

Review article

Muscle strength and golf performance: A critical review

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Abstract

Golf has become an increasingly popular sport and a growing body of research trying to identify its main physical requirements is being published. The aim of this review was twofold: first, to examine the existing scientific literature regarding strength training and golf in healthy, non-injured, subjects; and second, to reach conclusions that could provide information on how to design more effective strength training programs to improve golf performance as well as directions for future research. Studies which analyzed the relationship between muscle strength, swing performance variables (club head speed, driving distance, ball speed) and skill (handicap, score) were reviewed. Changes in swing performance following different strength training programs were also investigated. Finally, a critical analysis about the methodologies used was carried out. The results of the reviewed studies seem to indicate that: 1) a positive relationship exists between handicap and swing performance (even though few studies have investigated this issue); 2) there is a positive correlation between skill (handicap and/or score) and muscle strength; and 3) there is a relationship between driving distance, swing speed, ball speed and muscle strength. Results suggest that training leg-hip and trunk power as well as grip strength is especially relevant for golf performance improvement. Studies that analyzed variations in swing performance following resistance-only training programs are scarce, thus it is difficult to prove whether the observed improvements are attributable to changes in strength levels. Many of the studies reviewed presented some methodological errors in their design and not all strength assessment protocols seemed appropriate. Further studies should determine muscle strength needs in relation to final swing performance, using well designed experiments and strict isoinertial assessment protocols which adequately relate to specific golf motion, age and skill level. More studies with elite participants, either professional or amateur, would be especially desirable.

Key words: Golf swing, driving distance, club head speed, resistance training, strength assessment.

Introduction

In recent years, golf has experienced a considerable increase in popularity (Farrally et al., 2003; Theriault and Lachance, 1998). Interest in this sport has reached the scientific community and a growing body of research analyzing the requirements of competitive golf performance is being published. In a relatively recent review, Farrally et al. (2003) summarized the results of golf-related investigations published by the *World Scientific Congress of Golf* (WSCG), and identified the main areas of interest. One of these areas comprises issues related to

physical conditioning, exercise and nutrition (Carlson et al., 2001; Crews and Landers, 1987; Crews et al., 1986; Cheetham et al., 2001; Chettle and Neal, 2001; Etnier et al., 1997). According to the aforementioned authors, physical demands in golf are yet not well understood, even though growing attention is being paid to increasing muscle strength and flexibility to optimize driving distance. Scientific research about physical conditioning to improve golf performance is scarce, and most investigations regarding the mechanics of the golf swing and innovation in golf equipment and materials have been carried out by golf manufacturing companies (Farrally et al., 2003).

It is generally accepted that one of the most important determinants of golf performance is the resulting combination of accuracy and driving distance (Hetu et al., 1998; Hume et al., 2005; Sthromeyer, 1973; Yoon, 1998). The drive shot is especially relevant given that it usually has to cover the longest possible distance. The strategy to play the hole must be adjusted depending on drive shot success (Thompson et al., 2007). Driving distance correlates with average score in elite golfers, ($r = -0.24$ to -0.50) which may determine the difference in total score (Hale and Hale, 1990; Riccio, 1990; Wells et al., 2009; Wiseman and Chatterjee, 2006). This finding is in agreement with those obtained by Cochran and Stobbs (1968), who concluded that a 17 m increase in drive distance alone (no change in accuracy) would result in an improvement in golf score of 2.2 strokes per 18 hole round.

Driving distance is influenced by many factors, the most important being: skill, kinematics, shaft and club head characteristics, segmental sequence of action and power output reached (Fletcher and Hartwell, 2004; Milburn, 1982; Wiren, 1968; Yoon, 1998). Thus, it seems clear from these factors that a better understanding of the muscular implications and strength requirements of the swing would contribute to optimize physical conditioning for improving golf performance.

Several studies have analyzed the effect of different resistance-only training programs or combined routines (also including endurance, flexibility and balance training) on swing performance variables (Doan et al., 2006; Fletcher and Hartwell, 2004; Hetu et al., 1998; Landford, 1976; Lennon, 1999; Lephart et al., 2007; Seiler et al., 2006; Thompson et al., 2007; Thompson and Osness, 2004; Westcott et al., 1996). Despite quite different methodological designs, these studies seem to indicate a positive influence of strength and power development on golf performance.

The aim of this review is to examine the existing scientific literature regarding strength training and golf in healthy, non-injured, subjects. The strength assessment and training methods commonly used will be discussed and new lines of investigation suggested. It is expected that some conclusions can be reached that provide valuable guidance to coaches and fitness trainers on how to train muscle strength for improving golf performance.

