Strength and Conditioning for Golf Athletes: Biomechanics, Injury Risk, Physical Requirements, and Recommendations for Testing and Training

Authors

Chris Bishop[1], Alex Ehlert[2], Jack Wells[3], Simon Brearley[4], Alex Brennan[1], and Daniel Coughlan[4]

Affiliations

1. Faculty of Science and Technology, London Sport Institute, Middlesex University, UK
2. Department of Exercise Science, North Carolina Wesleyan College, North Carolina, USA
3. The Professional Golfers' Association, National Training Academy, Ping House, The Belfry, UK
4. DP World Tour Performance Institute, Surrey, UK

Correspondence

Name: Chris Bishop

Email: C.Bishop@mdx.ac.uk

Address: As above for affiliation 1

Running Head

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Abstract

Historically, golf is not a sport that has a strong tradition of strength and conditioning (S&C). However, a greater understanding of the health and performance-related benefits of S&C training has resulted in players starting to take their physical fitness much more seriously. As a result, professional players are hitting the ball much further than 20 years ago, primarily due to increases in club head speed (CHS). Owing to the unique nature of the sport, it is not always entirely obvious how S&C practitioners can impact golf performance. This article aims to provide practitioners with an overview of the biomechanics associated with golf, common sites of injury, required physical capacities and proposed recommendations for testing and training the golf athlete.

Key Words: Club Head Speed; X-Factor; Strength; Power.

Introduction

Golf is a highly skilled and technical sport that requires players to complete a round of 18 holes in as few shots as possible. At the elite level for males, the US Professional Golfers' Association (PGA) Tour and DP World Tour exist, and for female players, the Ladies PGA Tour and Ladies European Tour, all of whom will compete professionally to the par of the course being played. At the amateur level, players are given a handicap index, which provides them with a shot allowance relative to their skill or ability. Unlike team sports such as rugby or American football, golf is not traditionally a sport associated with strength and conditioning (S&C) training. Typically, a greater emphasis has been placed on technical, tactical and mental aspects of ball striking and short game skills, rather than the development of physical fitness (78). However, with an increased understanding of the physical demands of the game, S&C has now become an integral component of many elite players' routines (1).

Elite golf has a long competitive season (e.g., the PGA Tour started on 16 September, 2021 and will finish on 28 August, 2022), with the innate nature of the sport (at the elite level) making for a challenging lifestyle. Players frequently travel to different countries and time zones, playing back-to-back tournaments each week, often for many weeks in the season. Previous literature has outlined that over 2000 swings can be performed by a tournament professional through practice and competition each week (22,70). Spinal compressive forces over 7000 Newtons (N) and shear forces up to 600 N are also common for professional players during full swings (when using woods and long irons) (41). Enduring these repetitive forces makes it necessary for elite players to become increasingly robust, so that they can withstand the volume of stress placed on their bodies (61), whilst also being concurrently prepared to optimize their physical performance. According to their 'probability of performance-impact model', Brearley et al., (16) suggest that avoiding injury and illness can be seen as the most likely positive impact on the golfer from regular S&C training, which in turn, provides golfers with greater time availability to practice and compete.

When aiming to understand the physical needs of golf, assessing the biomechanical demands can help guide exercise selection for players. For example, electromyography (EMG) analysis suggests that an elite level golf swing recruits muscles in a proximal to distal pattern, with the larger muscles of the legs initiating the movement, before progressing up through the trunk, and then upper extremities (42,67). Improving the ability to produce force and transfer energy through the kinetic chain may result in higher club head speed (CHS) and greater shot distance, which is associated with better performance (14,39). Further to this, it is important to develop force production capabilities within the time constraints of the golf swing. Previous research has timed the duration of the downswing from the point where the club is stationary at the top of the backswing to the point where the club hits the ball, which has been shown to take less than 0.3 s in professional players, whereas the entire swing duration is 0.89 s (63). However, it is important to note that changes in ground reaction forces (GRF) will initiate much sooner than the top of the backswing in order to decelerate the system mass in preparation for the downswing (37). Furthermore, relative to the backswing, the downswing involves greater muscle activation in a shorter duration of time. This suggests that both force production (i.e., strength) and rate of force development (RFD) are likely to be a key physical qualities to develop so that golfers reach as close to their maximum force production ability as possible in the time constrained by the task. In turn, this should have a positive impact on CHS and distance (25,71). The positive implications of increased driving distance is supported by Broadie (17) who showed that when a PGA Tour player can drive the ball 20-yards further, this should equate to 0.75 strokes saved per round. Furthermore, the value of hitting the ball 20-yards further exponentially increases as skill level decreases. For example, a golfer who shoots 80 shots per round should save 1.3 strokes, whereas a golfer who shoots 100 should save 2.3 strokes (17).

