

Current golf performance literature and application to training

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Objectives: The review paper addresses current interests among golfers emphasizing importance of physical improvement specifically on flexibility, balance and stability, and strength and power.

Design: The review paper contains two different perspectives of golf literature, and establishes evidence-based training design.

Methods: Golf biomechanics has been investigated scientifically over several decades to identify the vital components of superior golf swing mechanism from various levels of golfers and computer simulations. This paper introduces two aspects of an up-to-date literature; 1) performance-based research on driving/shot performance and its variability, and 2) clinical-based research specifically on low back stress, spinal stabilization mechanism, and trunk/spinal muscular activation. The final part of the paper addresses the appropriate training design for golfers.

Results: Both performance and clinical aspects of information are well established to guide evidence-based training for golfers.

Conclusion: The recommendations are specifically for flexibility and resistance training to enhance overall physical fitness for golf performance.

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Key words: Golf training ■ performance application ■ injury prevention.

Introduction

Physical fitness has been shown to influence different sport performance and in recent decades, it is especially noticeable for competitive golfers. In the past, golf was treated as a skill oriented sport and effect of physical fitness such as body composition, strength, and power was somewhat ignored even at a professional level. The important physical component many golfers believed was flexibility. With the advent of technology in golf, a majority of competitive golfers now understand that fitness is also an essential part of their success.

Sport scientists are interested in investigating golf performance such as mechanism of superior driving distance and accuracy.³⁶ Past studies also investigated physical components of swing biomechanics such as shoulder-hip separation (aka, X factor) to understand rotary-specific flexibility that is necessary for golf.^{8,11,50} There are some studies to identify the importance of postural stability in golf by using force platforms to analyze sway pattern of center of pressure, weight transfer, and weight distribution between left and right legs.^{4,5,65} It is logical to think that training modules for overall physical improvement should be designed based on these types of research findings, and the focus of this review paper is to connect scientific findings and practicality of what golfers can do as supplemental fitness training to improve their game.

This review paper contains two key components of current literature in golf; 1) performance-based research and 2) clinical-based research. The final part of this review paper introduces the appropriate training design to improve

flexibility and strength from the evidence-based information.

Performance-based research

Golf not only provides a means of sport and recreation, it also can be a method of improving physical attributes such as cardiovascular fitness and balance.⁶⁴ Optimal physical conditioning has been a central principle of maximal performance in most sports but has been overlooked in golf. Those who play and teach golf are beginning to realize the need for adequate strength, flexibility, and balance training to optimize swing mechanics to enhance golf performance and potentially to prevent injuries.^{21,38}

Golf biomechanics applies the principles and technique of mechanics to the structure and function of the golfer in an effort to improve golf technique and performance.³¹ For example, when a golfer wants to increase the distance of their drives, a relatively large ground reaction force (GRF) must be produced.⁶⁷ This can be done by more powerfully transferring the GRF from the trailing foot to the leading foot during the downswing phase, using large muscle groups to facilitate force production, and uncocking the wrists when the lead arm is about 30° below the horizontal will also take advantage of the summation of force principle.¹⁸ These factors all contribute to generate large angular velocity of the club head, and ultimately ball displacement. However, it is also important to remember that correct physical conditioning will help to recruit the muscles in the correct sequence and to optimum effect.³¹ This section will examine the current knowledge and literature on coaching and training-related golf biomechanics from a

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performance perspective.

Biomechanical findings on driving performance

The X-factor is defined as the separation angle that occurs between the upper torso and pelvis at the top of the backswing^{8,56}, and greater displacement of X-factor has been directly associated with increased ball velocity.⁵⁶ As the downswing commences, the hips tend to counter rotate before the torso, resulting in a maximum separation angle between the torso and hips.¹¹ This maximum separation angle is termed the X-factor stretch. Figure 1 shows the X-factor created by the separation angle between the upper torso and pelvis at the top of the backswing as illustrated by Kenny.³⁴ This absolute and relative pelvic and upper-torso rotation during the golf swing is of great importance to professional golf instructors and has been thoroughly investigated in literature.^{11,31,49,50,53,71} Both an increased torso-pelvic separation at the top of the backswing and maximum torso-pelvic rotation is associated with an increase in ball velocity.⁵⁶ Joyce et al.³² hypothesized that rapidly maximizing the separation angle between the hips and torso eccentrically stretches the trunk muscles, which may increase the potential to utilize the stretch shortening cycle during the golf swing, leading to a potential increase in hitting distance.^{11,56}

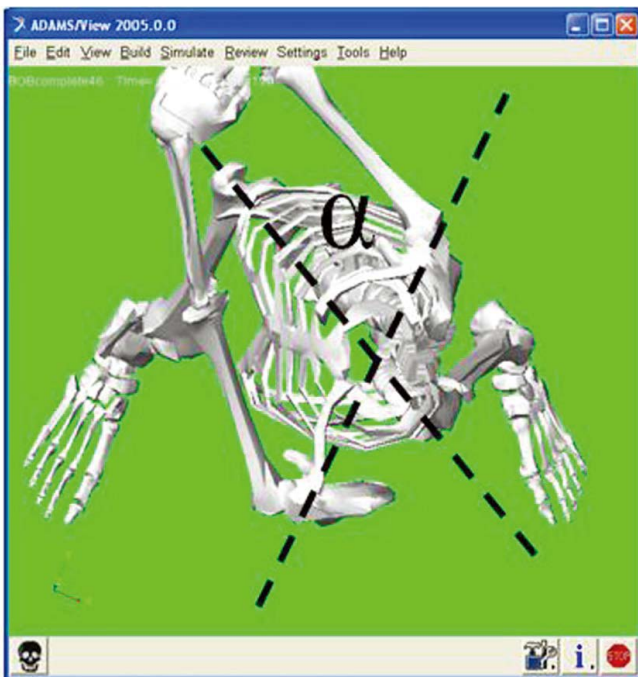


Figure 1 The X-factor as illustrated by Kenny.³⁴

The timing or sequence in which the body segments move is an essential part of the golf swing and produces the high club head speed required for an effective golf shot.⁵⁸ In order to achieve maximal angular velocity of the club head at ball contact, the downswing needs to utilize the summation of velocity principle, where the transfer of energy takes place from the larger proximal segments to the smaller distal segments, i.e. the hips, torso, arms and club head.⁴¹ In order to achieve optimal energy transfer and club head speed through

this proximal to distal sequencing during the downswing, Cheetham et al.¹¹ identified several attributes to be present in the golfer's kinematic sequence, namely:

- All the segments should accelerate and negatively accelerate before impact (with the exception of the club which should peak exactly at ball impact).
- The order in which the segment reaches peak velocity should be pelvis, torso, arm and club.
- Each of these peaks should be larger and later than the previous one.