Literature search

A literature search was conducted in the following databases: PubMed (National Library of Medicine, USA), SPORTDiscus (Sport Information Resource Centre, Ontario, Canada) and UMI Dissertation Service (ProQuest, Canada) using the keywords 'golf', 'swing performance', 'driving distance', 'ball speed', 'club head speed', 'strength', 'resistance training' and 'power'. The 'Science and golf' peer-reviewed proceedings of the WSCG book series between 1990 and present was reviewed. Manual searches in reference lists of selected published papers were also performed. The search yielded a total of 45 relevant documents which were carefully examined.

Relationship between skill level, swing performance and muscle strength

Relationship between swing performance and skill (handicap and score)

Several variables commonly used as outcome measures in golf research are closely related to one another and may be considered equivalent in terms of golf performance: club head speed (CHS), driving distance and ball speed. A relationship between these swing performance variables and handicap (HCP) has already been established. Fradkin et al. (2004) found a negative relationship between 5-iron CHS and handicap ($r = -0.95$; $p < 0.001$). Age and frequency of play, on the other hand, were found to have no significant impact on handicap variance. These results indicate that golfers with lower handicap (better skill level) have a faster CHS, regardless of age and training frequency. Even though this study did not test golfers' accuracy, the authors acknowledged its great importance in the game since players not only need to hit the ball a long distance but they also require their shots to be accurate. Smoliga et al. (2006) analyzed swing performance indicators for three groups of golfers differing in skill level: low ($n = 56$, $HCP < 8$), middle ($n = 25$, $HCP: 8-14.9$) and high handicap ($n = 9$, $HCP = 15$). Significant differences were observed in ball speed, carry distance and total driving distance between high handicap golfers and the most skilled group. No significant differences were found between groups for backspin or club speed. The authors suggested that consistent ball flight characteristics are a key contributor to golf proficiency. In a similar study, Keogh et al. (2009) found that a low-handicap group (LHG) ($n = 10$; $HCP 0.3 \pm 0.5$) had faster ($+12\%$; $p < 0.001$) CHS than a high-handicap group (HHG) of golfers ($n = 10$; $HCP 20.3 \pm 2.4$), which coincides with the results obtained by Fradkin et al. (2004). Wiren (1968) found that handicap was the best single predictor of driving distance ($r = -0.61$) while Sell et al. (2007) reported a significant correlation between CHS and driving distance

($r = -0.48$; $p < 0.001$). Therefore, a positive relationship seems to exist between handicap and swing performance variables, although there are still relatively few studies that have examined this issue.

Relationship between muscle strength and skill (handicap and/or golf score)

Studies that relate skill (handicap or score) to muscle strength are scarce. Kras and Abendroth-Smith (2001) studied the relationship between some fitness variables (body composition, flexibility, balance, cardiovascular endurance, grip endurance, grip strength and leg power) and an average score based on the last six reported golf scores during league completion in a group of 56 junior high-school golfers. Handicap was not considered. With regard to muscle strength, significant relationships were found between average golf score and leg power (standing long jump test) ($r = -0.36$; $p < 0.05$). Similarly, Wells et al. (2009) observed a significant correlation between total score and muscle performance (vertical jump, push-ups/pull-ups in 60 s and grip strength). Grip strength showed the highest correlation to score, both in the dominant ($r = 0.68$; $p < 0.001$) and non-dominant arm ($r = 0.71$; $p < 0.001$). Tsai et al. (2004) measured isometric hip abduction and adduction strength in side-lying with the hip joint in neutral position and normalized to body weight for both legs using a dynamometer. They found a negative correlation between left hip abduction and handicap ($r = -0.33$; $p < 0.05$). Sell et al. (2007) analyzed a sample of 257 male golfers and found that players with scratch (zero handicap) or better handicap obtained significantly better results in hip muscle, trunk and shoulder strength (isokinetic strength at $60^\circ \cdot s^{-1}$) than less proficient golfers. Taken together, and despite that the strength assessment procedures greatly differed between studies, these results suggest that there is a positive correlation between skill (handicap or golf score) and muscle strength, especially grip strength. This relationship seems to be observed in adult golfers as well as in junior players. Further investigations should be carried out to confirm these findings.