Naturally, this links perfectly to the importance of ball speed and CHS. Sweeney et al., (81) showed that 75% of ball speed was determined by CHS, with this figure rising to 82% when centeredness of impact was also included into the analysis. When considering a more longitudinal measure of golf performance (i.e., handicap index), Betzler et al., (9) showed that greater CHS was associated with lower handicaps in both males (r^2 = 0.34; r = 0.58) and females (r^2 = 0.67; r = 0.82). Relating to S&C specifically, improvements in both shot distance and CHS have been shown in numerous strength and power interventions (28) and with these physical capacities now being so critical in golf (71), this is an area that S&C practitioners can directly impact. Consequently, elite players are now taking a multi-dimensional approach to their physical development (39,78). Thus, players are becoming fitter, stronger and better prepared to deal with increasing demands on the distance and accuracy of their shots, which is now more important than ever, due to increases in course length (22).

Therefore, the aim of this article is to provide an evidence-based approach to training and testing for golfers. The first section will provide an overview of golf swing mechanics, the associated GRF, center of pressure (CoP) and muscle activation during the swing. An analysis of injury risk and the key physical attributes will then be discussed, before providing evidence-based recommendations for testing and training golf athletes.

The Golf Swing: The X-Factor, Ground Reaction Forces, Center of Pressure, Joint Work and Muscle Activation

The X-Factor

Figure 1 shows the golf swing broken into eight key phases (referred to as the "P System" by golf coaches), as defined by Han et al., (36), but with some slightly amended wording: 1) address position, 2) early backswing, 3) top of the swing, 4) club vertical (during the downswing), 5) mid downswing, 6) impact with the ball, 7) early follow-through, and 8) late follow-through. The importance of rotational ability cannot be overstated, with a term known as the 'X-Factor' commonly used in golf. This refers to the rotation of the thoracic spine relative to the pelvis at the top of the backswing (18). Similarly, the 'X-Factor stretch' is often referred to as the maximal X-Factor that occurs during the start of the downswing when the pelvis begins to rotate back towards the target, while the upper body remains stationary (i.e., creating a "stretch"). Previous research has highlighted that if the rotational gap between the pelvis and upper body (X-Factor stretch) can be widened, it can improve driving distance (2,45). This is supported by Cheetham et al., (19) who reported that higher skilled golfers exhibited a larger X-Factor stretch than less skilled players (57° vs. 50°, respectively), especially at the start of the downswing. Essentially, this indicates that higher skilled players tend to have a greater capacity to separate their pelvis from their thoracic spine region during the swing, which ultimately creates a more effective stretch-shortening cycle (SSC) action. The importance of the X-Factor is also shown through associative analysis, where Meister et al., (63) reported very strong relationships between peak X-Factor and CHS ($r = 0.9$) and the X-Factor at impact and CHS ($r = 0.94$).

There are several potential reasons for the association between X-Factor and CHS. Firstly, Hume et al., (42) state that elite players can generate more efficient SSC mechanics during the swing (X-Factor stretch) than amateurs, resulting in greater CHS (52). It is proposed that this separation of the pelvis and thoracic region increases the elastic energy due to the stretch reflex, increasing the velocity of the upper body as it rotates towards the ball (19). Secondly, a recent study found that the length of the hand path during the golf swing is positively associated with CHS (55). The authors suggested that greater torso rotation could increase the hand path length, allowing for more time to apply force and perform greater levels of work during the downswing (55). Thirdly, large X-Factor stretch values are generally achieved by initiating the downswing with rotation of the hips prior to any movement in the torso. This not only creates that desired separation, but also promotes a proximal to distal sequencing of joint actions during the downswing, which is commonly considered advantageous for achieving greater CHS (48,54). Taken together, X-Factor and X-Factor stretch may be positively associated with CHS due to: 1) greater utilization of the SSC, 2) more efficient proximal to distal sequencing and, 3) the golfer's ability to rotate the trunk and create a longer hand path, or some combination of these factors. These potential explanations provide a natural transition to a discussion of the importance of GRF and changes in CoP during the golf swing.

****** Insert Figure 1 about here ******

Ground Reaction Forces (GRF)

The production of force is required to transfer energy through the kinetic chain, with movement progressing from the ground up, transferring through the trunk, and ending in the club head. Specific investigations measuring GRF during the golf swing are perhaps more common than some may expect. For example, Hur et al., (43) reported GRF data in 3 semi-professional and 1 professional player, using a driver, 4-iron, 7-iron and pitching wedge. Although the authors' conclusion was that force did not differ between club types, this was likely a consequence of only recruiting 4 players in the study. Furthermore, individual differences between clubs were apparent (e.g., 700 N for a 4-iron vs. 501 N for a 7-iron, in one subject), highlighting the limitations of group mean data in this regard. Given the individual nature of golf, group mean data can be questioned unless sample sizes are particularly large. With that in mind, Chu et al., (20) used 308 golfers with a mean handicap of 8.4 to assess the relationship between biomechanical variables and driving performance (defined as ball speed). Vertical GRF was expressed as a % of bodyweight for the lead and trail legs, with the swing broken down into 4 phases: top of the swing, acceleration, 40 milliseconds prior to impact and impact – which the reader should note is not how we have defined the phases of the swing. Results can be seen in Table 1. When analyzing the data, the most stand-out point is that during what they describe as the acceleration phase (i.e., the entire downswing), there is a clear transition where GRF shifts from the trail leg to the lead leg, highlighting the importance of increasing vertical GRF to the lead leg early in the downswing (20). Finally, an additional important consideration is the interaction between GRF and CHS. Han et al., (37) used 63 golfers with a handicap ≤ 3 and reported significant correlations between CHS and combined vertical GRF using a driver, 5-iron and pitching wedge (r = 0.33-0.35) and vertical GRF in the lead leg alone (r = 0.33-0.44). These data indicate that although the relationship between GRF and CHS is only moderate, it is relatively consistent between different clubs.

