thorax anterior–posterior (or forward-backward) tilt can be compensated for by knee and hip flexion-extension, lateral thorax shift typically coincides with lateral head movement. This may be the reason that coaches have long viewed head movement as having such importance. The “head still dogma” was supported by the findings of Cochran and Stobbs, who proposed a “pendulum” model with a fixed pivot point, or fulcrum, located midway between the shoulders on the golfer. The idea was that keeping the axis of rotation immobile should result in a repeatable swinging motion of the pendulum. However, recent research has shown that the axis does not remain still during the full swing. Simulations have also shown that immobilizing the fulcrum has a negative effect on clubhead speed. In fact, to keep the head perfectly still during the swing requires the golfer to dissociate their head movement from the rest the body’s moving parts. It may be easier for the brain to couple head movement with other moving body parts than to try to operate each independently.

Horan and Kavanagh have shown that head movement patterns for professional golfers are consistent but vary from individual to individual. A common assumption is that less-skilled golfers move their head too much compared with expert golfers, but Sanders and Owens have reported that, for a small sample of expert and novice golfers (six of each), novices actually displayed less total head movement throughout the swing compared with expert golfers. The experts, however, showed more consistent head movement during late downswing and through impact, keeping their head behind the ball through impact more than the novices. Coaches may use head movement as an indicator of body movement (particularly lateral shift), but for the full swing there is no reason to advocate a particular pattern of head movement—including the absence of head movement.

Head masters. It has been shown that—for putting and possibly also chipping—expert golfers move their head in an egocentric pattern (i.e. the clubhead moves away from the target, and the head moves toward the target relative to the club), whereas novices move their head in an allocentric pattern (i.e. clubhead moves back, away from the target, and head also moves back). Expert golfers also felt that their head stayed still while performing the egocentric movement pattern, even though it didn’t. Although the range of movement was minimal, it is recommended that golfers avoid the allocentric head movement pattern typically adopted by beginners.

Eye on the ball. Mann and colleagues showed that expert golfers fixate their focal gaze more consistently and for longer (red) on the ball, and on the target, compared with high-handicap golfers. This phenomenon may give the feeling of a still head position during putting and may well be responsible for expert golfers reporting that their heads remained still during putting and in the full swing.
What is the “X-factor” and what role does it play in hitting a golf ball far?

The “X-factor” is a buzzword often found in contemporary golf instruction manuals. It was first introduced by Jim McLean in a Golf Magazine article in 1992 and refers to the differential in degrees of rotation between the pelvis and thorax during the golf swing. Based on data subsequently published as part of a larger study by McTeigue and colleagues, McLean showed how five of the longest-hitting professionals of the PGA Tour had a larger X-factor at the top of the backswing than five of the shortest-hitting professionals. He proposed that a direct relationship exists between the pelvis-thorax separation angle at the top of the backswing and clubhead speed at impact—that is, a larger separation angle is generally associated with greater clubhead speed, and longer drives. Many coaches now advocate a restricted pelvis turn during backswing to maximize the relative angle between the pelvis and thorax. An increase in the X-factor during the early downswing has also been shown to be associated with higher clubhead speeds and longer distances. This move—called the “X-factor stretch”—involves the rotation of the pelvis back toward the target while the thorax is still either completing the backswing or is stationary at the top of the backswing. It has been hypothesized that, by increasing the separation angle between the pelvis and thorax during transition, the abdominal and oblique muscles are dynamically stretched, leading to a more forcible contraction and a greater transfer of energy to the thorax. Empirical support for the role of the X-factor stretch was found by Cheetham and colleagues, who showed that a highly skilled group of golfers exhibited a significantly greater X-factor stretch than a lesser skilled group. Interestingly, they also found that no significant difference in the X-factor at the top of the backswing existed between groups. These findings led the researchers to suggest that the X-factor stretch is potentially more important than the X-factor when generating high clubhead speeds, although more recent research has indicated that they are of equal importance.