Relationship between muscle strength and swing performance

Studies investigating the relationships between physical fitness variables, ball speed and performance (Bayios et al., 2001; Carlson et al., 2001; Ferris et al., 1995; Forthomme et al., 2005; Heitman et al., 2000; Pugh et al., 2003; Pyne et al., 2006; Signorile et al., 2005) are common for sports such as baseball, tennis, volleyball and handball. Table 1 summarizes the results of a limited number of studies which analyzed the relationship between muscle strength and golf swing performance variables.

Yoon (1998) measured muscle strength and its relation to swing speed. He observed a significant correlation between swing speed and combined leg and hip muscle power ($r = 0.37$), grip strength ($r = 0.29$), trunk power ($r = 0.63$) and combined trunk and arm strength ($r = 0.33$). In a stepwise multiple regression analysis, power factors (trunk power, hand grip strength and normalized leg and hip power) were meaningful in predicting swing

Table 1. Summary of descriptive studies that correlate muscle strength and golf swing performance variables.

Study	Sample size (n)	Sample profile	Strength items	Golf performance variables	Results
Gordon et al. (2009)	n = 15 (M)	age 34.3 ± 13.6yr; HCP 4.9 ± 2.9	Total body rotation power (MB); chest strength (pec-deck)	CHS	CHS and chest strength ($r = 0.69$); CHS and total body rotation power ($r = 0.54$)
Keogh et al. (2009)	n = 20 (M)	age 22.9 ± 3.4yr; HCP 0.3 ± 0.5 to 20.3 ± 2.4	Bench press; hack squat; GSCWC; isometric prone hold	CHS; target accuracy; HCP	LHG had greater CHS (12%) and GSCWC strength (28%); CHS correlated to: HCP, target accuracy, GSCWC strength
Kras and Abendroth-Smith (2001)	n = 56 (M)	age 15 to 18yr; No HCP	GS; GE; LP	average score	Average golf score and: age ($r = 0.41$), leg power ($r = 0.36$)
Sell et al. (2007)	n = 257 (M)	age 45.5 ± 12.8yr; HCP <0 to 20	TR; SRIR; SRER (strength at 60°/s); HAB; HADD	DD (self-reported); HCP	HCP correlated to: hip, trunk and shoulder strength
Thompson (2002)	n = 31 (M)	age 65.4 ± 6.7yr; HCP ?	Chest press; leg press; leg curl; shoulder press; lat pulldown; seated row; biceps curl; back extension; abdominal crunch	CHS	CHS correlated to: chest press, leg press, shoulder press, lat pulldown, seated row, biceps curl
Tsai et al. (2004)	n = 82	age ?; HCP <0 to 19	Isometric hip strength	DD (self-reported); HCP	LHAB and HCP ($r = -0.33$), DD ($r = -0.32$). LHAB different among groups
Wells et al. (2009)	n = 15 (M); n = 9 (F)	age 22.7 ± 5.1yr; HCP ?	Abdominal muscle endurance test; VJ; GS; push-ups and pull-ups in 60s	golf ball's initial trajectory; BS; CD for drive and 5-iron	F: DLVJ and BS ($r = 0.57$), DD ($r = 0.61$). M: VJ and BS ($r = 0.50$), DD ($r = 0.62$); pull-ups and BS ($r = 0.55$), DD ($r = 0.53$); push-ups and BS ($r = 0.48$), GS and BS ($r = 0.65$)
Wiren (1968)	n = 51 (M)	age 17 to 73yr; HCP <14	17 strength items	Timing; DD; wrist cock; CHS; SS; HCP	DD correlated to muscle strength and timing. HCP and DD ($r = 0.61$)
Wu et al. (2009)	n = 20 (M)	age 15 ± 1.7yr; HCP 10 ± 6.1	LHAB; LHF; TF; TE; SRIR; SRER; TR	BS	BS and: LHAB ($r = 0.56$), LHF ($r = 0.60$), TF ($r = 0.52$), TE ($r = 0.56$), SRIR ($r = 0.63$), SRER ($r = 0.60$)
Yoon (1998)	n = 14 (M)	age 18 to 38yr; HCP < 3	Leg and hip power, trunk power, combined arm and trunk power, GS	SS	SS and: leg and hip power ($r = 0.37$), GS ($r = 0.29$), trunk power ($r = 0.63$), combined arm and trunk power ($r = 0.33$), height ($r = 0.26$), arm length ($r = 0.20$)