****** Insert Table 1 about here ******

Center of Pressure (CoP)

The CoP is a single point representing the average location of the vertical GRF, and has been extensively analyzed within research. Additionally, this is also utilized by golf coaches when seeking to assess and understand the golf swing. Ball & Best (3) analyzed simulated drives in 62 professional or high handicap (11 ± 8) golfers, performed on twin force plates. Two common styles relating to CoP were evident: front foot and reverse style swings. Both styles started with an even CoP which moved to the trail foot during the backswing and then shifted to the lead foot during the downswing. Despite these similarities, notable differences were still evident between styles. Front foot players continued to move their CoP to the front foot through to impact with the ball, whilst the reverse group, shifted their CoP towards the trail foot for ball impact and follow-through (3). Interestingly, both weight distribution styles were evident across professional and higher handicap players, suggesting that neither should be considered a technical fault; rather just a specific style that players may prefer. In a separate study, Ball & Best (4) investigated the association between CHS and CoP in the front and reverse foot groups, respectively. For the front foot group, an increased range of CoP movement and the rate at which that CoP shifted towards the front foot were associated with increased CHS at ball contact (r = 0.53 and 0.46, respectively). For the reverse group, CoP being positioned closer to the mid-stance position (as opposed to the trail foot), coupled with a larger rate of movement towards the trail foot were associated with increased CHS at ball contact (r = 0.75 and 0.69, respectively). Finally, Smith et al., (76) used 22 high-level golfers (handicap: +3 to 4) and showed that 74% of CHS could be explained by three key components: 1) timing of medio-lateral changes in CoP, 2) rate of change in medio-lateral changes in CoP and, 3) the timing of the medio-lateral changes in center of gravity during late backswing. The key message from this research, which is in agreement with the aforementioned information from Ball & Best (3), was that golfers who exhibit earlier movement of their CoP towards the front foot prior to the downswing, may be able to generate greater CHS.

Joint Work and Muscle Activation

Nesbit & Serrano (67) undertook a biomechanical analysis of the golf swing in four right-handed players: a male professional, a male with a handicap of 5, a male with a handicap of 13 and a female with a handicap of 18. The top three regions of the body which performed the most work, was consistent across all players, with the forthcoming values expressed as a % of total work: 1) lumbar spine (21.3-26.5%), 2) right hip (17.2-20.5%), and 3) thoracic spine (17.8-19.5%). No other region of the body provided a contribution > 10%, except for the female player who showed that 11.9 and 11.5% was performed by the left hip and right elbow, respectively (67). Despite the inherent differences between individuals during the golf swing (33), these data provide some indication of joints in the body that are commonly exposed to high amounts of work. From a programming perspective around the spinal column, practitioners should look to emphasize exercises which concurrently focus on hip and thoracic mobility, whilst retaining lumbar spine stability. The mobility emphasis in the hips and thoracic regions may potentially reduce the stress placed on the lumbar region, by providing greater opportunity to increase the X-Factor stretch, without using the lumbar region more than required. Where hip extension is concerned, greater strength and power should provide players with greater capacity to produce force ballistically, during the downswing and follow-through, which in turn, should help to improve CHS.

From a muscle activation perspective, Cole & Grimshaw (21) provided a review of the biomechanics of the golf swing, with an overview of muscle activation during different phases of the swing (although specific muscle activation values relative to maximal voluntary isometric contractions was not provided).

- Throughout the backswing, multiple studies have shown that both internal and external oblique muscles help facilitate rotation of the trunk (40,70,86), whilst the erector spinae aid in stabilization of the trunk as well (70,86). Importantly though, the hamstrings also show moderate levels of activation (6,60), as they resist knee extension. This is suggested to be important during the swing, to: i) allow greater range of motion at the trunk and, ii) help to dissipate loads across the joints in the lower body (21).
- During the downswing, forceful contractions of the gluteus maximus, gluteus medius and hamstrings occur in the trail leg, which act to push the hip into extension in that rotational movement of the swing (6,60,86). This is coupled with a concurrent activation of the adductor magnus in the lead leg (6), which serves to assist rotation of

the pelvis by pulling the lead leg backwards (21). For the upper body, the obliques work in an opposing fashion to the backswing and the pectoralis major reaches maximal activation on both sides, just prior to impact (57).

- During the follow-through, gluteus medius activation remains high (6,60), although as this phase of the swing nears completion, activation naturally starts to decrease. In contrast, hamstring activation remains high throughout the follow-through as they continue to provide stabilization to the pelvis and knee joints during the continued rotation of the swing. In addition, only small reductions in oblique (86) and pectoralis muscle activity (46) have been shown during the follow-through.

When considering this information practically, it supports the notion that exercises which develop strength and ballistic force production capabilities in the gluteus complex, hamstrings, obliques and pectoralis major muscles should be prioritized.