Does a greater body turn help me hit farther?

The “X-factor” is defined as the separation angle between the pelvis and thorax during the golf swing, specifically at the top of the backswing. When viewed from above, the intersection of the pelvis axis (defined as an imaginary straight line running through the hip joints—red line) and the thorax axis (defined as an imaginary straight line running through the shoulder joints—blue line) in the horizontal plane forms an “X,” hence the term “X-factor.”

An increase in the X-factor during the early downswing has also been shown to be associated with higher clubhead speeds and longer distances. This move—called the “X-factor stretch”—involves the rotation of the pelvis back toward the target while the thorax is still either completing the backswing or is stationary at the top of the backswing. It has been hypothesized that, by increasing the separation angle between the pelvis and thorax during transition, the abdominal and oblique muscles are dynamically stretched, leading to a more forcible contraction and a greater transfer of energy to the thorax. Empirical support for the role of the X-factor stretch was found by Cheetham and colleagues, who showed that a highly skilled group of golfers exhibited a significantly greater X-factor stretch than a lesser skilled group. Interestingly, they also found that no significant difference in the X-factor at the top of the backswing existed between groups. These findings led the researchers to suggest that the X-factor stretch is potentially more important than the X-factor when generating high clubhead speeds, although more recent research has indicated that they are of equal importance.

Angle of separation The “X-factor” is defined as the separation angle between the pelvis and thorax during the golf swing, specifically at the top of the backswing. When viewed from above, the intersection of the pelvis axis (defined as an imaginary straight line running through the hip joints—red line) and the thorax axis (defined as an imaginary straight line running through the shoulder joints—blue line) in the horizontal plane forms an “X,” hence the term “X-factor.”

X-factor statistics The longest- and the shortest-hitting golfers on the PGA Tour on average did not differ in the amount of thorax rotation (68° versus 69°) but they did differ in the amount of pelvis rotation (50° versus 65°). When expressed as a percentage of thorax rotation, the differential between the thorax and pelvis rotations, or the X-factor, accounted for 43 percent and 27 percent for the longest and shortest hitters, respectively. Interestingly, John Daly—the number one ranked driver in 1990—had the third-largest pelvis rotation of all the tournament professionals analyzed. He also had the largest X-factor. These findings indicate that, contrary to popular belief, a restricted pelvis rotation is not a prerequisite for a large X-factor. These findings also suggest that caution should be applied when attempting to extrapolate results from group-based analyses to specific individuals.

X-factor differences

<table>
<thead>
<tr>
<th>Angle of separation</th>
<th>X-factor</th>
<th>Pelvis rotation</th>
<th>Thorax rotation</th>
<th>Differential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top of backswing</td>
<td>50°</td>
<td>65°</td>
<td>68°</td>
<td>13°</td>
</tr>
<tr>
<td>Downswing</td>
<td>50°</td>
<td>68°</td>
<td>69°</td>
<td>11°</td>
</tr>
</tbody>
</table>

Highly-skilled players

Lower-skilled players

<table>
<thead>
<tr>
<th>X-factor differences</th>
<th>X-factor differential</th>
<th>Pelvis rotation</th>
<th>Thorax rotation</th>
<th>Differential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top of backswing</td>
<td>50°</td>
<td>65°</td>
<td>68°</td>
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</tr>
<tr>
<td>Downswing</td>
<td>50°</td>
<td>68°</td>
<td>69°</td>
<td>11°</td>
</tr>
</tbody>
</table>

X-factor differential during backswing

X-factor differential during downswing

Backswing and downswing Mean differences between highly skilled (scratch handicap or better) and low-skilled (15 handicap or higher) golfers in X-factor at the top of the backswing and maximum X-factor during the downswing, as reported by Cheetham and colleagues: On average, the highly skilled golfers stretched their X-factor by 19 percent at the beginning of the downswing, which was significantly greater than the 13 percent stretch exhibited by the less-skilled golfers. However, there was no statistically significant difference in the X-factor at the top of the backswing.
What neuromuscular patterns characterize an effective golf swing?

