

## **The Sequence of Body Segment Interactions in the Golf Swing**

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## Introduction

Golf is widely regarded to be a challenging game to master. The difficulty of the sport becomes clear when we consider that a large component of the game relies on a full swing that, not only requires the club to be swung by the body at high speed, but also with great precision. In fact, the higher the speed of the club, the more critical precision becomes; this presents a conundrum for the golfer who recognises high clubhead speed can be advantageous if controlled, as it may lead to longer drives (Hume et al., 2005). Fortunately, an effective swing both increases clubhead speed and also increases accuracy. The exact recipe, however, varies between golfers and situations because of differences in physical characteristics, histories, and demands of the shot (see Chapter XX: Inter- and Intra-individual Movement Variability in the Golf Swing). Instead, we can present general biomechanical principles that golfers should be aware of, so that they can explore swing techniques that improve performance, constrained or guided by those principles.

Although each golfer's body is unique, in general, our bodies possess many common characteristics. Our bodies have evolved to fulfil certain purposes that aided our survival, such as long distance running (Bramble & Lieberman, 2004) and throwing (Roach et al., 2013), which were vital for successful hunting. Mass is concentrated at our core, meaning proximal muscles (e.g. pectoralis major and gluteus maximus) tend to be wider, stronger, and heavier than muscles that move our most distal body segments. This structure gave us our advantage when hunting; swinging our legs underneath our body during running allowed us to run long distances while expending relatively little energy. For example, the tibia is shorter compared to the more proximal femur, this decrease in distal bone length helps decrease the moment of inertia of the lower extremity and subsequently aids running economy. The diameter of long bones also tapers off in a proximal to distal fashion, further helping to reduce moment of inertia. Examining effective running biomechanics also reveals the importance of reducing moment of inertia, as can be seen by the flexed knee bringing the mass of the leg close to the body during the forward swing – another step in decreasing energy demand (Novacheck, 1998). Similarly, the need to execute a powerful throwing motion led to the development of long-bone length, diameter and tendon insertion points well suited for generating high rotational speeds (Roach et al., 2013). This meant the upper extremity was much more capable of high speed movements compared to moderate speed, endurance movements of the lower extremity. These biomechanical characteristics remain with us and have important implications for the golf swing, in particular, the sequence of body segment movements, which is the focus of the rest of this chapter.

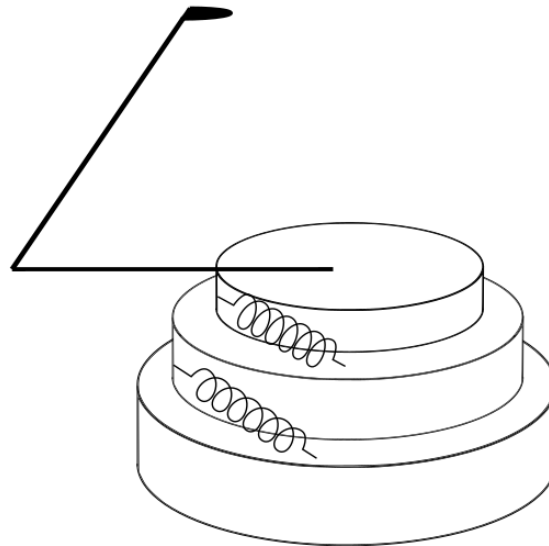
## Review of Current Research

### *Early Work on Proximal to Distal Sequencing*

The book *'The Search for the Perfect Swing'* by Alastair Cochran and John Stobbs (1968) constituted a ground breaking contribution to our understanding of the golf swing. Their achievement is even more impressive when considering the limitations in technology for measurement and computation nearly half a century ago. Much of this chapter refers back to the original models and reasoning of Cochran and Stobbs, as their work has influenced many researchers of golf biomechanics, and much of their work remains relevant today.

Cochran and Stobbs modelled the swing as three cylinders of decreasing diameter stacked on top of each other and free to rotate about a common vertical axis (Figure 1). Each successive cylinder, which represented different components of the golfer's core, was connected to the lower one by a spring, which could inhibit rotation when being stretched but also, and more importantly, store elastic energy. Representing the lead arm and the club in this model were two levers constituting a double pendulum. The proximal end of the lead arm lever was connected to the top cylinder and the distal end as a free hinge to the proximal end of the club lever. If the cylinders in

Figure 1 were rotated clockwise until the springs were stretched to their limit, it would be advantageous in terms of clubhead speed to release the springs sequentially from bottom to top. In other words, once the bottom spring has done all the work it can on the system, the top spring could be released in order to continue accelerating the top cylinder. Following this sequence, therefore, allows the springs at the bottom to transfer energy more efficiently to the club. This was one of the first accounts of the proximal to distal sequence of segmental motion in the golf swing.