Injury Analysis

As with any injury analysis, providing clear definitions is critical to determine prevalence and duration away from the sport, and there has been a large volume of literature that has investigated the prevalence of lower back injuries in golf (34,51,61,62). However, it is worth highlighting that there is a distinct lack of prospective epidemiological studies in golf, which has been acknowledged in a recent international consensus statement on the reporting of injuries and illnesses in the sport (66). McHardy et al., (62) undertook a survey of injuries in golf using 588 players (473 males, 115 females) from 8 different clubs and defined injury as any that: i) occurred during practice or competition that prevented further play, ii) impeded normal performance or, iii) required any medical treatment. When considering location of injury, the lower back was most commonly reported (18.3%), followed by the elbow and forearm (17.2%), foot and ankle (12.9%) and shoulder or upper arm (11.8%) (62). When aiming to define the self-reported mechanism of injury, the golf swing accounted for 46.2% and overuse in the sport for another 23.7% of cases, meaning that just over 30% of injuries were unrelated to the golf swing. In a similar study design, Gosheger et al., (34) interviewed 703 golfers (643 amateurs and 60 professionals), and reported 82.6% of injuries as overuse and 17.4% as single traumatic events. However, it is worth noting here that the aforementioned mechanisms in these two studies were self-identified and although a player is likely able to inform *when* and *how* an injury occurred, this does not necessarily make it the underlying cause. Instead, this is one of the primary purposes of undertaking a screening and fitness testing battery, so players and practitioners can understand the strengths and weaknesses of their physical fitness and injury history. When establishing when injuries occurred, McHardy et al., (62) reported 23.7% occurred at ball impact, 21.5% during the follow-through phase, with only 8.6% during the backswing. When considering location of injury, these trends largely follow previous guidelines by McHardy et al., (61) who reported the three most common injury sites for both amateur and professional players to be: i) lower back (professional = 22-24%; amateur = 15-34%), ii) wrist (professional = 20-27%; amateur = 13-20%), and iii) elbow (professional = 7-10%; amateur = 25-33%). This is further supported by Fradkin et al. (29) who undertook a survey of golf injuries in ~500 players in Australia. A total of 185 injuries were recorded, with 58 (31%) reported for the lower back, 31 (17%) for the shoulder and 19 (10%) for the elbow.

More recently however, Robinson et al., (73) undertook a systematic review of musculoskeletal injuries in professional golfers and reported injury location as a percentage of the total injuries reported in each empirical investigation (of which there were five). Four out of five studies reported the lumbar spine as the most common area of injury, ranging from 24-34% (34,35,58,80), with only one reporting the cervical spine as having a higher percentage of injury (25%) compared to the lumbar region (22%) (77). As such, whilst some differences exist in common areas of injury, there does seem to be over-whelming evidence supporting the lower back as being one of the primary areas of concern. When coupled with the understanding of the X-Factor stretch, it is clear that optimizing range of motion in the hips and thoracic regions is not only important for golf performance, but also long-term health in the sport (65). Consequently, these data reinforce the need for a holistic approach to testing and programming all-year round for golfers. Furthermore, it is worth acknowledging that to the authors' knowledge, there are no studies which have shown that improved physical capacities reduce the risk of injury in golf specifically. However, given the associated health (65) and performance benefits (28) of S&C training for the sport, integrating such training methods are likely to produce a more robust player, enhancing their overall health and potential ability to withstand overuse injuries. That said, further research in the area of training interventions and their ability to reduce injury risk in golfers is definitely required.

An Overview of the Relationships with Club Head Speed and Effects of Strength and Conditioning Training Interventions

Previous literature has acknowledged the importance of strength and power for improving golf performance, such as CHS, ball speed and ultimately, driving distance (71). This view is supported in a systematic review by Ehlert (27) who investigated the associations between CHS and different physical attributes and the reader should refer to this work for a more detailed outline of these relationships. Pooled correlations were reported between CHS and lower body strength (r = 0.46-0.63), upper body strength (r = 0.41), lower body power (r = 0.38-0.55), and upper body power (r = 0.51-0.60). Collectively, these findings suggest moderate to strong relationships whereby greater levels of strength and power are associated with greater CHS. Whilst useful, some studies included recreational or "less skilled" golfers with a handicap ≥ 10 (49,53,75), which affects the homogeneity of the sample being studied. Consequently, this can impact the magnitude of the correlations when pooled together. Further to this, correlations do not imply causation and so, intervention studies are likely to be more effective at improving our understanding of the efficacy of strength and power training for golf.

In a separate systematic review, Ehlert (28) also investigated the effects of S&C training interventions on golfing measures of performance, such as: CHS, ball speed, carry distance and total driving distance. Whilst nearly all training studies focused on strength and power exercises, some also included trunk exercises as well. Isometric mid-thigh pull (IMTP) ES data were divided into skilled vs. less skilled players (handicap = < 10 and ≥ 10, respectively) and short vs. long duration (≤ 8 weeks and > 8 weeks, respectively), with data presented in Table 2. Results show that strength and power training has only a small effect on increasing CHS, regardless of skill level. However, when assessing changes in ball speed and distance metrics, skilled players exhibit noticeably larger improvements than less skilled players for the other three golf metrics (Table 2). When interpreting these differences between groups, it seems logical to suggest that if less skilled players are unable to demonstrate comparable improvements, that other factors such as 'center of strike' (i.e., connecting with the ball in the center of the club-face) may be an important factor which translates to increased distance and ball speed (8).