MB: Medicine Ball; CHS: Club Head Speed; CD: Carry Distance; SS: Swing Speed; BS: Ball Speed; DD: Driving Distance; HCP: Handicap; LHG: Low Handicap Golfers; GSCWC: Golf-Specific Cable WoodChop; VJ: Vertical Jump; DLVJ: Dominant Leg Vertical Jump; GS: Grip Strength; GE: Grip Endurance; LP: Leg Power; TR: Trunk Rotation; SRER: Shoulder Right External Rotation; SRIR: Shoulder Right Internal Rotation; HAB: Hip Abduction; HADD: Hip Adduction; LHAB: Left Hip Abduction; LHF: Left Hip Flexion; TF: Trunk Flexion; TE: Trunk Extension. M: Males; F: Females. Only significant correlations ($p < 0.05$) are reported.

speed, with trunk rotation strength as the most significant predictor. Thus, a significant relationship was observed between muscle trunk power and swing speed in elite golfers (HCP < 3). However, one possible drawback of this study would be the small sample size ($n = 14$) and the wide age range (18-38 yr) of participants. Wu et al. (2007) observed a significant correlation between ball speed and left hip (abduction $r = 0.56$; flexion $r = 0.60$), trunk (flexion $r = 0.52$; extension $r = 0.56$) and right shoulder (internal rotation $r = 0.63$; external rotation $r = 0.60$) muscle strength. These findings agree with those of Tsai et al. (2004) who found that left hip abduction strength correlated to driving distance ($r = 0.32$; $p < 0.01$). Even though the number of participants ($n = 82$) was high, some important limitations were observed: the authors did not report the players' age and driving distance was not evaluated but self-reported.

Other recent studies have correlated swing performance indicators to muscle strength and power, in

addition to other physical fitness variables such as flexibility, endurance, balance and anthropometric measurements. Wiren (1968) examined factors that could influence driving distance and categorized them under four different headings: strength, anthropometry, flexibility and timing. As a result, 13 strength-related items showed correlation with driving distance, the most significant ones being: right wrist palmar flexion strength ($r = 0.59$), right ankle plantar flexion strength ($r = 0.49$) and left shoulder horizontal extension strength ($r = 0.48$). Age showed a correlation of $r = 0.55$. Wiren (1968) suggested that strength and timing seem to be the factors most related to driving distance. Wells et al. (2009) linked several physiological measures to golf performance. The authors established the following categories of analysis: balance, flexibility, abdominal muscle performance, peripheral muscle performance (upper- and lower-body) and golf performance. When analyzed by gender, female results revealed trends and significant correlations be-

tween dominant leg vertical jump and drive ball speed ($r = 0.57$; $p < 0.05$) and driving distance ($r = 0.61$; $p < 0.01$). Results from male participants indicated significant correlations between vertical jump and drive ball speed ($r = 0.50$; $p < 0.05$) and driving distance ($r = 0.62$; $p < 0.01$); between pull-ups and drive ball speed ($r = 0.55$; $p < 0.05$) and distance ($r = 0.53$; $p < 0.05$); between push-ups and drive ball speed ($r = 0.48$; $p < 0.05$); and between grip strength and drive ball speed ($r = 0.65$; $p < 0.01$). Gordon et al. (2009) investigated the relationship of strength, power and flexibility to CHS. The results showed a significant correlation between chest strength and CHS ($r = 0.69$; $p < 0.05$), and between total body rotation power (distance reached with a 3 kg medicine ball with a hip toss movement) and CHS ($r = 0.54$; $p < 0.05$), in a group of 15 male golfers (HCP 4.9 ± 2.9). Keogh et al. (2009) compared a group of 10 LHG (HCP 0.3 ± 0.5) with a group of HHG male golfers (HCP 20.3 ± 2.4). Results showed that strength in golf-specific cable woodchop exercise was significantly greater in LHG than HHG, and significantly correlated to CHS. Trends were also evident for bench press strength, greater in LHG than in HHG and significantly correlated to CHS. Thompson (2002) observed that strength variables (10RM in chest press, leg press, lat pulldown, shoulder press, biceps curl, and seated row exercises) in recreational older golfers ($n = 31$) showed a significant relationship with CHS. In this case, it would have been adequate to consider the addition of skill level (handicap or score) to the list of dependent variables in order to analyze strength in differently skilled subjects.