Knowledge of the muscles that are most active at various times during the golf swing is important, not only from a golf coaching standpoint, but also from a strength and conditioning perspective. Using a technique known as electromyography (or EMG), scientists have been able to shed some light on how the muscles work during the golf swing. By attaching electrodes to the surface of the skin adjacent to specific muscle groups or by inserting fine-wire indwelling electrodes directly into individual muscles, the magnitude and duration of electrical activity within the muscle(s) can be measured.

Although it is impractical to analyze the action of all muscles simultaneously, a number of studies have considered the activation characteristics of key muscles of the trunk, shoulder, chest, forearm, and lower limbs during the golf swing. When combined, these provide a reasonable picture of the sequencing and timing of muscle activity during the golf swing. Most studies have examined muscle activity during the following phases: backswing; forward swing; acceleration phase; early follow-through; and late follow-through.

The information presented here may help to identify where musculotendinous injuries may occur, and to direct muscle strengthening programs that can increase the robustness of muscle and connective tissue to acute and chronic trauma. Further research is required on mid- to high-handicap golfers as most studies, to date, have focused almost exclusively on low-handicap or professional golfers. More studies investigating muscle activity in female golfers are necessary as much of the extant literature has considered only male golfers.

What muscles do I use during my golf swing?

**Backswing**
The most active muscles during the backswing (the period between address and the top of the swing) are the right trapezius (upper, middle, and lower portions), right rhomboid, right levator scapulae, left serratus anterior (upper and lower portions), and left subscapularis. (It is worth noting that the situation is mirrored for left-handed golfers.)

**Forward swing**
The most active muscles during the forward swing (between the top of the backswing and the horizontal position of the club during the downswing) are the right gluteus maximus (upper and lower portions), right gluteus medius, right biceps femoris, right semimembranosus, left adductor magnus, left biceps femoris, and left vastus lateralis.

**Acceleration**
The acceleration phase is the movement between the horizontal position of the club during the downswing and ball impact. The most active muscles during this phase are the serratus anterior, external abdominal obliques, and left biceps femoris.

**Early follow-through**
The early follow-through is defined as the period between ball impact and horizontal position of the club during the follow-through. The most active muscles during this phase are the serratus anterior, external abdominal obliques, and left biceps femoris.

**Late follow-through**
The late follow-through is defined as the period between horizontal position of the club during the follow-through and the end of the swing. Here the active muscles are latissimus dorsi, external abdominal obliques, biceps femoris, and gluteus maximus.
Golf is one of very few sports that see the performer wear only one glove, instead of a pair. Propelled by a better understanding and application of materials science and technology, the glove has come a very long way from its original concept in the late 1800s as a simple means of protection against unwanted calluses. Popular magazines of the time promoted a glove specifically targeted at golfers, with pleats offering more room for movement around the knuckles. These first gloves were generally either fingerless or backless and ensured that the hands remained blister-free.

It wasn’t until the 1930s, when professional golfers began to wear gloves, that their popularity grew. In addition to protecting the hand from the wear and blistering from repeated swings, the glove also offered a layer between the back-hand and club, thereby creating a firmer grip throughout the swing. Eager to try anything that might improve their game, touring professionals quickly adopted the glove as standard equipment. As new players appeared, they were more likely to have already begun playing golf with a glove, and so, by the 1950s and 1960s, it had become firmly embedded within the golfer’s bag. Modern breathable and waterproof materials, combined with new machining and sewing techniques, have led to today’s high-tech piece of equipment.

Generating friction

\[ F_t = \mu F_n \]

If the glove (or grip) is warm or wet, the coefficient of friction will be reduced, making it more likely that the hands will slip.

Comfort and performance

Breathable material

Advanced fabric technology ensures the material of the glove remains soft to the touch and keeps its shape.