Body weight shift during the golf swing is another popular coaching topic that has received ample attention in literature. Ball and Best⁴ describes the weight transfer during the golf swing as the movement of weight between the feet. Hume et al.³¹ explains that in golf, as in any other throwing or hitting activity, the velocity of projection can be increased if the player's momentum follows the intended direction of the projectile displacement. Transferring your body weight from the trailing foot towards the leading foot during the golf swing can thus improve the hitting distance by improving the club velocity at impact.^{31,59} While comparing high-skilled golfers to low-skilled golfers, Okuda et al.⁵⁹ found that during the backswing event, the vertical GRF of high-skilled golfers was significantly smaller on the leading foot, and significantly larger on the trailing foot. Hume et al.³¹ concludes that high-skilled or low handicap golfers transfer a greater portion of their body weight at a faster rate during the downswing.

Golf has also been the subject of numerous modelling investigations mainly due to the underlying complexity of the movement that is not easily explained through experimental techniques.⁶ In recent times, there have been some attempts to model full-body movement of the golfer. McGuan's⁴⁶ simulation was an early full-body model of the downswing. Kenny et al.³⁵ developed and validated a full-body computer simulation for a golfer using the driver club and seven-iron and also a driver-specific model to investigate the effects of using longer shafts for the drive shot.³⁶ Kenny et al.^{35,36} found that when using longer drivers, both club head and ball velocities along with ball carry (total ball distance) tend to increase with no loss of accuracy. Concomitantly, models were able to ascertain that while more effort is required to swing the longer driver, muscle force increments were realistically achievable. Models such as these can provide crucial insight for the trainer and coach into muscle activation patterns, predicted muscle force and joint torque output, and changes to these when considering strength adaptations and club properties.

Shot Performance indicators

US PGA Tour and the European Tour statistics that are commonly presented concern golfers' average drive accuracy and distance. Average drive distance by the PGA Tour's top 30 longest drivers has increased by 35.5 yards since widespread measurements began in 1980, to the present day (see Figure 2a).⁶⁰ Driving accuracy, which is the percentage of shots that land on the fairway, has not demonstrated an

equivalent increase (see Figure 2b). It appears that top golfers have utilized club material advancements, bettered their physical condition, but sacrificed drive shot accuracy a small margin (< 8%) for increases in drive distance.

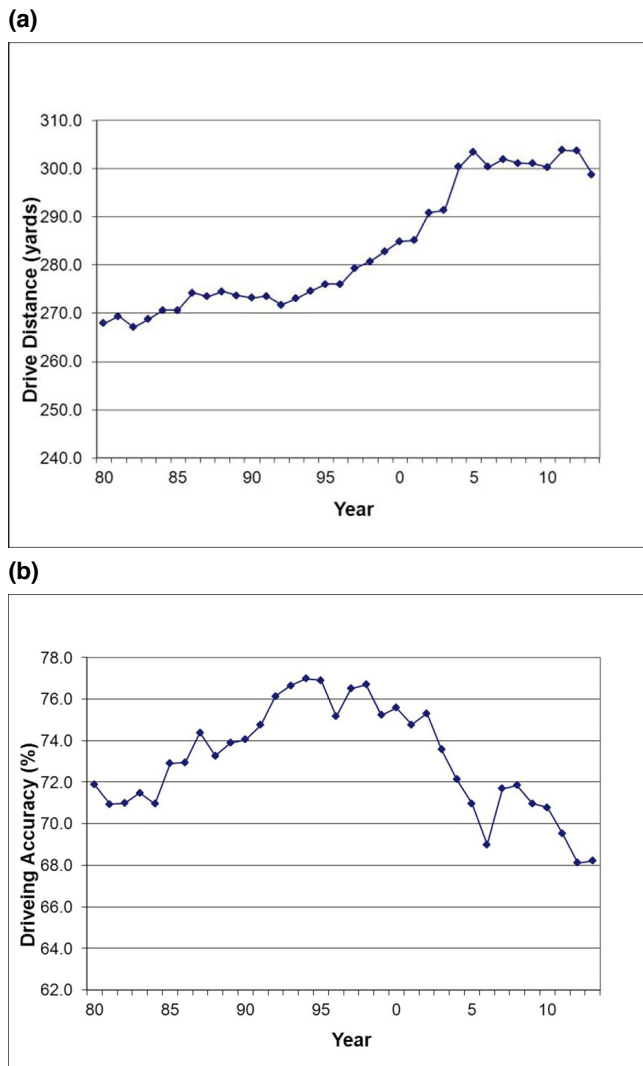


Figure 2 PGA Tour top thirty golfers' drive distance and accuracy (<http://www.pgatour.com/>).⁶⁰

How a golfer performs on the golf course in competitive situations, or under test conditions on the range or in the laboratory can vary depending on the performance criteria. During the game itself, drive distance, drive accuracy, approach accuracy, and putting are all needed for good overall performance, combined with physical attributes. The flight of a golf ball is influenced greatly by ball launch conditions of initial ball velocity, ball backspin and launch angle.⁵⁵ The path the ball takes depends on the nature of the club head and ball impact characteristics, which includes club head velocity, clubface loft, clubface orientation (open or closed), impact point (in relation to the heel/toe/sole/crown), ball spin (backspin and sidespin component), and ball launch angle (rise) and side angle (deviation).