After reviewing all these studies, a relationship seems to exist between muscle strength and golf performance variables (i.e. driving distance, CHS, ball speed). However, it must be taken into consideration that the methodological approach of the examined studies was very different. While Gordon et al. (2009), Keogh et al. (2009), Wells et al. (2009) and Yoon (1998) measured muscle power at least in one golf-specific exercise, other investigations (Tsai et al., 2004; Wiren, 1968; Wu et al., 2007) determined muscle performance from strength values obtained from various types of isometric or isoinertial tests which bear little resemblance to golf actions. After reviewing the results, and due to the differences in assessment methodology (different muscle groups and type of muscle groups and actions evaluated), it is not possible to determine whether driving distance or swing/ball speed are more related to trunk and upper-body or to lower-body strength. Nevertheless, the results suggest that leg, hip and trunk power, as well as grip strength are especially relevant to golf performance. It is also worth noting that the profile of the participants in these studies is quite heterogeneous in relation to handicap (skill level) and age, which makes it difficult to generalize the obtained conclusions to other populations. Most of the reviewed papers analyzed the relationship between some physical fitness variables and swing performance, which is critical to establish the physical conditioning requirements of golf. However, only three of the aforementioned studies (Tsai et al., 2004; Wu et al., 2007; Yoon, 1998) have delved into the relationship between muscle strength and swing performance, which proves insufficient to

establish causality. Further research should address the relationship between muscle strength and power in trunk, upper- and lower-extremities and swing performance in order to understand how these variables affect the kinematic sequence of the golf swing, especially in elite golf players.

Changes in swing performance as a consequence of strength training

Most of the studies that have analyzed changes experienced in golf swing following a training program emphasizing muscle strength, power, flexibility, plyometrics, balance, or a combination of any of these physical fitness components, have showed statistically significant improvements in some or all of the variables related to swing performance. Although some exceptions do exist (Pinter, 1992; Reyes, 2002), when an improvement in strength has occurred, a subsequent increase in ball speed has always been observed regardless of the type of strength training program undertaken.

Following training, increases in club head speed (1.6-6.3%) have been observed (Doan et al., 2006; Fletcher and Hartwell, 2004; Hetu et al., 1998; Lennon, 1999; Lephart et al., 2007; Seiler et al., 2006; Thompson, 2002; Thompson et al., 2007; Thompson and Osness, 2004; Westcott et al., 1996). Lephart et al. (2007), Thompson et al. (2007), Seiler et al. (2006), Hetu et al. (1998) and Westcott et al. (1996) obtained the most noticeable improvements. It is worth mentioning the results obtained with regards to driving distance, where increases of 4-5% have been reported (Fletcher and Hartwell, 2004; Landford, 1976; Lephart et al., 2007; Wenzel, 1968).

Results obtained following a strength training program

Landford (1976) studied the effects of a 10-wk strength training program (Table 2) on driving distance and accuracy (approach test), in a sample of 42 subjects (32 males and 10 females) who were divided into two groups: experimental and control (HCP ≤ 10). Significant improvements ($p < 0.01$) were observed in all analyzed variables except the approach test. According to the author, strength training had a positive influence in driving distance, without having negative effects on accuracy. In contrast, Reyes (2002) did not find any significant increase in driving distance in low- and high-handicap golfers (HCP 19 ± 9 vs. 21 ± 8 for the experimental and control groups, respectively) following a training-induced increase in maximal isometric strength. However, since the swing implies a complex kinetic chain of muscle actions, using maximum isometric force measurements to assess muscle strength for golf is somewhat questionable.

Due to the very few existing studies that have analyzed changes in golf swing performance following a resistance-only training program, it is not possible to discern whether the observed improvements are related to strength gains or other factors. Thus, the results obtained so far are inconclusive and additional research is warranted.