Modern breathable materials and ventilation holes keep the hand cool and reduce unwanted moisture.

Elasticated stitching is designed to mold to the grooves of the player’s hand.

Water repellent

Ergonomic features provide support and eliminate discomfort, while ensuring even contact between glove and grip.

Smooth bindings provide comfort when gripping the club with both hands, and elastic helps the fit of the glove.

Carefully placed mesh aids knuckle and finger flexion during the swing.

Ergonomic features provide support and eliminate discomfort, while ensuring even contact between glove and grip.

Modern breathable materials and ventilation holes keep the hand cool and reduce unwanted moisture.

Fabric technologies have revolutionized the performance of sports clothing, and the humble golf glove has benefited from such advancement. Today, glove materials are combined to provide a breathable, lightweight, and comfortable membrane that also repels external moisture.

Material improvement

Breathable

Modern breathable materials and ventilation holes keep the hand cool and reduce unwanted moisture.
What are the core movements that set Tour pros apart?

From watching the Tour pro on television, most people can easily recognize their swings as powerful and efficient. Not surprisingly, the bulk of biomechanical studies have confirmed that professional golfers achieve faster body rotation and a better-timed sequence of the rotating segments—both of which lead to faster clubhead speed compared with high-handicappers. These differences between professionals and less-skilled golfers seem fairly obvious, but what exactly are the characteristics of the swing which lead to faster body rotation and, ultimately, faster clubhead speeds?

**Top of backswing**

<table>
<thead>
<tr>
<th>High-handicap golfer</th>
<th>Professional golfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thorax tilt toward target</td>
<td>Minimal change in thorax tilt from address position</td>
</tr>
<tr>
<td>Lateral pelvis shift away from target</td>
<td>Minimal change in lateral pelvis position from address position</td>
</tr>
<tr>
<td>Foot pressure near outside of foot</td>
<td>Constant pressure on inside of each foot</td>
</tr>
</tbody>
</table>

**Impact**

<table>
<thead>
<tr>
<th>High-handicap golfer</th>
<th>Professional golfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis has not rotated toward the target</td>
<td>Pelvis has rotated toward the target</td>
</tr>
<tr>
<td>Weight has not shifted to left side</td>
<td>Weight has shifted to left side</td>
</tr>
</tbody>
</table>

There are many finely tuned and highly coordinated movements of the arms, hands, and club that contribute to faster clubhead speed, but limb movements represent the end of the kinematic chain and these must be preceded by proper movements in the core—the pelvis and thorax. In terms of core movement, there are several key moves the professional golfers make that distinguish them from the average golfer. In particular, professional golfers maintain lateral stability and posture during the backswing to a greater extent. Core stability can be seen by looking for lateral tilting of the thorax and lateral shifting of the pelvis—professionals show minimal change in both of these key indicators during the backswing. In the downswing, the professionals rotate their pelvis toward the target earlier than the average golfer—this is commonly referred to as “clearing the hips.” In fact, professional golfers begin the downswing with pelvis rotation, whereas the average golfer tends to begin the downswing with thorax and shoulder rotation. Finally, at impact, the professional’s pelvis and thorax are both opened toward the target.

These core movements are achieved as a consequence of the golfer’s interaction with the ground. Professional golfers impart greater anterior–posterior shear forces and reduced lateral shear forces on the ground compared with less-skilled golfers. The skilled golfer’s foot pressure is to the inside (medial) and toward the heel (posterior) of each foot. This interaction with the ground promotes stability at the transition of the backswing. This then sets up a quick, powerful rotation during the downswing, which is initiated by the anterior–posterior shear forces. The average golfer struggling with low clubhead speed could learn a great deal from studying the core movements of professional golfers.