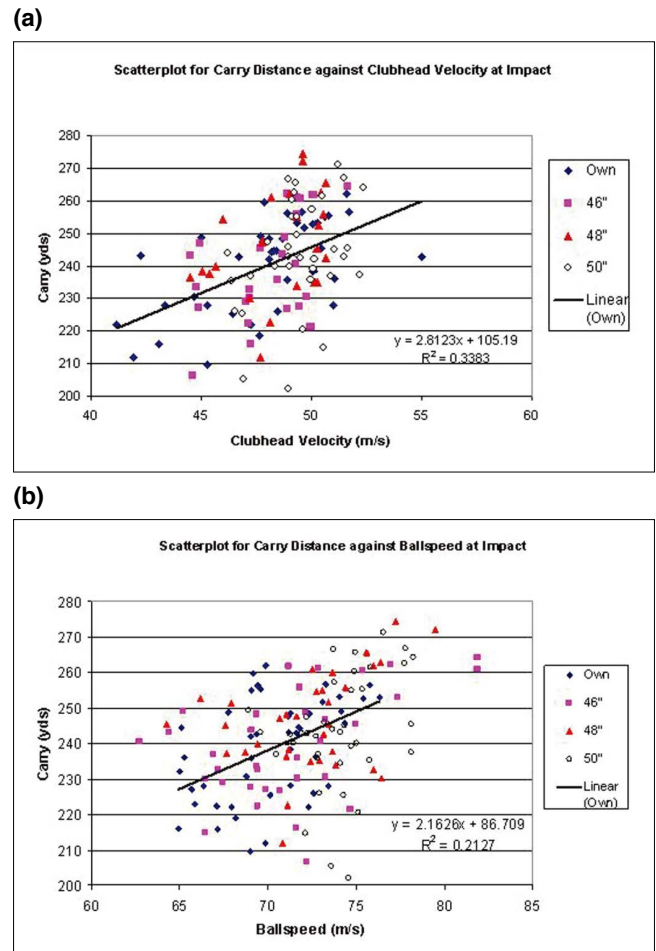


Figure 3 Influence of club head and ball velocity launch conditions on carry distance, for different length drivers.³⁴

Figure 3 (a and b) illustrates, as example, the influence of drive shot club head and ball velocity on carry distance for a sample of seven category 1 (<5 handicap) golfers with clubs of different length.³⁴ Quintavalla⁶¹ investigated the effects of club head velocity on driver launch conditions and drive distance and noted the diminishing returns of overall distance with increasing club head speeds. That is, impact efficiency decreases and the conditions of spin and launch angle placed on the ball as club head velocity increases causing a reduction in the assumed drive distance benefits that increased impact velocity might offer. It is possible that golfers may improve their game with better physical conditioning, particularly power and upper body stability for the drive, thus overcoming some of the reduced impact efficiency for high velocity drive shots.

Performance variability for different populations

Traditionally, movement variability has been viewed as an error or a property of movement to be minimized or completely eradicated from a movement pattern in order to achieve a more consistent outcome.²⁵ Arutyunyan³ examined aiming accuracy in pistol shooting in expert and novice marksmen and it demonstrated the existence of compensatory movements by experts in their efforts to stabilize the endpoint

(outcome). This work cast doubt on the previous view from motor program theory of movement variability as detrimental to the outcome of a movement pattern. As it is unclear whether movement variability is beneficial or detrimental to motor skill performance, researchers have begun examining this aspect of human performance in relation to the golf swing. It has been targeted as an important future research direction^{7,21} in order to improve training and teaching methods and understandings of the determinants of a successful golf swing. Using the traditional approach of variability as detrimental to outcome, coaches would teach a consistent movement pattern. However, as has been highlighted previously, this may be erroneous. Knight⁴⁰ advocated a Dynamical Systems Theory (DST) approach to understanding the golf swing. In golf, no two shots are identical due to the effect of the environment, different flag position and changing weather constraints. From a DST perspective a “perfect” or “optimal” swing cannot exist owing to the intra-individual constraints that are constantly interacting and evolving over time, that produce a movement pattern. In a study by Brown et al.⁹ examining the swing characteristics of low-handicap female golfers (n=16) using a twelve-camera 3-D motion capture system, no common optimal technique characteristics could be determined across all sixteen participants in the downswing phase in particular.

There remains a question surrounding the validity of investigations concerning anything other than elite level golfers. On one hand, it could be said that the best data pertaining to variation in shot performance due to different club parameters are obtained by using only elite golfers, or category 1 golfers. This helps to reduce performance deviation, and inter- and intra-subject variability as the golfers are generally more skilled and able to reproduce quality shots. However, elite golfers constitute only a very small proportion of the golfing population and researchers have studied groups of non-elite golfers to study variations in swing kinematics and kinetics, impact characteristics, and shot performance.^{10,62,66} Fradkin et al.²³ conducted a study to examine how well club head velocity correlates with golf handicaps. A very strong linear relationship was found between golfers’ mean club head velocity at impact and handicap ($p < 0.001$, $r = 0.950$) (Equ 1):

$$\text{Mean club head velocity} = e 4.065 - 0.0214 \times \text{handicap} \quad (\text{Equ. 1})$$

Investigation of golf swing techniques at the intra-individual level of analysis is warranted, particularly at the elite level, as suggested by Kenny et al.³⁷ and Brown et al.⁹ It is not suggested here to dispense with group analysis but further investigation of group results at the individual level is required in order to prevent masking of individual strategies.

Clinical-based research: the impact of the golf swing upon the lumbar spine

This section reviews some of the findings from current research pertaining to the full golf swing as it affects the lumbar spine. There are several versions of the golf swing, and the information presented here will pertain to the modern “one-plane” swing unless otherwise noted.

Biomechanical causes low back stress

Low back pain is the number one musculoskeletal complaint and time-loss injury in golf.^{22,26,47,48} This should not be too surprising given the magnitude of stress encountered during the full golf-swing. Studies show that compressive forces reach 6-8 times body mass during the full swing, and that these forces peak close to impact.⁴² For an athlete weighing 686.7 N (mass of 70 kg or 154 lbs), these compressive loads reach up to 5494 N, which approaches the amount of stress associated with injuries to the vertebral endplate and annulus fibrosus occur (around 7900 N in porcine models).⁴⁴ However, repetitive submaximal loading can also cause fatigue-induced injuries of the intervertebral disc.² This is an important consideration given that the golf swing is repetitive in nature, and most golfers perform well more than 100 full swings per round when one considers practice and warm-up activities.