**Figure 1.** Mechanical model of the golf swing proposed by Cochran and Stobbs (adapted from Cochran & Stobbs, 1968).

Additionally, the contraction of the springs releasing not only accelerates the higher cylinder, but as a consequence, decelerates the lower cylinder. Verifying this unstated behaviour of Cochran and Stobbs' model, Bunn (1972) argued that, to maximise the linear speed of the last segment in a kinematic chain, each segment should reach its respective maximum velocity in a proximal to distal sequence. This meant that a segment should reach its maximum velocity after its proximal neighbour had begun decelerating. Bunn's reasoning was based on the components of the system's angular momentum – if distal segments could be tucked in close to the body until late in the movement, moment of inertia could be minimised and angular velocity maximised – a movement principle well built into our anatomy as discussed above. At impact, if the segments were released away from the body, the radius of rotation of the lead arm and club could be increased, thereby increasing linear velocity of the club. The summation of speed principle was not originally crafted with the golf swing in mind, but it was rather a more general principle applicable to many sporting actions; however, the implications for golf are clear. Putnam (1993) later substantiated these claims with mathematical equations of motion. Putnam also showed that distal segments were not only accelerated by muscle torques at the proximal joint, but also interaction torques, which were dependent on inertial forces and contact forces between neighbouring segments. Thus, each segment will influence the motion of its neighbouring segment, by joint forces in a way dependent on its state (position and rate of change of that position). The proximal to distal sequencing of distal segments arises because of the mechanical behaviour of linked systems.

Cochran and Stobbs stated that the double pendulum had to be driven "*smoothly and strongly*" and that the angle of wrist cock should be maintained until "*the time that uncocking will take place of its own accord*" (Cochran & Stobbs, 1968, p. 50). In other words, the swinging lead arm

and club experience centrifugal force that, in the club's case, will want it to continue moving in a straight line away from the arc of the swing. This will serve to uncock the wrists on the downswing bringing the lead arm and club into a straight line with no need for wrist torque. Jorgensen (1970) showed mathematically that, to maximise clubhead speed at impact a negative wrist torque 'hindering' the wrist angle uncocking was necessary.

The core of the golfer in Figure 1 is represented by stacked cylinders decreasing in size from bottom to top. This configuration reflects a key difference in proximal core segments compared to distal limb segments. While distal limb segments rotate around a more horizontally oriented axis (i.e. upper arm ad/abduction) and they are connected end-to-end, proximal core segments tend to rotate around a more vertically oriented axis running through the middle of the stacked segments. These differences relate to how energy and momentum is transferred between them. Empirical evidence for proximal to distal sequencing between core segments will be discussed next, followed by the addition of distal limbs and the club in later sections.

### *Core Rotation Sequence and the X-Factor*

In a 1992 article for Golf Magazine, golf instructor, Jim McLean, observed that long drivers on the PGA TOUR seemed to have a greater difference in shoulder and hip turn compared to the shortest drivers on tour (McLean, 1992). McLean called this swing feature the 'X-Factor' because of how imaginary lines connecting the hip joint centres and shoulder joint centres crossed and resembled an "X" when viewed from above. We should note that "hip" and "shoulder" turn, as they are often called in popular golf publications, are not meant to represent rotation of the femur in the hip socket and rotation of the humerus in the shoulder girdle, respectively. Rather, these terms are intended to indicate rotation of the pelvis and rotation of the upper ribcage, or thorax, respectively. We will use the terms pelvis and thorax rotation in place of the golf terms hip and shoulder turn for the rest of the chapter.

Subsequent research has shown the relative angular displacement between the pelvis and thorax about an axis oriented approximately normal to the swing plane at the transition from backswing to downswing, which roughly corresponds to McLean's conception of the X-Factor, to have a strong relationship with clubhead speed (Brown et al., 2011; Chu et al., 2010; Myers et al., 2008). Unfortunately, variations in coordinate system, segment, angle and transition timing definitions complicate comparisons between studies. Surprisingly, even though clubhead speed and handicap are strongly related (Fradkin et al., 2004), X-Factor has not been shown to discriminate between skill levels (Cheetham et al., 2001; Cole & Grimshaw, 2009; Egret et al., 2004; McTeigue et al., 1994), with the exception of Zheng et al (2008) who found a significant difference only in the two extreme skill groups. X-Factor is related to swing speed, but does not seem to be acquired; instead it appears to be individual specific and likely related to body anthropometrics and joint mobility and flexibility. Accordingly, discussion may be necessary to determine whether coaches should encourage golfers to increase their X-Factor. Notably, McLean's article had a marked impact on how the golf world thought about coordination between the core segments of the golfer.