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**Tilt-shift**

The image of the professional golfer (right) demonstrates two key characteristic core movement patterns at the top of the backswing. First, the thorax is tilted away slightly from the target (white line), keeping close to the address position, and second, the pelvis has maintained its lateral position during the backswing (blue line). These core movements are possible because of a balanced interaction with the ground. The professional golfer also shows reduced lateral shear forces and a constant pressure on the medial aspect of each foot (red lines). In contrast, the high-handicap golfer (left) has shifted the pelvis laterally (blue line), tilted the thorax toward the target (white line), and allowed foot pressure to move to the lateral aspect of the rear foot (red lines).

**Read the hips**

A side-on view at impact: the professional golfer (right) has rotated the pelvis toward the target. The high-handicap golfer on the left has kept the pelvis square to the target at impact, limiting clubhead speed. In addition to rotating the pelvis toward the target, the professional has also shifted the pelvis toward the target during the downswing, evidenced by the right heel being slightly raised off the ground at impact.
Is weight transference significant? How much should I shift my weight during the swing?

Weight transference is a coaching term used to convey the proportion of the golfer’s total weight that should be distributed over each foot during the swing. More accurately, biomechanists have defined weight shift as the change in the proportion of total downward force under the front foot throughout the movement. According to popular coaching manuals, for full swings the weight should begin balanced evenly between both feet (about 50 percent each) at address. According to popular coaching manuals, for full swings the weight should begin balanced evenly between both feet (about 50 percent each) at address. Conventional coaching advocates that the weight should shift toward the rear foot during the backswing and then rapidly forward toward the front foot in the downswing, and research seems to support this. However, other patterns of weight transfer have been identified which are associated with expert performance. Two distinct weight-transfer techniques—the so-called “front-foot” and “reverse” styles—have been identified, while a swing technique called “stack and tilt” is anecdotally popular among some players and coaches. The front-foot style matches the conventional idea of weight transfer. The reverse style is distinguished by the weight shifting back toward the rear foot during mid-downswing. The stack-and-tilt swing, in terms of the proportion of total downward force under the front foot, can be generalized as “staying centered over the ball” rather than shifting weight toward the rear foot during the backswing. Axial rotation and lateral tilt of the thorax achieve comparable angular speed profiles throughout the downswing. Given that there is room for the torso to tilt and the pelvis to shift laterally, this action would explain the weight shift toward the front foot in the swing. Furthermore, the peak in downward force occurring before impact (event ED) represents the force required for decelerating pelvis rotation and lateral movement, which is the beginning of the kinematic chain. In light of these scientific findings, the reverse-style weight transfer appears to be associated with exceptional performance. An awareness of the two patterns presented here, and experimentation with pressure mats, will enable the player to explore which swing technique fits best.

![Weight transfer styles](image)

<table>
<thead>
<tr>
<th>Weight transference</th>
<th>Front-foot style % weight under front foot</th>
<th>Reverse style % weight under front foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>TA</td>
<td>54%</td>
<td>22%</td>
</tr>
<tr>
<td>MB</td>
<td>50%</td>
<td>20%</td>
</tr>
<tr>
<td>LB</td>
<td>19%</td>
<td>42%</td>
</tr>
<tr>
<td>TB</td>
<td>17%</td>
<td>80%</td>
</tr>
<tr>
<td>ED</td>
<td>24%</td>
<td>82%</td>
</tr>
<tr>
<td>MD</td>
<td>22%</td>
<td>80%</td>
</tr>
<tr>
<td>BC</td>
<td>17%</td>
<td>42%</td>
</tr>
<tr>
<td>NF</td>
<td>20%</td>
<td>19%</td>
</tr>
<tr>
<td>FP</td>
<td>54%</td>
<td>78%</td>
</tr>
</tbody>
</table>

![Total force vectors](image)

- **Front-foot style**
  - Backswing
  - Downswing
  - Follow-through

- **Reverse style**
  - Backswing
  - Downswing
  - Follow-through

![Fancy footwork](image)

- **Weight-watching** The nine events for a low-handicap golfer: take-away (TA), mid-backswing (MB), late backswing (LB), top of backswing (TB), early downswing (ED), mid-downswing (MD), ball contact (BC), follow-through (MF), finish position (FP). The percentage bars represent average values for the proportion of total vertical force under the front foot from 0 percent = no weight under front foot, 100 percent = all weight under front foot. Red values correspond with the front-foot group and blue values with the reverse-style group.