When considering the duration of strength and power interventions, CHS again shows the smallest improvements out of the four included metrics. Although it is the most commonly reported measure in the golfing literature (27,28), the current evidence indicates that greater improvements can be seen in other measures of golf performance. As a final point, the use of confidence intervals or ranges in data is important to emphasize here. For example, the ES value for total distance in studies conducted ≤ 8 weeks was 1.42. However, with an ES range of 0.14 to 4.26 (noting that true confidence intervals were not actually calculated in this review), this highlights that the true effect could be anywhere between trivial (0.14) trivial) to very large (4.26). Such variation is indicative of the varied and individualized responses that players may show from training interventions and how that translates to enhancing golf performance. This notion is also supported by Bliss et al., (13) who investigated the effects of an 8-week plyometric program on golf swing performance in adolescent male players (mean handicap = 4.7 ± 3.0 for the intervention group and 5.2 ± 2.5 for the control group). Mean changes in CHS were 3.01% and -0.78% for the intervention and control groups, respectively. However, individual changes for the intervention group ranged from minor reductions in CHS (just under 0%) to notably larger improvements (> 8%). Thus, with golf being an individual sport, practitioners are advised to undertake routine testing to determine the efficacy of their training interventions on the physical capacities for each player. Doing so, will enable a deeper understanding of what may have worked for one player, may not for another, and will subsequently help to individualize training programmes when they are being reviewed.

****** Insert Table 2 about here ******

Practical Applications: Testing and Training

Testing

Lower Body Strength

Table 3 provides an overview of the selected tests and metrics for the golf athlete, with the forthcoming information providing a justification for their selection. When considering lower body strength, Oranchuk et al., (68) reported a moderate correlation between back squat 1RM and CHS (r = 0.64) in 12 NCAA collegiate golfers. However, stronger associations have been reported (r = 0.81) between CHS and load lifted during the 1RM back squat relative to body mass, this time in 25 NCAA Division 1 golfers (69). When considering isometric strength assessments, Sanders et al., (74) recently reported very strong correlations between the IMTP peak force and driver carry distance (r = 0.91) and 6-iron carry distance (r = 0.91) in 13 high level youth players (mean age: 15.6). Wells et al., (88) also investigated the relationship between CHS and peak force during the IMTP in 27 high level male adult players (handicap ≤ 5), with significant moderate associations evident (r = 0.48). It is worth noting that the magnitude of these relationships differs quite substantially between Sanders et al., (74) and Wells et al., (88) work, which may potentially be explained by the differences in age and sample size. Wells et al., (88) also investigated the associations between RFD (at 0-50, 0-100, 0-150 and 0-200 ms) and CHS. However, the use of RFD was not recommended owing to the large coefficient of variation (CV) scores, which were > 15% at every time integral. However, although the magnitude of these relationships with CHS appears to be test-specific, the relevance of strength for the golf athlete seems hard to dispute. In addition, it seems prudent to suggest that given we know the duration of a golf swing (i.e., 0.89 s) (63), peak force could be monitored at that given time point on the force-time curve, and then expressed as a percentage of their overall peak force value. Such information would enable practitioners to have an understanding of how much of their maximal force production capability can be expressed relative to the time constraints of a golf swing. Anecdotally as well, the position of the IMTP is not too dissimilar to the address position in golf; thus, our experience is that this has helped players buy-in to the concept of strength testing. Finally, if practitioners do not have access to force platforms, a dynamic assessment of strength (e.g., back squat depending on training age) may be a viable alternative to the IMTP test. However, 1RM testing can be easily questioned given the time it takes to undertake this in the field; which is a luxury many practitioners do not have. Thus, given the vast methods of measuring barbell velocity (e.g., linear position transducer, Push Band or even a smartphone app), this may be a more time-efficient and appropriate measure of monitoring lower body strength in the field, if the IMTP cannot be used.

Upper Body Strength

For upper body strength, less information appears to be available; however, Keogh et al., (47) reported a moderate correlation (r = 0.50) between CHS and bench press 1RM. Torres-Ronda et al., (83) reported slightly stronger relationships between bench press 1RM, but this time with both peak (r = 0.61) and average ball speed (r = 0.62), in 44 Spanish players with a mean handicap of 1.5 ± 5.5. Further to this, given the high amounts of muscle activation in the pectoralis muscles during the downswing (93% relative to maximal voluntary isometric contraction [MVIC]) and follow-through (74% MVIC) phases of the swing (60), it stands to reason that practitioners may wish to measure pushing strength. However, similar to if and when practitioners use the back squat, the most appropriate way of gathering actionable data in the field may be measuring barbell velocity during the bench press. When pulling strength is considered, a weaker correlation (r = 0.30) has been previously reported between pull up strength (in kg) and CHS in professional players (39). Despite this weaker relationship for pulling strength, there should still be an emphasis on programming upper body pulling exercises, to ensure some level of strength equilibrium in the upper body; even if it is not assessed routinely.