Burden et al. (1998) suggested that low-handicap golfers could increase clubhead speed by starting the downswing with pelvis rotation toward the target, followed by the thorax and that this pattern adhered to the summation of speed principle. Cheetham et al. (2001) found similar results and introduced a discrete variable called "X-Factor Stretch", which is the amount X-Factor was increased as a result of delaying thorax rotation early in the downswing. Cheetham and colleagues found that highly skilled golfers increased the angular separation of the pelvis and thorax during the downswing more than less skilled golfers did. Although small groups were compared, it is worth noting that there was no difference in X-Factor between the groups, only the amount X-Factor stretched, or increased, during the downswing. The effect of X-Factor Stretch could be explained by

its initiation of the stretch-shortening cycle. Although it is not understood completely, the stretch-shortening cycle is thought to invoke several mechanisms important for generating speed:

- a) By effectively increasing the range of motion, the distance over which the distal segment is able to accelerate is increased, which increases the amount work done and therefore the kinetic energy and speed of the distal segment.
- b) Pre-stretching the muscle enables it to begin the concentric contraction phase with a higher active state and force value (van Ingen Schenau et al., 1997).
- c) Stretching muscles can also trigger the stretch reflex, which increases neural activity within the muscle initiating a contraction to resist the stretch. The force-velocity relationship for skeletal muscle also indicates that stronger responses can be achieved if the muscle is stretched quickly (Komi, 2000).

Incidentally, Roach et al. (2013) pointed out that decoupling the pelvis and thorax was an important adaptation that allowed increased torque production in the core, critical for throwing actions. X-Factor Stretch seems to be what Cochran and Stobbs had in mind when they created their model consisting of the cylinders stacked on top of each other connected by springs. During the downswing, if the pelvis starts rotating toward the target earlier than the thorax, then the oblique abdominals would be put on stretch – the same way the spring connecting the cylinders can be stretched by increasing the angular displacement between them. For golfers to increase their X-Factor stretch there are many exercises available to increase thorax mobility and pelvis stability (please refer to Chapter XX: Strength and Conditioning in Golf).

The contribution of the stretched core muscles associated with the X-Factor Stretch to clubhead speed has been disputed by Kwon et al. (2012). In a sample of 14 elite level golfers, the authors showed that the 'swing plane' is only close to planar during the execution phase of the swing (from shaft horizontal on the downswing to shaft horizontal on the follow-through). Kwon and colleagues defined a 'functional swing plane', which was a minimisation of trajectory errors for different phases of the swing. During the early downswing, the hands and club drop from a more upright plane onto a shallower plane for the execution phase, which is consistent with the findings of Vaughan (1981). The thorax was shown to rotate on a more horizontal plane, which led the authors to suggest that torque supplied to the arms from the thorax would consequently act to pull the club below the functional swing plane as impact approached. This deviation from the functional swing plane at impact would either cause a mishit with suboptimal clubhead speed or a compensation to get the moving distal segments back on plane, which would be inefficient, difficult to control and also result in suboptimal clubhead speed. It is not clear, however, if the authors considered a brief contribution of the thorax and its subsequent deceleration, as with the proximal to distal sequencing discussed thus far, or if they considered the thorax to be doing work on the arms for the entire swing, which would most likely act to pull the club away from the swing plane. Furthermore, they did not explain why they thought segments rotating in slightly different planes would not meaningfully exchange energy. We suggest research needs to be conducted to determine the mechanism linking X-Factor Stretch to clubhead speed, if any.

#### *Adding the Upper Extremity*

If we add the upper extremity to the core segments discussed so far, we may expect that:

- a) Maximum speeds are reached in a proximal to distal sequence and
- b) The magnitude of those maximum speeds increases proximal to distal.