![Fancy footwork](image)

- **Feel the force** Here the total force is visualized as a vector, with its length representing the magnitude of the force, and its direction showing the direction of the ground’s reaction force to each foot. At TB, vertical force (weight) is greater under the rear foot (furthest away from target) than the front foot (closest to target). At ED, the rear foot vector points posteriorly, which means the rear foot is pushing anteriorly into the ground. The front foot short closed in the target is pushing in the opposite direction (posteriorly). The opposition directions of the ground reaction forces by each foot cause rotation. At BC, the directions of both force vectors have reversed.

![Fancy footwork](image)

- **Ground reactive force** The downward force for each of the golfer’s feet is shown: red for the front foot, black for the rear foot. The top graph is an example of the downward forces involved with a swing consistent with the front-foot style, and the bottom one a swing consistent with the reverse style. The downward force for each foot does not necessarily equal the golfer’s weight (weight in N = mass in kg x acceleration due to gravity at 9.8 m/s²). Because of angular momentum, the rotation can drive the golfer into the ground or lift the golfer off the ground. For this reason some players’ heels leave the ground during ball contact.
Being a good golfer is not just about being able to hit the ball well and consistently, but also about knowing which shots to make in which circumstances—making the right decision at the right time in the right place. This mostly means setting up each shot to give you the best chance of making par or better.

How a player decides on the most appropriate shot at any one time is governed by many factors. Is it best to play it safe, or take a risk? Do you “take on” the hazard—water or sand—or avoid it? How a player is performing against their handicap or an opponent, their position on the leader board, or their current mental state following a run of good or bad luck can all dictate whether a conservative or risk strategy is selected.

Although it seems obvious that a more able golfer would take fewer risks throughout their round, given their aptitude and the potential cost of the risks, and that a novice would have more to gain from a riskier strategy, this may only be partly true: research does also reveal that our general risk-taking behavior throughout the 18 holes may say more about our character than our score. Top golfers instinctively select a strategy for each shot based on the environmental cues they observe and their past experiences. Firstly, by scanning the hole they are consistently assessing the risks. They evaluate the probability of a particular shot type being successful, and assess the penalty if it goes wrong and the reward if they pull it off.

How we assess risk is very much dependent on what we have to lose if it all goes wrong. Even for players of a high standard, playing it safe does not mean avoiding the rough—or even hazards—as much as ensuring that the next shot will enable them to use a predictable swing, resulting in accurate length and line.
What is the optimal pattern of wrist torque for maximizing clubhead speed?

There is a lot of discussion about the release of the wrists during a swing as impact approaches. The so-called “late hit,” popular in many coaching manuals, is characterized by keeping an acute angle between the lead forearm and the club shaft for as long as possible during the downswing. Cochran and Stobbs proposed that although the “natural wrist release”—caused by centrifugal force of the swinging club—provides plenty of clubhead speed, slightly more could be squeezed out of the swing if the wrists actively applied torque late in the downswing. They also noted that in order for this strategy to work the wrist angle would have to be released later than in the natural release.