Additionally, shear stresses also occur during the golf swing, and when the cyclic repetition of the swing is considered, then these shear forces meet or exceed current recommendations for avoiding injury.²⁴ Loading studies suggest that the pars interarticularis incurs damage from shear loads ranging from 600-4000 N. Interestingly, golf produces anterior shear forces on average between 800-1200 N.

Another important consideration for lumbar stress is the associated amount of X-factor stretch and the quantity of lateral flexion (degrees) coupled with the rotational velocity (degrees per second) achieved during the downswing (these together are the “crunch factor”). As mentioned above, the degree of axial rotation during the modern golf swing is often quantified as the X-factor, which peaks at the top of the backswing, and decreases during the downswing. Preliminary data from our lab has shown that by shortening the backswing, and thereby reducing the X-factor, one can ameliorate the amount of compressive forces encountered during the downswing.¹⁷ Another consideration is the “crunch factor”, mentioned above. For a right-handed golfer, the spine moves into right lateral flexion during the downswing (see Figure 4), and the prevailing hypothesis is that this motion may become injurious when one considers the magnitude of forces that occur simultaneously during this motion. Studies show that flexion and side-bending produce the highest amounts of shear stress in the spine, and electromyography indicates that the right side of the trunk has higher muscle activation during this phase of the golf swing.^{15,16,17} Interestingly, many right-handed golfers complain of right-sided back pain. Furthermore, there is evidence to show adaptive anatomical changes of the right-sided vertebral body and facet joints, which are evident upon radiographic examination in trained golfers.⁵¹ There is also evidence to show that lateral bending during a lifting task produces high and potentially injurious forces to the facet joints of the spine of 350 N.⁵⁷ During the downswing through the impact, golfers who have limited ROM in hip rotations (internally and externally) tend to have reverse spine. Those golfers tend to experience this lateral bending during the impact zone in golf swing.

Torsion is especially stressful for the lumbar spine, and the facet joints are the primary restraint to torsion stress.¹ The



Figure 4 Through the impact of swing

“crunch factor” becomes even more clinically relevant when considering lateral flexion, which also adds a loading stress to the facet joint on the right side for a right-handed golfer. Typically the lumbar facets will open, or have tension, on the right-side of the vertebral column as the thoracic spine moves into right rotation during the backswing. Elite golfers typically initiate the downswing with their pelvis rotating to the left (for right-handed golfers), which accentuates the torsion already in the spine.⁶⁸ To maintain spine angle, a right-handed golfer’s spine moves into a position of right lateral flexion during the downswing while the trunk rotates rapidly to the left. Left rotation “closes” the right facet joint and adds compressive forces. Therefore, the coupling of right lateral flexion with left rotation adds considerable stress to the right facet joint. This repeated stress encountered by golfers certainly explains the changes evidenced by radiographs.⁵¹ There is supporting statement that the articular cartilage of the spinal facet joints may become injured with 250-500 N of force during torsion stress testing.¹ Another consideration is that facet joint arthritis increases with age, and this likely limits their spinal mobility, and may increase their chances of encountering low back pain with golf.³³

Spinal stabilization mechanism

The human body does a remarkable job of stabilizing the vertebral segments against the stress encountered during dynamic activities. In addition to passive stabilizers, various trunk muscles work to stabilize the vertebral column, and this is especially important during the golf swing. Dynamic trunk stabilizers are considered to be local or global based upon their anatomical orientation.²⁹ For example, larger muscles such as

the rectus abdominis and obliques produce powerful movements but do not attach directly to the spine. Therefore, these muscles may assist in stabilization, but they do not control segmental motion as well as the local muscles, which attach directly to the spine, e.g. multifidus.⁶² Muscle activation reduces intradiscal pressures, and distributes forces along the vertebral column, and prevents the spine from buckling, which can occur with as little as 90 N of compressive force without stabilization.^{12,13,39} Strength & conditioning is paramount to provide a proper training stimulus to develop the trunk or “core” stabilizers from an injury prevention perspective, whereas rehabilitation seeks to restore proper activation of the musculature once an injury occurs.

Unlike their healthy counterparts, there is evidence to show that individuals with low back pain do not properly anticipate spinal perturbation associated with rapid limb movement.³⁰ Previous injury causes a distortion of normal neuromuscular activation by delaying reflexive muscle actions, and by limiting feedforward activity of the trunk musculature prior to upper or lower extremity motions.^{30,70} These deficits are due to poor neuromuscular control, and are associated with central nervous system adaptations to the injury, which probably serve to spare joint reaction forces along the spine that occur concomitantly with muscle activation.¹⁶ This delay in neuromuscular activation potentially leaves the spine unprotected once rapid limb movement occurs. The nervous system must be rehabilitated with specific training, and through its plasticity is trainable following injury.⁷⁰ Therefore, rehabilitation professionals should focus on control of core activation, and not just strength development, following injury in the initial stages of recovery.

Trunk and spinal muscle activation mechanism

There are studies supporting that adverse neural adaptations are specifically associated with golfers experiencing low back pain, and these maladaptations imply motor control deficits of the core stabilizers.^{15,16,19} Static activation of the transverse abdominis with abdominal hollowing is associated with poor endurance for golfers with low back pain.¹⁹ Furthermore, golfers with a history of low back pain show reduced erector spinae muscle activation at the top of the backswing, during the start of the downswing, and at ball impact compared to golfers without low back pain.^{15,16} Reduced erector spinae activation may be compensatory in order to minimize compressive joint reaction forces. However, there is evidence to show that low-handicap golfers with low back pain activate the right external oblique to a greater extent than other golfers, and the implication is that these golfers might be rotating to the left relatively faster than other groups.¹⁶ Increased axial rotation speed would translate to higher club speeds at impact, but would simultaneously increase torsion-stress to the spine. Coupled with reduced erector spinae activation at impact, these golfers would encounter higher stress without as much relative muscle activation to stabilize or protect the spine.¹⁶