Cheetham et al. (2008) reported the maximum speeds and timing of the pelvis, thorax, arms and club. They found that PGA professionals achieved higher peak segment speeds than a group of amateur golfers, and that the magnitudes of those peak segment speeds followed the familiar proximal to distal order. The timing between the peak speeds of successive segments, on average, followed the proximal to distal sequence for the professionals, but not for the amateurs. The comparison of timing between groups however, did not reach statistical significance. The authors noted the high timing variability for the amateurs, which is an important finding on its own and also likely contributed to the unclear distinction between groups. Neal et al. (2008) looked more closely at sequencing between 'well timed' shots and 'poorly timed' shots, which were self-identified by the study participants. Their study design added to that of Cheetham and colleagues, who may have unintentionally included poor shots in a study of optimal sequencing and timing. However, Neal et al. (2008) found no differences between well timed and poorly timed shots. They explained that golfers tend to attribute high quality to a shot when contact is good and are relatively insensitive to timing differences.

If we reconsider the throwing example in the introduction, if the implement being thrown were a spear, one of the keys to success is to maintain its orientation so that its long axis is close to parallel with its velocity vector – this prevents an end over end torque from ruining the throw. Swinging a golf club on the other hand is much different as the club rotates roughly around its long axis but also substantially around axes orthogonal to the long axis. Indeed, Anderson (2007) postulated that adding a golf club to the open link system might interfere with the proximal to distal sequencing shown for other "evolved" sports, such as throwing discussed at the start of this chapter. Accordingly, the club as an extension to the distal most segment of our body does not follow the natural tapering of volume, mass and length found in body segments and likely requires an adaptation of coordination in the golf swing to achieve optimal speeds and control. Analysis of a data set consisting of nearly 500 low handicap and scratch golfers showed that the angular velocities of the pelvis, thorax and arms peaked at about the same time in the swing, while the clubhead velocity peaked later and very close to impact. Anderson (2007) noted that body segments peaked at around same time and the non-body segment – the club – peaked later, which could be considered evidence counter to the principle of proximal to distal sequencing along the segments mentioned. Anderson's findings are in contrast to the findings of others (Cheetham et al., 2008; MacKenzie and Sprigings, 2009; Neal et al., 2008). Furthermore, Anderson (2007) found that several kinetic quantities such as angular momentum and kinetic energy did not follow a proximal to distal sequence. Similar to angular velocity, distal segments showed higher peak total kinetic energy, but timings of peak energies were approximately the same for the body segments and later for the club. It is difficult to explain the differences from the rest of the literature reported by Anderson (2007); the movement model used and the kinematics calculations, although seemingly valid, make comparisons between studies difficult. In support of Anderson's findings, Nesbit and Serrano (2005) found that work was mainly done by the lumbar region, however, the timing of peak work found by Nesbit and Serrano generally followed the proximal to distal sequence.

The aforementioned empirical studies made inferences from groups, or large samples, of golfers (Anderson, 2007; Cheetham et al., 2008; Neal et al., 2008), as is common in sports biomechanics research. However, Ball and Best (2007) showed that different swing styles exist among low handicap golfers, and that the specific style does not relate to playing ability. The fact that several swing styles may exist in Anderson's (2007) large data set, may explain the discrepancy between his results and those of other researchers. Representing a group of golfers by a mean value and simple measure of dispersion around the mean, such as standard deviation, may mask individuals within the group who exhibit common timing profiles and are sensitive to timing differences. As laid out by Button et al. (2006), coordination profiling may be the path to understanding nuance in movement patterning where individual variability is sufficiently large, which it appears to be in the golf swing. Additionally, it is possible that smaller sample studies were

prone to sampling bias, which could have the effect of magnifying the presence of proximal to distal sequencing.

Work by Kenny et al. (2008) also showed evidence against the proximal to distal sequencing principle in the golf swing. The authors created a forward dynamics model and set the muscle torques using the 3D kinematics of an elite level golfer. The authors found that the kinetic energy for the arms peaked before those of the pelvis and thorax segments and suggested that the proximal to distal sequence may not be optimal. However, as MacKenzie and Sprigings (2009) point out, Kenny et al. (2008) did not actually investigate 'optimal' sequencing, rather the sequencing of one elite level golfer and assumed that golfer's movement pattern was optimal. In Kenny et al.'s (2008) forward dynamics model, they could have manipulated muscle torque sequencing to find an optimal sequence, which has been done by others particularly when looking at wrist torque.