More recently, many studies have looked into optimizing the release behavior of the wrists before impact. In general, three main wrist release strategies have been investigated: the “natural release,” which requires no muscular torque; a “delayed wrist action,” in which wrist torque is applied to maintain the wrist angle and promote the late hit; and the “delayed-active wrist action,” similar to the delayed wrist action but followed by an active wrist torque to accelerate the club into the ball. Simulation studies have agreed that the delayed-active torque technique offers potential for maximizing clubhead speed. Sprigings and Mackenzie showed that if wrist torque is applied to maintain the wrist–shaft angle until the lead arm reaches “eight o’clock” when viewed from the front (the “delayed wrist action”), at which point the torque is applied in the opposite direction to actively release the wrists, clubhead speed could be maximized (by about 1.6 percent faster than natural release). However, the timing window in which these torques need to be applied is extremely sensitive, which suggests that the benefits associated with delayed-active wrist torque are difficult to achieve. If the active torque is mistimed by just 50 ms (half the time it takes to blink), clubhead speed would be slower than the natural release. This sensitivity to timing suggests optimizing wrist action is highly dependent on the player’s proprioception, or feel. All of which suggests that, for the average golfer, it is probably more worthwhile keeping a relaxed grip and trying to release naturally.

Can the “late hit” help my driving distance?

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How do grip forces change during the golf swing?

The grip is one of the most important facets of the golf swing because it represents the only interface between the golfer and the club throughout which all force and energy must be transmitted. Many golf instruction manuals recommend that the grip should be kept as loose as possible to allow a full and unrestricted release of the golf club, but also firm enough to prevent the club from slipping, particularly during the impact phase. A loose grip can also help to maximize the "feel" of a golf shot and reduce the likelihood of overuse and repetitive strain injuries occurring in the hands, wrists, and forearms. Another recommendation that appears to be prevalent in the golf coaching literature is that grip firmness should remain fairly constant throughout the golf swing. However, a basic mechanical analysis indicates that this supposition cannot be correct. When a golf club is swung, centrifugal forces are generated, which are proportional to the amount of acceleration and deceleration of the golf club. These load forces have been estimated to be up to 450 N for very fast swings. Additional forces change because it represents the only interface between the golfer and the club throughout which all force and energy must be transmitted.

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How firm should my grip be?

Owing to difficulties with measuring grip forces, only a few biomechanical investigations have focused on this aspect of the golf swing. Budney measured grip forces under the last three fingers of the left hand, on the base of the first three fingers of the right hand, and under the left thumb, using an instrumented driver fitted with strain gauges. Although individual differences were reported, the three golf professionals analyzed exhibited grip forces which were closer to those recommended in the coaching literature than did the three amateur golfers. However, owing to the small number of golfers analyzed in this study, the generality of these findings is limited. In a more extensive recent study, Komi and colleagues showed that 20 golfers (male and female), regardless of playing ability, had their own unique grip force "signature"—that is, grip forces were highly consistent for each golfer over repeated shots but varied considerably between golfers. Certain trends were evident across golfers, however, such as local peaks in grip force just before and after impact, and an overall higher force on the left hand than the right hand for nearly all golfers tested. The data here are for right-handed golfers but it is worth noting that the situation is mirrored for left-handed golfers.

Measuring grip forces

In the swing Analyses of grip forces using grip and glove sensors in conjunction with high-speed video have revealed highly individualized grip force patterns across golfers regardless of playing standard. An example force–time profile for the left and right hand, and both hands combined, is shown here, along with six key points and corresponding swing position images.

Handy hints Force sensors use a semi-conductive ink that is applied between electrical contacts and thin polyester sheets, giving the sensors a resultant thickness of just 0.1 mm. These extremely thin and lightweight sensors can be fitted around the circumference of the golf grip, or attached to the gloves themselves, to allow the changing forces at numerous locations to be measured simultaneously.

Grip forces

Getting a grip Even as far back as the late 1970s, scientists were able to measure grip forces throughout the swing by using a modified grip equipped with a series of strain gauges. Results collected from professional and amateur players began to reveal demonstrable differences in force patterns between skill levels.
Can biomechanical analyses help to increase consistency?

Can the “swing plane” improve how I hit the ball?

The “swing plane” concept was originally introduced by Seymour Dunn in the 1920s but popularized by Ben Hogan during the 1950s in his classic instructional text, Five Lessons: The Modern Fundamentals of Golf. The swing plane is now generally considered to be an imaginary two-dimensional surface, extending from the center of the golf ball through the top of the golfer’s sternum, along which the clubhead should travel during the swing. It is thought to be an important aid to improving the swing because it supposedly enables the golfer to deliver the club more consistently at impact, leading to less dispersion of shot outcomes.