Lower Body Power

For lower body power, jump testing is commonly used to assess an athlete's lower body ballistic force production capabilities and golf is no exception. For example, Wells et al., (88) showed CMJ propulsive impulse to have a large relationship with CHS (r = 0.79). Hellstrom (39) reported significant correlations between CMJ peak power and CHS (r = 0.61), indicating the importance of power as a key physical component to develop. Finally, Wells et al., (87) and Oranchuk et al., (68) also found significant correlations between CHS and CMJ height (r = 0.50 and 0.73, respectively). Thus, if practitioners do not have the ability to measure any form of jump strategy metrics (e.g., propulsive impulse) via force plates, monitoring metrics such as jump height and peak power may be viable options of indicating whether improvements are evident from training interventions, which can easily be done via smartphone applications now (5). However, an additional factor that practitioners must consider for golfers is whether changes in jump performance also occur alongside changes in body mass. Essentially, increases in body mass may be desirable to help enhance measures such as CHS and ultimately, shot distance (28,83); however, it is of course possible that such increases would have a negative effect on jump height. Thus, it is our suggestion that the use of jump height should be reserved for when no other monitoring options are available. In addition, a recent article highlighted that it is hard to contextualize changes in ratio data, unless the component parts are concurrently monitored (11). With impulse also being a ratio (calculated as net force multiplied by time), net peak force and phase duration should also be monitored alongside impulse, to contextualize any changes that occur between test sessions. Finally, and again somewhat anecdotally, as previously mentioned, the duration of the golf swing takes 0.89s (63), which is not dissimilar to that of a CMJ prior to take-off (11).

Upper Body Power

For upper body power, a couple of studies have utilized medicine ball throws for distance as an outcome measure. For example, Lewis et al., (50) used a sample of PGA professional players, reporting moderate (r = 0.57) and strong (r = 0.71) correlations with CHS, for rotational and seated medicine ball throws, respectively. Comparable results are also evident in male and female youth players by Coughlan et al., (24). In males, moderate to strong relationships with CHS were evident for the seated medicine ball throw to the left (r = 0.67) and right (r = 0.61), plus the rotational medicine ball throw to the left (r = 0.71) and right (r = 0.62). In females, comparable results were evident but only for the rotational medicine ball throw to the left (r = 0.57) and right (r = 0.56). Further to this, the use of rotational medicine ball throws likely holds some notion of specificity for golfers, given the similarity in movement pattern (15). Given this similarity, the consistency in relationships between CHS and upper body power measures in both professional and youth players, and previously reported high reliability for these tests (ICC = 0.97-0.99) (7), it seems prudent to suggest the integration of medicine ball throws for distance into a golfer's physical test battery.

Range of Motion

Range of motion testing is also an area that has received notable attention in the golf literature. Doan et al., (25) positioned a camera directly above a player's head, who were seated with their legs and hips secured by Velcro straps. Players then positioned a dowel behind their head (as per where a barbell would rest) and rotate their torso three times in each direction. Computer software was then used to measure the angle of rotation in the backswing and follow-through directions. Mean values range from 74-85° for the backswing and 73-81° for the follow-through (25). Keogh et al., (47) also used the same methods of analysis and reported weak correlations between CHS and backswing rotation (r = 0.34) and follow-through rotation (r = 0.29). Finally, Marshall & Llewelyn, (56) assessed range of motion at the shoulders, hips and trunk, but then reported the results as a total range of motion. Relationships with CHS were small for both males (r = -0.40) and females (r = 0.28); however, the amalgamation of eight range of motion assessments into a single cumulative total, must be questioned. Although the evidence does not show the relationships to be as strong as measures of strength and power, perhaps range of motion assessments should be included initially in testing batteries to determine whether any obvious deficits exist, relative to the aforementioned values. If they do not, then it is questionable whether such measures are consistently needed when testing golfers.

Using Testing Data in Practice

Although the evidence in golf has provided justification for the tests and metrics to consider, a final thought for practitioners is to determine their usability in practice. A recent article on jump testing, highlighted that once tests have been chosen, practitioners should determine their sensitivity to change – that is, to determine whether change is real or greater than the error in the test (11). Thus, it is our suggestion that as part of the routine monitoring process or when assessing the efficacy of our training interventions, practitioners set target scores for each golfer. A recent article by Turner et al., (84) provides a detailed overview for how to do this at both the group and individual level. However, with golf being an individual sport, practitioners could consider using the CV that is gathered from multiple trials of a given test, to set the minimum target score needed that is deemed real. For example, if a golfer records 2000 N of peak force in an IMTP, with this metric showing a CV value of 3.6%, the calculation would be: 2000 x 0.036, which equals 72 N. Thus, any improvement or reduction greater than 72 N (either side of 2000), would be considered a real change. The benefits of this method are that each player will exhibit their own CV value; thus, target scores or real change are individualized relative to their own variability. In addition, monitoring the CV enables us to determine the absolute reliability of a test or metric, and therefore, whether further data analysis is even warranted. Finally, when tracking change over time, percentage change in performance scores can also be compared to baseline CV values, in order to determine whether improvement is also greater than the measurement error of the test (11).