Optimal trunk activation and stabilization occurs with the spine in a neutral position.²⁸ Golfers that exhibit poor posture

with their setup and swing, especially those with prolonged flexion (C-posture) may lose the protective role of the multifidi and erector musculature.⁶⁹ Swing faults can be associated with poor instruction, or the lack thereof, and also by physical limitations. Therefore, it is important to couple proper swing instruction and coaching with a rehabilitation program. There is evidence to show that both interventions together have successfully rehabilitated golfers.^{27,28}

Two published case studies of golfer rehabilitation following low back injury addressed transversus abdominis and multifidus activation during their program.^{27,28} Activating the transversus abdominis occurred in supine with the knees flexed while performing the abdominal hollowing maneuver; Whereas the multifidus was activated in the prone, quadruped and supine positions.^{27,28} These muscles were exercised with 10 repetitions performed 3 to 4 times per day, and the actions were held for five seconds while building up to 20 to 30 second holds. The studies found that the golfers were able to return to golf pain-free following the program, which lasted for up to 12 weeks.²⁷

As the athlete gains volitional control over the various core muscles, one should progress exercise to weight-bearing, antigravity muscle involvement.^{27,28} This is where traditional conditioning exercises allow for the continued rehabilitation of a golfer. Various activities should include large muscle groups of the lower extremities such as the rectus femoris and the hamstring muscle groups, which attach to the pelvis and are associated with co-activations of the deeper core stabilizers.²⁸ Furthermore, it is recommended that a comprehensive program should include stretching, strengthening, and power-development exercises.⁵²

Strengthening and power-development activities progress the neuromuscular control, and it is always advisable to have an athlete with a history of low back pain to perform a bracing maneuver prior to strengthening and power exercises. There is evidence that strengthening exercises may also prevent injury.^{20,26,43} Strengthening and power development exercises should be specific to golf, and should allow for proper activity progression to avoid re-injury. For example, the golfer should have sufficient strength and be symptom-free during various strengthening activities before power exercises are introduced. In fact, a prudent progression method is to have the athlete reduce their load and move the weight through the range of motion more quickly while maintaining control of the resistance.

Training design

Various types of training tools and information are available for all levels of golfers. As mentioned, enhancing flexibility, stability, and strength-power are essential parts of physical components to improve golf performance and reduce a risk of injuries. The following sections are recommendations on training design to address aforementioned physical demands.

Flexibility

Based on the literature, X factor is a major factor of increasing displacement of backswing to generate club head speed at the impact without any compensations. In order to do

so, flexibility exercises in proximal ends of the segments such as neck, shoulders, and hips are appropriate areas to improve overall mobility to dissociate hip and trunk.

First, neck should have approximately 80° of rotation to both sides, and 50° of flexion.¹⁴ Specific to golf motion if a player does not have the adequate ROMs, position of the trunk and shoulder may be forced to compensate to achieve to the desired club position (or not even get to the position) at the top of backswing. Static stretching of neck extensor muscles will improve the ROM in neck flexion, and stretching neck rotator muscles such as sternocleidomastoid will improve the ROM in neck rotation.

Second, tri-planar shoulder mobility is important to get to a desired back swing position. Based on the Figure 5, the leading arm is in shoulder horizontal abduction and the trailing arm is in external rotation. As expected, ROM is approximately in 45° for horizontal abduction and 90° in external rotation.¹⁴ If one of those are lacking, the club head will likely be out of plane and may cause “over-the-top” swing. In addition to static stretching such as arm-cross for horizontal abduction for lead arm, and external rotation for back arm, dynamic stretching is also useful.

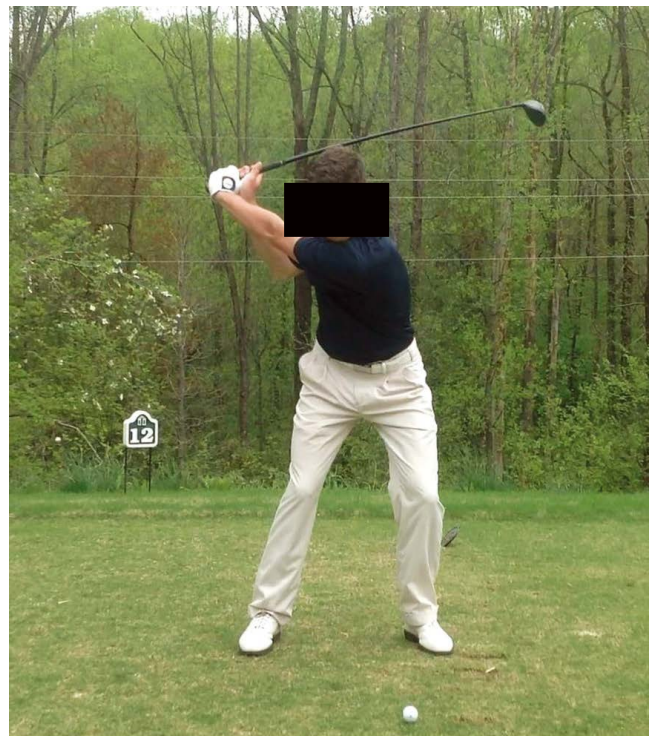


Figure 5 The top of back swing

Third, hip mobility especially in flexion and transverse plane becomes an important aspect of golf swing. As the golf swing is broken down phase by phase, both hips are in flexion at the address and the leading hip is moving towards external rotation (ER) and the trailing hip towards internal rotation (IR) during the back swing. Then the hips rotate reversely (the leading hip to IR and the trailing hip to ER) through the rest of the swing. Expected ROM is approximately 120° in hip flexion and 45° in both IR and ER.¹⁴ If there is a lack of

(a)



(b)



Figure 6 Examples of hurdle stretching for hip joint

flexibility, ability to rotate hip and separate the hip from trunk rotation will likely be limited. Specifically, lack of hip flexion will likely cause C-posture and lack of hip rotation will cause sway (shift body alignment to the trailing foot) and slide (shift body alignment to the leading foot) during the swing. Stretching exercises are important for golfers with tight hip flexors and IR of the lead hip, and reduced rotation of the lead hip will cause compensatory rotation of the trunk, which may create excessive torque and lead to vertebral injury.²² To gain hip rotation flexibility, dynamic stretching such as leg swing as well as hurdle stretches are recommended (see Figures 6a&b).