Many mathematical and simulation studies have been conducted to test what Cochran and Stobbs originally suggested (i.e., that the end element in the model, the wrist hinge, should uncock by forces extending it on its own accord). In order for this to occur, a negative torque needs to be applied to maintain an acute wrist angle and to keep the club as close as possible to the swing hub (Coleman and Rankin, 2005; Neal and Wilson, 1985; Sprigings and Mackenzie, 2002). Keeping the club close reduces the moment of inertia while the more proximal segments build up angular velocity. It is now generally accepted that wrist torque through ulnar deviation has relatively little effect on increasing clubhead speed and, in fact, is more likely to negatively affect the timing of the swing for all but the best golfers. MacKenzie and Sprigings (2009) built on past simulation studies by looking at the optimal muscle activation sequence across proximal and distal segments in the golf swing. The authors found that, for the most part, the optimal sequence followed a proximal to distal pattern. The muscle torque initiating thorax rotation was first to become active in their model, followed by the abduction torque at the shoulder and wrist ulnar deviation shortly after. There was, however, one exception: an additional element in the upper extremity – forearm rotation – was activated last, which constituted a deviation from a proximal to distal sequence. MacKenzie and Sprigings explained that ulnar deviation contributed very little to accelerating the golf club because close to impact ulnar deviation is perpendicular to the direction of the golf club's movement. Forearm rotation is the final element in the sequence and, assuming the golf club shaft and lead forearm were not parallel, contributes substantially to clubhead speed at impact. This pattern of activation fits with the findings of Marshall and Elliot (2000), who have looked mainly at throwing and tennis ground strokes. More specifically, long axis rotation of the upper arm is important for generating linear speed at the end point and occurs later than the proximal to distal sequence suggests.

### **Implications for the Game**

Findings in the literature on the importance of proximal to distal sequencing in the golf swing remain equivocal and have not reached a consensus. Simulation studies have shown that proximal to distal sequencing is consistent with optimality (MacKenzie and Sprigings, 2009), although with a slightly modified set of segments than originally proposed by Cochran and Stobbs (1968). To summarise, the pelvis should reach its maximum angular velocity first, followed by the thorax and the lead arm, at which point only negative torque should be applied at the wrist to maintain its acute angle until late in the downswing; the wrists should either uncock naturally due to centrifugal force or, if the golfer's skill level permits, a well-timed positive wrist torque can be applied, and finally forearm rotation tops up clubhead speed and squares the face for impact.

Many empirical studies have shown this sequence is not present, even in elite level golfers. This can be explained a number of ways:

- Many studies have used different models and calculations for various reasons. Although these discrepancies do not necessarily invalidate the findings of these investigations, they do make comparisons between studies difficult.
- The game of golf consists of more than hitting a ball with a full swing in laboratory conditions. Many players may be able to achieve low handicap or even professional status because of outstanding performance in other areas of the game, such as short game and putting and a strong psychological component.
- Golfers are all constrained in different ways by their physical strengths and weaknesses, as well as strengths and weaknesses that have crept in over years of training, practice and development in varying environments. These constraints may lead golfers to discover swings that work well, although not optimally (see Chapter XX: Inter- and Intra-individual Movement Variability in the Golf Swing).

With these considerations in mind, golfers and practitioners should consider whether instilling a proximal to distal sequence might be beneficial. If a golfer who is free of major physical limitations struggles to achieve satisfactory distance, the timing of the swing may be at fault. Similarly, symptomatic shot patterns (e.g. high weak fade) are often consistent with poor timing or sequencing. In these situations, 3D systems such as AMM3D and Golf Biodynamics offer practical solutions for analysing the sequencing of the swing and for intervening to improve. As with most aspects of the golf swing, one solution does not fit all. Elite level golfers looking to fine tune their performance may not find it worthwhile to rebuild their swings to follow the proximal to distal sequence. Similarly, it may not be safe for golfers with physical constraints to try to achieve the sequence swing outlined in this chapter. X-Factor Stretch in particular needs further research to determine possible links and mechanisms to lower back injury, which is already a large and growing problem in golf.

### Summary and Future Directions

We have identified support in the literature as well as counter examples for a particular proximal to distal sequence of segment interactions in the golf swing. Although the movements of the golfer's segments can be measured with great precision, and scientific understanding of their role in the swing has reached great heights, "*combining the movements is where the art begins*" (Cochran & Stobbs, 1968, p. 47). There will always be examples of golfers with idiosyncratic swings who outperform those with simple, rhythmic, and well-timed swings. Rather than prescribing to-the-millimetre specifications of how the body should move in this chapter, we have offered guiding principles that golfers and practitioners should be aware of, and carefully consider, when technically inspecting their own or others' swings.

In a paradox where empirical studies may not be able to find what is optimal and simulation studies may not be able to find what is practical, we urge both sides to work to narrow these limitations. Empirical studies should focus on individual movement and coordination patterns or groups based on a common profile so that important findings are not covered up by group means. Simulation studies should continue to expand their models not just to represent a single golfer but a population of golfers with varying constraints.

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