Results obtained following a combined training program

Several studies have analyzed changes in swing performance indicators following a conditioning program in which strength training was combined with other physical fitness components (flexibility, balance, cardiovascular endurance, etc.). In the study of Fletcher and Hartwell (2004), 11 golfers (29 ± 7.4 yr; HCP 5.5 ± 3.7) took part in an 8-wk combined training program of general strength and plyometrics (Table 2). Following training, an improvement in golf performance (+1.5% in CHS and +4.3% in drive distance) was observed in the experimental group ($n = 6$) whereas no significant changes were found in the control group (+0.5% in CHS and -0.7% in drive distance; $n = 5$). Authors assumed that changes in drive performance were due to an increase in muscle strength. In the investigation of Seiler et al. (2006), the experimental group followed a 9-wk core and rotational stability training program while the control group performed a standard strength training program for the same time period. The experimental group obtained better results with an increase of 3.8% in CHS (95% CI: 2.6–4.8%; $p < 0.001$) compared to 1.2% for the control group (95% CI: 0.0–1.0%; $p < 0.05$). Nevertheless, in these two studies no physical conditioning assessments were conducted, thus it is impossible to determine if the observed changes in driving performance and club head speed are a consequence of strength or balance training. Doan et al. (2006), observed significant ($p < 0.05$) pre- to post-training improvements in all measures, after an 11-wk strength (Table 2), power and flexibility program (+7–24% in strength, and +7–16% in flexibility). In this study, qualitative video analysis and putting distance control tests were used. Contrary to their hypothesis, there were no differences between pre- and post-training putting test values. The results showed an increase in CHS (+1.6%) without a negative impact on putting consistency in elite golfers, even though relationships between strength changes and CHS were not indicated. Lephart et al. (2007) examined the effects of strength (Table 2), balance and flexibility following an 8-wk golf-specific exercise program. A biomechanical analysis of swing mechanics was included. Results showed significant improvements ($p < 0.05$) for right torso rotation strength at speeds of 60°s^{-1} (+7.5%) and 120°s^{-1} (+13.3%), and left torso rotation at 60°s^{-1} (+8.9%), isometric hip strength (left hip abduction: 8.6%; right hip abduction: 9.9%; left hip adduction: 8%), range of motion, and left-leg balance between pre- and post-training. These changes led to an improvement of the effectiveness indicators of the swing (+7.7% carry distance; +6.8% total distance; +5.0% ball velocity; +5.2% club speed). Thompson and Osness (2004) examined senior golfers involved in an 8-wk strength and flexibility program. Following training, significant improvements were observed in club head speed (+2.7%). Strength measurements improved significantly (+60.4% biceps curl, +35.6% chest press, +38.3% shoulder press, +36.9% seated row, +41.1% leg press and +38.5% leg extension; $p < 0.05$). In a second study (Thompson et al., 2007), improvements in club head speed were observed (+4.9%) following strength, cardiovascular endurance, flexibility and dynamic balance train-

ing. Improvements in 30-s chair stand test and 2-min step test were also significant ($p < 0.05$). These results are similar to those reported by Hetu et al. (1998) and Westcott et al. (1996) who studied changes in golf performance following a strength (Table 2) and flexibility training program. Significant increases in several physical fitness measurements (+6.2% grip, +14.2% chest press, +18.1% leg extension and +47.3% trunk rotation) were related to an improved drive performance (+6% in CHS). Research carried out by Lennon (1999) included two studies: in the first one, subjects participated in an 8-wk strength and flexibility training program; while the second one showed the effects of a 1-yr strength, flexibility, endurance and balance training program (details of the programs were not disclosed). The author suggested that an improvement in physical condition and golf performance was observed in both cases, but he did not report a detailed description of the extent of the improvements (Table 2). Pinter (1992) examined the effects of strength ($n = 6$), flexibility ($n = 6$) and a combination of both types of training ($n = 7$) on drive CHS. Following 8-wk training (Table 2), the author did not find any significant differences between pre- and post-tests in ball speed. This lack of statistical significance could be explained by the low number of subjects included in each group as well as the instructions to ‘swing as in competition’ as opposed to ‘swing for maximum distance’ when the drive test was performed. Moreover, since in this study there were no pre-post strength assessments, it is not possible to determine whether the results were a consequence of changes in muscle strength levels.

From the above data, it would seem that improvements in strength, combined with flexibility and balance training can lead to an increase in CHS, ball speed, carry distance and total distance. However, these investigations present several methodological limitations worth noting. In some studies no strength assessments were conducted. In addition, there is a lack of analysis of changes in muscle strength levels following training and its results on swing performance. Indeed, this may be the reason why it is not possible to reach significant conclusions about the relationship between both variables. Carefully controlled studies with better experimental designs should be carried out in order to assess the influence of different types of strength training on golf swing performance.

Methodological issues

Strength assessment in golf

Investigations examining strength and its relationship to golf performance have been characterized by the use of different methodologies to assess muscle strength and/or power. Transversal and descriptive studies have employed all kinds of tests: isometric (Keogh et al., 2009; Tsai et al., 2004; Wells et al., 2009; Wu et al., 2007), isokinetic (Sell et al., 2007), isoinertial (Gordon et al., 2009; Keogh et al., 2009; Kras and Abendroth-Smith, 2001; Thompson, 2002; Wiren, 1968; Wu et al., 2007), muscular endurance (Keogh et al., 2009; Wells et al., 2009), muscle power (Yoon, 1998), medicine ball throwing distance (Gordon et al., 2009) and jump tests (Kras and Abendroth-Smith, 2001; Wells et al., 2009; Yoon, 1998). Studies where a

Table 2. Summary of longitudinal studies examining changes in golf performance following strength training.