****** Insert Table 3 about here ******

Training Requirements

Warming up for Golf

Physical warm-ups are activities designed to prepare the body for a subsequent activity or event (59). While exact protocols and approaches differ, most warm-ups aim to improve performance and reduce risk of injury by raising body and muscle temperature, and by activating, mobilizing, and potentiating relevant musculature (30,44). A recent systematic review highlighted several considerations for developing warm-up protocols for golfers (26). Firstly, warm-ups that prioritize static stretching should not be prioritized before golf, as studies have demonstrated that intensive static stretching can reduce metrics of golf performance (31,32) and static stretching is typically outperformed by warm-up conditions that focus on dynamic stretching or activity (64,79). In contrast, several studies have reported beneficial effects from various dynamic warm-up protocols compared to control or comparison conditions (23,64). For example, Moran et al., (64) asked golfers to perform a series of full range of motion dynamic stretches targeting key muscles (e.g., quadriceps, hamstrings, deltoids) and movement patterns (e.g., trunk rotation) of the golf swing. This warm-up resulted in straighter swing paths and greater CHS and ball speed compared to static stretching and a control condition. Adding resistance exercise or potentiation methods to a dynamic warm-up may also be beneficial. For example, several studies have reported positive changes in golf performance measures after golfers performed barbell resistance exercises (82), resistance band exercises (82), and countermovement jumps (12,72).

From a practical standpoint, there are several factors that should be considered when designing warm-up protocols for golfers (12). Firstly, dynamic exercises should ideally target muscles and movement patterns that are relevant to the golf swing. The golf swing is a whole-body dynamic activity involving significant contributions from muscles such as the pectoralis major and the hip extensors (60). Further, the generation of GRF, rapid shifts in CoP, and greater separation of the pelvis and torso (X-Factor stretch) are all considered important to effective swinging (42). As such, including dynamic exercises like squat variations, lunges, and torso rotations is likely to be beneficial. Second, many golf facilities have limited equipment availability which may restrict the use of barbells or other resistance training equipment as part of a pre-golf warm-up routine. However, external resistance provided by resistance bands has had positive effects in several studies (82), and resistance bands have the advantage of being easy to transport and feasible to use at nearly any facility. Bodyweight countermovement jumps are also a feasible option to add to a dynamic warm-up given the lack of equipment requirements and the positive findings reported in previous studies on CHS (12,72). Finally, it is currently unknown how long the effects from a warm-up persist. Given that golf rounds last multiple hours, it may be useful to implement brief "re-warming" protocols that a golfer can use on the course. For example, an abbreviated dynamic stretching routine could potentially be used to stay loose during slow periods of play (i.e., waiting on the group ahead to complete a hole). In addition, when players experience delays in competition (e.g., due to bad weather), warming up again is likely to be one of the most effective uses of time, so that they are as physically and mentally ready as possible when play resumes.

Programming

Planning training for the elite golf athlete is challenging as the season typically runs for most of the year. Whilst the highest level players (i.e., PGA and DP World Tours) may choose which events to enter, enabling some time off at different stages throughout the season, events typically run all year round. Current evidence on S&C periodization for golf is very limited and with a lack of clarity around obvious down-time for golfers, the goal for many athletes is to simply train consistently throughout the year (which is what the majority of professional players seem to do). That said, there are a couple of logical suggestions we would make for practitioners. Firstly, if a player is playing tournaments weekly (which take place from Thursday to Sunday), practitioners may wish to front load a golfer's training at the start of the week (e.g., more volume on a Monday). Secondly, if players are happy to continue training through tournaments, simple strategies during competitions such as reducing the eccentric focus on exercises may help to minimize fatigue. Such an example relating to strength could be to replace a back squat with a box squat or trap bar deadlift. The latter two exercises still help to develop strength, but range of motion is reduced and they are both more concentric-dominant in their focus. Tables 4 and 5 provide two example training programmes for the golf athlete, that we have used in practice and are a representation of the aforementioned information in this article.

****** Insert Tables 4 and 5 about here ******

Whilst the evidence in this article provides guidance for which physical characteristics to test and train (i.e., both upper and lower body strength and power), practitioners are advised to understand a little more about the individual requirements for their golfers as well. This would enable more targeted and individualized training interventions, which ensure a high degree of specificity to the sport – noting that this can be challenging to accomplish (15). Although Tables 4 and 5 provide example programmes for golf athletes, there are a multitude of methods by which to gain adaptation for enhanced strength and power. For example, if a golfer is struggling to perform a back squat with the desired technique (as defined by the practitioner's coaching), alternatives such as front or box squats may serve as viable alternatives which help to drive improvements in lower body strength, whilst simultaneously working on developing the desired back squat technique (10). Thus, each player's individual movement characteristics must be considered when designing training programmes, within the context of improving strength and power for enhanced CHS.