These types of stretching exercises mentioned are easy to perform with no specific needs such as equipment. It is strongly recommended that a series of dynamic stretching is performed prior to resistance training as a warm-up as well as gaining flexibility.

Resistance Training

Resistance training has various benefits to improve physical characteristics such as increasing cross-sectional area of trained muscles and increase rate of action potential to increase force output.⁶³ Various skill levels of golfers are now starting to believe that resistance training can benefit overall golf performance, especially to increase club head velocity for longer driving distance. However, appropriate periodization along with correct technique is required to maximize the effect of resistance training for sport performance.⁶³ It is highly recommended that golfers should consult with qualified strength and conditioning specialists to initiate tailored training plans to avoid rapid increase in training volume.

Speculation is about the effects of rotational resistance training using cables and other devices as resistance. Golf is indeed a rotary sport performed in a repetitive fashion. It is important for fitness professionals to think that rotational resistance training is good for golfers. However, there is no scientific literature to support this with evidence. When the golf swing is carefully observed, it is flexibility from aforementioned region of the body along with triple extension of the lower extremity joints (hip, knee, and ankle) to generate GRF at the impact (see Figure 4). Based on the motion analysis, it actually makes sense to engage in the triple extension exercises in a vertical plane. Strength exercises such as partial or full squats, step-ups, lunges are great examples of exercise to emphasize the triple extension. Power exercises such as mid-thigh pull and upward med-ball throw can emphasize the short burst of triple extension.

In the clinical-based research section in this review, importance of stabilization mechanism was mentioned. Axial loading exercises such as squats, standing dumbbell (DB) shoulder press can stimulate the spinal stabilizer. Along with using unstable surface training which shows some evidence of improvement in balance for specific tasks⁵³, closed-chain exercises on stable surface can also be beneficial to overall stabilization for golfers. Logically speaking, it is also important to note unstable surface training are typically performed in slowly controlled motion with low external resistance. This approach is contradictory to maximizing force

(i.e., high resistance) and power (i.e., high velocity with high force) outputs. The authors are not opposed to unstable training but fitness professionals should be aware that unstable surface training may serve a different purpose such as improvement of proprioception but not necessarily a direct translation of improving power output. Having mentioned, it is a reason for why resistance training becomes such an important role to gain force output to enhance power output. The key components of resistance training specifically for golfers can be focused on several points:

- 1) good postural alignment (neutral spinal position) while in standing position.
- 2) good balance and stability in closed-chain exercises on stable surfaces first and progress onto unstable surfaces if desired.
- 3) if there is no anatomical limitation, full ROM exercises, if not, progress the ROM to get to the full ROM.
- 4) vertical plane oriented exercises to emphasize push and pull of tripe extension from lower extremity.

The first table is the example of exercise selections emphasizing multi-joint exercises with some focus on triple extension (see Table 1). Depending on the availability, the focus of training can be separated to “push” and “pull” days. The second table is an example of proper periodization for relatively untrained golfers to help guide appropriate training volume gain (see Table 2).

As can be seen in Table 2, the 13 weeks of a training period is divided into blocks of various training volume. Block 1 is to learn correct lifting technique as a general preparation with

light intensity. Then sub-maximum effort of testing should be conducted to calculate percentage of training intensity for the following blocks. Block 2 is to gradually increase training volume (sets x repetitions x weight). There is a de-load week between the block 2 and 3. The primary purpose of de-load week is to dissipate fatigue from the previous training block.⁴⁵ The block 3 is a repetitive cycle of the block 2 and could be modified with higher overall volume.

Summary

As seen above, physically fit golfers can be advantageous to improve their golf game. This review paper focuses on a necessity of physical demands in flexibility, stability, and strength-power for better driving as well as reduce risk of injuries specific to the low back area. As training is included as a supplement to golf, proper progression on training intensity as well as correct technique on selected exercises should be emphasized to maximize the effect of the training.

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References

- 1) Adams MA, Hutton WC. The relevance of torsion to the mechanical derangement of the lumbar spine. *Spine* 1981;6:241-248.
- 2) Adams MA, Hutton WC. Gradual disc prolapse. *Spine* 1985;10:524-531.
- 3) Arutyunyan DA, Gurfinkel VS, Mirskii ML. Investigation of aiming at a target. *Biophysics* 1968;13:536-538.

Table 1 An example of exercise section.

Push day	Pull day
Dynamic warm up on total body	Dynamic warm up on total body
Over-head squat (partial to full)	Upward med-ball throw
Barbell back squat (partial to full)	Barbell mid-thigh pull
DB chest fly	Close-grip clean pull from knee
DB step-ups	DB (seated) / cable (standing) 1-arm row
DB shoulder press	DB reverse fly
Abdominal exercise	Abdominal exercise
Static stretch on selected area	Static stretch on selected area

DB = Dumbbell

Table 2 An example of training volume

	Block 1		Block 2		De-load	Block 3
Weeks	Week 1-2 (2 weeks)	Week 3	Week 4-5 (2 weeks)	Week 6-8 (3 weeks)	Week 9 (1 week)	Week 10-13 (4 weeks)
Focus	Learning technique	Testing	Light intensity	Moderate intensity	Very light intensity	Moderate intensity
Sets	2-3	NA	2-3	3-4	2	3-4
Reps	5	NA	10	5	10	5
%	NA	Sub-max	65-70%	75-80%	60-65%	80-85%