Study	Sample size(n)	Sample profile	Type of training	Strength training program	Duration	Changes in strength	Changes in golf performance
Doan et al. (2006)	n = 10 (M); n = 6 (F); no CNT; RA?	age 19.3 ± 1.5 yr; M: average HCP zero. F: HCP 5-10	RT, MB, flexibility	FW, 3 workouts: 3 x 10-12 reps (wk 1-5); 3 x 7-8 reps (wk 6-11). MB 2 x 10 reps (wk 1-5) and 4 x 8 reps (wk 6-11)	11 wk; 3 d/wk	Improvements in all exercises (relative strength +7-24%)	+1.62% CHS (NS in M or F only groups)
Fletcher and Hartwell (2004)	n = 11 (M) (6 EXP, 5 CNT); RA	age 29 ± 7.4 yr; HCP 5.5 ± 3.7	RT, plyometrics, stretching	FW: 3 x 6-8 reps. Plyometrics: 4 exercises, 3 x 6 reps	8 wk; 2 d/wk	No results	+1.5% CHS EXP; +4.3% DD EXP
Hetu et al. (1998)	n = 17 (12 M, 5 F); no CNT; no RA	age 52.4 ± 6.7 yr	RT, plyometrics, flexibility	FW and body-weight: 2 x 10-12 reps to 2 x 6-8 reps with heavier loads; MB: 2 x 15 reps	8 wk; 2 d/wk	+6.2% Grip; +14.2% CP; +8.1% LE; +38.8% sit-reach; +47.3% TR	+6.3% CHS
Landford (1976)	n = 16 (M); n = 5 (F); RA EXP; n = 16 (M); n = 5 (F) RA CNT	age 18 to 56 yr; HCP 0-27 EXP; HCP 0-21 CNT	RT	8 exercises; 2 sets. 1, 6, 20 and 30 reps depending on the exercise	10 wk; 3 d/wk	Gains for EXP in BP, RGS and LGS	M: increase in DD in EXP. F: NS for EXP. DD correlated to BP, RGS, LGS
Lephart et al. (2007)	n = 15 (M)	age 47.2 ± 11.4yr; HCP 12.1 ± 6.4	RT, flexibility, balance	Elastic resistance tubing: 3 x 10-15 reps bilateral	8 wk; 3-4 d/wk	TR (+8.9% LT 60°/s; +7.5% RT 60°/s; +13.3% RT 120°/s), isometric (+8.6% LH abd; +9.9% RH abd)	+7.7% CD; +6.8% TD; +5.0% BS; +5.2% CHS
Lennon (1999)	Study A: n = 14; CNT; RA Study B: n = 28 (M)	A: age 16 ± 0.4yr; HCP ? B: ?	A: RT and flexibility B: RT, flexibility, endurance, balance	Unspecified	A: 8 wk; 4 d/wk B: 1 yr; 4 d/wk	A: grip strength, leg strength. NS changes CNT B: improvements, unspecified	A: greater distance, unspecified B: Best-ever performance, unspecified NS changes pre-post
Pinter (1992)	n = 25 (M); RA in 4 groups (n = 7 each plus n = 7 CNT)	age 19 to 23 yr; HCP < 4	RT, flexibility, or combination of both	A: RT group: FW: 3 x 10 rep (60% RM) to 3 x 4 rep (85% RM); B: Flexibility training; C: RT (same as A) + 6 flexibility exercises; D: CNT (no strength or flexibility training)	8 wk; 3 d/wk	Not assessed	NS changes pre-post
Reyes (2002)	n = 19 (10 EXP, 9 CNT); no RA	age 32 to 84 yr; HCP 17 ± 9 EXP; HCP 21 ± 8 CNT	RT	Isometric training; 12 exercises; heaviest load that can be held for 10 to 20 s in each exercise	7 wk	Increase in mean strength	NS correlation between increase in strength and DD
Seiler et al. (2006)	n = 10 EXP; n = 10 CNT	EXP: age 15 ± 2 yr; HCP 13. CNT: age 15.8 ± 2 yr; HCP 6	Core and RST (EXP), traditional RT (CNT)	Unspecified	9 + 2 wk	No results	CHS: +3.8% EXP, +1.2% CNT
Thompson and Osnes (2004)	n = 31 (M); (19 EXP, 12 CNT); RA	age 65.1 ± 6.2 yr; all HCP levels	RT, flexibility	Weight-training machines: 10 upper- and lower-body exercises: 1 x 12 reps (80% RM)	8 wk	+60.4% BC; +35.6% CP; +38.3% SP; +36.9% SR; +41.1% LP; +38.5% LE	CHS: +2.7% EXP

Table 2. Continued.