There have been several biomechanical investigations into the swing plane concept but these have typically been equivocal and contradictory. For example, in three-dimensional kinematic studies by Vaughan and Neal and Wilson, it was found that the plane of the shaft of the golf club was not constant for any substantial period of time during the golf swing. In contrast, Lowe and Fairweather reported that the downswing and follow-through phases of the swings of expert golfers were approximately planar. More recently, Coleman and Anderson showed that it was possible to fit a single plane to the motion of the golf club during the downswing for a group of experienced golfers, but the fit varied between golfers and also between clubs (that is, a pitching wedge, a 5-iron, and a driver).

Despite being the focus of a number of scientific investigations, the swing plane still remains a contentious concept and further empirical research is warranted. However, Jenkins has suggested that the concept might be used as an “idealized replica” to help golfers develop a mental image of what their golf swing should look like in their quest to improve. Indeed, in his original writings, Hogan noted great improvements in the techniques and performances of golfers that he had personally taught after encouraging them to visualize the backswing and downswing movements along the swing plane.

Plane simple
Ben Hogan famously visualized the swing plane as a large pane of glass running from the ball parallel to the target line and placed over the golfer’s head so that it rests on their shoulders, the theory being that the shoulders, arms, and hands should all move along this plane throughout much of the golf swing. The angle of inclination of the swing plane is determined by the golfer’s stature and the distance they stand from the ball at address, which is dictated by the club used (for instance, a pitching wedge, 5-iron, or a driver; see above).

Got that swing
No two golfers swing the golf club along identical swing planes. Tiger Woods (above) approximates the swing plane during both the backswing and follow-through, whereas Jim Furyk (above right) moves above and below the swing plane during different portions of the backswing and follow-through. Both are Major champions.

Computer aid
Recent research has contradicted Hogan’s original ideas by showing that the trajectories of the shoulder, elbow, and wrist joints during the swing do not move along a single plane whereas the clubhead does at least for a portion of the swing. This computer-generated stick figure shows a real golfer nearing impact.
Is there evidence for an optimum movement model?

It is tempting to treat the golf swing technique as an optimization problem, in that every position the golfer moves through has an ideal. This is the approach Mann and Griffin attempted to support by combining the swings of over 100 professional golfers. However, while it might be theoretically possible to create a simulation or robot capable of such a perfect, repeatable sequence, the human player has many more variables to contend with, both internal and external, so that a single, fixed swing pattern is not what’s required. In other words, each player must consider their own strengths and weaknesses, which have arisen from their past experience and can be psychological as well as physiological. The player must then use that knowledge to simplify the task of coordinating nearly 800 separate muscles, which must be precisely controlled to create a functional swing.

A synergy is a conceptual linkage of parts (such as muscles) that reduces the information the brain needs to supply to operate the movement. When coaches refer to “movements” in the golf swing (for example, lead the downswing with the hips) they are supplying a small amount of information that collectively represents a great deal of information. Synergies operate in a similar way. What makes a golf swing good is not just the positions it moves through but, probably more importantly, the stability of these temporary synergies which are very individual-specific and, if stable, will lead to predictable golf shots.

Biomechanical studies confirm that individual variation is the rule rather than the exception and, although swings of good golfers may have certain commonalities, each golfer still has their own signature. It may be reasonable to imagine a perfect swing for an individual playing a specific shot, but throughout a round of golf, a tournament, or a career, to perform well the individual must be able to adapt the swing to suit the specific situation and the shot being played. Instead of a perfect swing, it is probably better to talk about an adaptable swing that adheres to general biomechanical principles and can accommodate many different situations. Practice drills which improve kinesthetic awareness are probably very influential in improving golf-specific synergies.

Creating a functional swing

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