NA = Not Applicable

- 4) Ball KA, Best RJ. Different centre of pressure patterns within the golf stroke I: Cluster analysis. *J Sports Sci* 2007;25:757-770.
- 5) Barrentine SW, Fleisig GS, Johnson H et al. Ground reaction forces and torques of professional and amateur golfers, Chapter 5, in *Science and golf II*, Eds. Cochran AJ, Farrally, MR, London, E&FN SPON, 1994.
- 6) Betzler N, Monk S, Wallace E et al. From the double pendulum model to full-body simulation: Evolution of golf swing modeling. *Sports Technology* 2008;1:175-188.
- 7) Bradshaw EJ, Keogh JW, Hume PA et al. The effect of biological movement variability on the performance of the golf swing in high- and low- handicapped players. *Res Quarterly* 2009;80:185-197.
- 8) Brown SJ, Selbie WS, Wallace ES. The X-factor: An evaluation of common methods used to analyse major inter-segment kinematics during the golf swing. *J Sports Sci* 2013;31:1156-1163.
- 9) Brown SJ, Nevill AM, Monk SA et al. Determination of the swing technique characteristics and performance outcome relationship in golf driving for low handicap female golfers. *J Sports Sci* 2011;29:1483-1491.
- 10) Byrne D, Kenny IC. Characterisation of swing patterns for high and low handicap golfers, Proceedings of the International Society of Biomechanics in Sports Conference, 2008, Seoul, South Korea.
- 11) Cheetham PJ, Martin PE, Mottram RE et al. The importance of stretching the "X-Factor" in the downswing of golf: The "X-Factor Stretch", Proceedings of the International Congress on Sport Science Sports Medicine and Physical Education, 2000, Brisbane, Australia.
- 12) Cholewicki J, McGill SM. Mechanical stability of the in vivo lumbar spine: implications for injury and chronic low back pain. *Clin Biomech* 1996;11:1-15.
- 13) Cholewicki J, Panjabi MM, Khachatryan A. Stabilizing function of trunk flexor-extensor muscles around a neutral spine posture. *Spine* 1997; 22:2207-2212.
- 14) Clark MA, Lucett SC, Sutton BG. Range of motion assessments, Chapter 7, in *NASM Essentials of Corrective Exercise Training*, Burlington, Jones & Burtlett Learning, 2010.
- 15) Cole MH, Grimshaw PN. Trunk muscle onset and cessation in golfers with and without low back pain. *J of Biomech* 2008;41:2829-2833.
- 16) Cole MH, Grimshaw PN. Electromyography of the trunk and abdominal muscles in golfers with and without low back pain. *J Sci Med Sport* 2008;11: 174-181.
- 17) Dale R, Farr T, Marshall C. Spine kinetics during the modified one-plane golf swing, Proceedings of the American Physical Therapy Association Meeting, 2010, Boston, USA.
- 18) Davies C, DiSaia, V. Explosive power for longer drives, Chapter 6, *Golf Anatomy*, Champaign, Human Kinetics, 2010
- 19) Evans C, Oldreive W. A study to investigate whether golfers with a history of low back pain show a reduced endurance of transversus abdominis. *J Manipulative Physiol Ther* 2000;8:162-174.
- 20) Evans K, Refshauge K, Adams R et al. Predictors of low back pain in young elite golfers: a preliminary study. *Phys Ther Sport* 2005;6:122-130.
- 21) Farrally MR, Cochran AJ, Crews DJ et al. Golf science research at the beginning of the twenty-first century. *J Sports Sci* 2003;21:753-765.
- 22) Fradkin AJ, Cameron PA, Gabbe BJ. Golf injuries--common and potentially avoidable. *J Sci Med Sport* 2005; 8:163-170.
- 23) Fradkin AJ, Sherman CA, Finch CF. How well does club head speed correlate with golf handicaps, *J Sci Med Sport* 2004;7:465-472.
- 24) Gallagher S, Marras WS. Tolerance of the lumbar spine to shear: a review and recommended exposure limits. *Clin Biomech* 2012;27:973-978.
- 25) Glazier PS, Wheat JS, Pease DL et al. The Interface of Biomechanics and Motor Control, Chapter 3, *Movement System Variability*, Eds. Davids K, Bennett S, Newell K, Champaign, Human Kinetics, 2006
- 26) Gosheger G, Liem D, Ludwig K et al. Injuries and overuse syndromes in golf. *Am J Sports Med* 2003;31:438-443.
- 27) Grimshaw P, Giles A, Tong R et al. Lower back and elbow injuries in golf. *Sports Med* 2002;32:655-666.
- 28) Grimshaw PN, Burden AM. Case report: reduction of low back pain in a professional golfer. *Med Sci Sports Exerc* 2000;32:1667-1673.
- 29) Hodges, P. Lumbopelvic stability: a functional model of the biomechanics and motor control, Chapter 2, *Therapeutic Exercise for Lumbopelvic Stabilization*, Eds. Richardson CA, Hodges P, Hides J, Edinburgh, Churchill Livingstone, 2004.
- 30) Hodges PW, Richardson CA. Altered trunk muscle recruitment in people with low back pain with upper limb movement at different speeds. *Arch Phys Med Rehabil* 1999;80:1005-1012.
- 31) Hume PA, Keogh JW, Duncan R. The Role of Biomechanics in maximising distance and accuracy of golf Shots. *Sports Med* 2005;35:429-449.
- 32) Joyce C, Burnett A, Ball K. Methodological considerations for the 3D measurement of the X-factor and lower trunk movement in golf. *Sports Biomech* 2010;9:206-221.
- 33) Kalichman L, Li L, Kim DH et al. Facet joint osteoarthritis and low back pain in the community-based population. *Spine* 2008;33:2560-2565.
- 34) Kenny I. Biomechanical and modelling analysis of shaft length effects on golf driving performance. Unpublished thesis, University of Ulster, 2006.
- 35) Kenny IC, McCloy A, Wallace ES et al. Segmental sequencing of kinetic energy in a computer-simulated golf swing. *Sports Eng* 2008;11:37-45.
- 36) Kenny IC, Wallace ES, Otto SR. Influence of shaft length on golf driving performance. *Sports Biomech* 2008;7:322-332.
- 37) Kenny IC, Wallace ES, Otto SR. Driving performance variability among elite golfers, Proceedings of the International Sports Engineering Conference, 2008, Biarritz, France.
- 38) Keogh JW, Hume PA. Evidence for biomechanics and motor learning research improving golf performance. *Sports Biomech* 2013;11:288-309.
- 39) Kim YE, Choi HW. Paraspinal muscle activation in accordance with mechanoreceptors in the intervertebral discs. *J of Engine in Med* 2013;227:138-147.
- 40) Knight CA. Neuromotor issues in the learning and control of golf skill. *Res Quarterly* 2004;75:9-16.
- 41) Langdown BL, Bridge M, Li FX. Movement variability in the golf swing. *Sports Biomech* 2012;11:273-287.
- 42) Lim YT, Chow JW, Chae WS. Lumbar spinal loads and muscle activity during a golf swing. *Sports Biomech* 2012;11:197-211.
- 43) Lindsay D, Horton J. Trunk rotation strength and endurance in healthy normals and elite male golfers with and without low back pain. *NAJSPT* 2006;1:80-89.
- 44) Lundin O, Ekstrom L, Hellstrom M et al. Injuries in the adolescent porcine spine exposed to mechanical compression. *Spine* 1998;23:2574-2579.
- 45) Mann JB, Thyfault JP, Ivey PA et al. The effect of autoregulatory progressive resistance exercise vs. linear periodization on strength improvement in college athletes. *J of Strength and Cond Res* 2000; 24:1718-1723.
- 46) McGuan S. Exploring Human Adaptation using Optimized, Dynamic Human Models, Proceedings of the Annual Meeting of the American Society of Biomechanics, 1996, Georgia, USA.
- 47) McHardy A, Pollard H, Luo K. Golf injuries: a review of the literature. *Sports Med* 2006;36:171-187.
- 48) McHardy AJ, Pollard HP, Luo K. Golf-related lower back injuries: an epidemiological survey. *J of Chiropractic Med* 2007;6:20-26.
- 49) McLaughlin PA, Best RJ. Three-dimensional kinematic analysis of the golf swing, Proceedings of the World Scientific Congress of Golf, 1994, London, United Kingdom.
- 50) McTeigue M, Lamb SR, Mottram R et al. Spine and hip motion analysis during the golf swing, Proceeding of the World Scientific Congress of Golf, 1994, London, United Kingdom.
- 51) Mefford J, Sairyo K, Sakai T et al. Modic type I changes of the lumbar spine in golfers. *Skeletal Radiology* 2011;40:467-473.
- 52) Meira EP, Brumitt J. Minimizing injuries and enhancing performance in golf through training programs. *Sports Health* 2010;2:337-344.
- 53) Meister DW, Ladd AL, Butler EE et al. Rotational Biomechanics of the elite golf swing: Benchmarks for Amateurs, *J Appl Biomech* 2011;27:242-251.
- 54) Michell TB, Ross SE, Blackburn JT et al. Functional balance training, with