Conclusion

In summary, practitioners working in golf should have an understanding of some of the key factors associated with the golf swing (e.g., X-Factor stretch, GRF, CoP and personal injury history) as this will help offer guidance on both testing and training prescription. Specifically, and perhaps surprisingly to some, strength and ballistic force production capabilities in both the lower and upper body should be a priority for golfers, with many professionals training consistently all year round to drive continued physical adaptation. As a final point of consideration, less is currently known about the efficacy of S&C training interventions and the effects that they can have on swing kinematics and injury risk, and should be a point of investigations for the S&C practitioner in the future. This would provide greater interaction between the player, golf coach and S&C and medical practitioners, which would only serve to benefit the player further.

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Figure 1. Description of the phases of the golf swing. Image definitions going from left to right, starting on the top row are as follows: Image 1 = Address position. Image 2 = Early backswing. Image 3 = Top of the backswing. Image 4 = Club vertical (during downswing. Image 5 = Mid downswing. Image 6 = Impact. Image 7 = Early follow-through. Image 8 = Late follow-through. *Note:* definitions are aligned with recent suggestions by Han et al., (36), but with some amended wording.

Table 1. Mean ± standard deviation (SD) data for vertical ground reaction force (GRF) expressed as a percentage of body weight (adapted from Chu et al., [20]).

GRF as a % of BW	Top	Acceleration	40 ms	Impact
Leading foot (% BW)	29.0 ± 12.1	93.9 ± 28.5	95.1 ± 30.5	74.7 ± 29.7
Trailing foot (% BW)	64.5 ± 14.3	46.4 ± 17.3	41.0 ± 21.2	35.5 ± 21.0

BW = body weight; ms = milliseconds.

Table 2. Effect size data with 95% confidence intervals showing the magnitude of change in golfing performance after S&C training interventions (adapted from Ehlert [28]).

	Club Head Speed	**Ball Speed**	**Carry Distance**	**Total Distance**
Skilled golfers	0.38 (0.18, 0.63)	1.39 (0.29, 2.95)	0.90 (0.36, 1.80)	1.54 (0.38, 4.26)
Less skilled golfers	0.50 (0.15, 1.60)	0.63 (0.38, 0.87)	0.28 (0.11, 0.52)	0.50 (0.24, 0.96)
Short duration	0.54 (0.18, 1.60)	1.20 (0.29, 2.95)	0.91 (0.36, 1.80)	1.42 (0.14, 4.26)
Long duration	0.37 (0.15, 0.63)	1.06 (0.38, 1.94)	0.40 (0.11, 0.89)	0.34 (0.24, 0.96)

Effect size scale as used by Ehlert (28): < 0.35 = trivial; 0.35-0.80 = small; 0.81-1.50 = moderate; > 1.50 = large.

Note: skilled = handicap < 10; less skilled = handicap ≥ 10; short duration = ≤ 8 weeks; long duration = > 8 weeks.

Table 3. Proposed fitness testing battery for the golf athlete.

Physical Quality	Test	Metrics
Lower body strength	Isometric mid-thigh pull	Peak force, peak force measured at the equivalent time of the duration of a golf swing
Upper body strength	Bench press	Mean velocity
Lower body power	Countermovement jump	Propulsive impulse, peak force, propulsive phase duration, peak power* and jump height*
Upper body power	Seated and rotational medicine ball throw	Distance
Range of motion	Seated trunk rotation (divided into backswing and follow-through directions)	Degrees

** Peak power and jump height can be monitored via the My Jump 2 app, when force plates are not accessible.*

Table 4. Example training programs for the golf athlete with a concurrent emphasis on strength and power development.

For the warm-up, dynamic stretches to consist of 1 set of 8 repetitions for: bodyweight squats, forward and lateral lunges, inchworms, world's greatest stretch and push up with rotation + sufficient warm-up sets on all key lifts below (A1, B1 and C1).

Lift/Exercise	Sets	Repetitions	Load	Rest
A1. Trap bar deadlift	3	3-6	80-90%	4 minutes
A2. Countermovement jump	3	3-6	-	Do in rest
B1. DB chest press	3	3-6	80-90%	4 minutes
B2. Rotational medicine ball throw	3	3-6 each side	Up to 10% BM	Do in rest
C1. Bent over row	3	3-6	80-90%	4 minutes
C2. Cable pallof press	3	3 x 20-s each side	DoT	Do in rest

BM = body mass; DoT = dependent on technique.

Table 5. Example training programs for the golf athlete with a concurrent emphasis on strength and power development.

For the warm-up, dynamic stretches to consist of 1 set of 8 repetitions for: bodyweight squats, forward and lateral lunges, inchworms, world's greatest stretch and push up with rotation + sufficient warm-up sets on all key lifts below (A1, A2 and B1).

Lift/Exercise	Sets	Repetitions	Load	Rest
A1. Back squat	3	3-6	80-90%	4 minutes
A2. Jump squat	3	3-6	20-30%	Do in rest
B1. Push press	3	3-6	80-90%	4 minutes
B2. Standing medicine ball throw	3	3-6	Up to 10% BM	Do in rest
C1. Neutral grip pull up	3	3-6	80-90%	4 minutes
C2. Kneeling cable chop	3	6 each side	DoT	Do in rest

BM = body mass; DoT = dependent on technique.