- or without exercise sandals for subjects with stable or unstable ankles. *J of Athle Train* 2006;41:393-398.
- 55) Moriyama K, Yamaguchi T, Yabu M et al. The influence of mechanical impedance of the golf club and the golf ball on ball spin. *Engineering of Sport* 2004;337-343.
 - 56) Myers J, Lephart S, Tsai, YS et al. The role of upper torso and pelvis rotation in driving performance during the golf swing. *J Sports Sci* 2008; 26:181-188.
 - 57) Natarajan RN, Lavender SA, An HA et al. Biomechanical response of a lumbar intervertebral disc to manual lifting activities: a poroelastic finite element model study. *Spine* 2008;33:1958-1965.
 - 58) Neal R, Lumsden R, Holland M et al. Body Segment Sequencing and Timing in Golf. *Int J Sports Sci Coach* 2007;2:25-36.
 - 59) Okuda I, Gribble P, Armstrong C. Trunk rotation and weight transfer patterns between skilled and low skilled golfers. *J Sport Sci* 2010;9:127-133.
 - 60) PGA, PGA Tour Club Head Speed', [online], 2013 available: <http://www.pgatour.com/stats.html> [accessed 10/6/2013].
 - 61) Quintavalla SJ. Experimental determination of the effects of clubhead speed on driver launch conditions and the effect on drive distance for balls used by the PGA tour, USGA Technical Report RB/cor2006-01.
 - 62) Sherwin I, Kenny IC. An examination of putting movement and performance variability using standard, belly and long-handled putters, Proceedings of the British Association of Sport and Exercise Sciences, 2013, South Glamorgan, United Kingdom.
 - 63) Stone M, Stone M, Sands W. Physical and physiological adaptations to resistance training, Chapter 10, The concept of periodization, Chapter 13, in *Principles and practice of resistance training*. Champaign, Human Kinetics, 2007.
 - 64) Tsang WW, Hui-Chan CW. Effects of exercise on joint sense and balance' in elderly men: Tai Chi versus golf. *Med Sci Sports Ex* 2004;36:658-667.
 - 65) Wallace ES, Grimshaw PN, Ashford RL. Discrete pressure profiles of the feet and weight transfer patterns during the golf swing. Proceedings of the World Scientific Congress of Golf, 1994, London, United Kingdom.
 - 66) Wallace ES, Graham D, Bleakley EW. Foot-to-ground pressure patterns during the golf drive: a case study involving a low handicap player and a high handicap player, Proceedings of the World Scientific Congress of Golf, 1990, London, United Kingdom
 - 67) Williams KR, Cavanagh PR. Mechanics of foot action during the golf swing and implications for shoe design. *Med Sci Sports Ex* 1983;15:247-255.
 - 68) Williams KR, Sih BL. Changes in golf clubface orientation following impact with the ball. *Sports Engineering*. 2002;5:65-80.
 - 69) Williams M, Solomonow M, Zhou BH et al. Multifidus spasms elicited by prolonged lumbar flexion. *Spine* 2000;25:2916-2924.
 - 70) Zazulak B, Cholewicki J, Reeves NP. Neuromuscular control of trunk stability: clinical implications for sports injury prevention. *The J of the Ameri Academy of Ortho Surgeons* 2008;16:497-505.
 - 71) Zheng N, Barrentine SW, Fieisig GS et al. Kinematic Analysis of Swing in Pro and Amateur Golfers. *Int J Sports Med* 2008;29:487-493.