Study	Sample size (n)	Sample profile	Type of training	Strength training program	Duration	Changes in strength	Changes in golf performance
Thompson et al. (2007)	n = 18 (M) (11 EXP, 7 CNT); RA	age 70.7 ± 7.1yr	RT, endurance, flexibility, balance, rotational power	Stability ball training: 1 x 15reps (wk 1-2); 2 x 12-15 reps (wk 3-4); 3 x 12 reps (wk 5-6); 3 x 8reps (wk 7-8)	8 wk; 90 min/wk	Improvements in chair stand test and step test	CHS: +4.9%
Westcott et al. (1996)	n = 17 (13 M, 4 F); n = 5 CNT; no RA	age 57 yr	RT, flexibility	Weight-training machines: load that allowed 8 to 12 reps	8 wk; 3 d/wk	+56% 10RM LE; NS for CNT	CHS: +6% EXP

EXP: Experimental group; CNT: Control group; RA: Random Assignment; HCP: Handicap; DD: Driving Distance; CD: Carry Distance; CHS: Club Head Speed; TD: Total Distance; BS: Ball Speed; MB: Medicine Ball; TR: Trunk Rotation; LT: Left Torso; RT: Right Torso; LH: Left Hip strength; RH: Right Hip strength; BC: Biceps Curl; CP: Chest Press; SP: Shoulder Press; SR: Seated Row; LP: Leg Press; LE: Leg Extension; RST: Rotational Stability Training; RGS: Right Grip Strength; LGS: Left Grip Strength; FW: Free Weights; NS: Non-Significant ($p > 0.05$). Only significant improvements ($p < 0.05$) are reported.

longitudinal analysis of strength training was performed opted for isometric (Tsai et al., 2004), isokinetic (Lephart et al., 2007) or isoinertial (Doan et al., 2006; Hetu et al., 1998; Keogh et al., 2009; Landford, 1976; Sthromeyer, 1973; Thompson and Osness, 2004; Westcott et al., 1996) tests, as well as rotational trunk power by throwing a medicine ball with subsequent qualitative video analysis (Doan et al., 2006; Hetu et al., 1998). Equipment used to assess strength consisted mainly of dynamometry (used in free-weight exercises as well as weight-training machines), isokinetic machines (Byodex System; Cybex), force platforms, 3D electromagnetic motion analysis system (trunk rotation), digital video cameras and, in one occasion, a potentiometer (Yoon, 1998). Moreover, few of the previously discussed studies (Gordon et al., 2009; Kras and Abendroth-Smith, 2001; Wells et al., 2009; Yoon, 1998) actually analyzed strength variables which are able to explain performance in sports training or competition settings.

Most research seems to support the idea that using isometric (constant angle) or isokinetic tests (constant velocity) to assess dynamic performance is not adequate since these types of muscle actions usually have a relatively poor relationship to dynamic athletic performance (Abernethy et al., 1995; Baker et al., 1994; Murphy et al., 1995; Murphy and Wilson, 1996; Wilson and Murphy, 1996). Therefore, dynamic actions in isoinertial conditions (constant gravitational load) together with adequate testing protocols would seem more appropriate to evaluate muscle strength and power for golf, where the swing is characterized by high accelerations. However, although there exist large neural and mechanical differences between isometric and isokinetic tests and functional movements (Harris et al., 2007), several studies indicate that the ability to exert maximal isometric force appears to have some common traits with the ability to generate force rapidly, at least in sports with high strength demands such as Olympic weightlifting, football, throwing and track sprint-cycling (Haff et al., 1997; McGuigan and Winchester, 2008; Stone et al., 2003, 2004).

Characteristics of the participants

The performance level and characteristics of participants may influence the results of the

investigations. With regards to performance represented by handicap, the samples used in the previously analyzed studies are quite heterogeneous: studies with high-performance level (HCP < 5) subjects (Gordon et al., 2009; Pinter, 1992; Yoon, 1998), low-performance level (Fletcher and Hartwell, 2004; Lephart et al., 2007; Wiren, 1968; Wu et al., 2007), or studies with participants of different handicap (Doan et al., 2006; Keogh et al., 2009; Landford, 1976; Sell et al., 2007; Thompson and Osness, 2004; Tsai et al., 2004) are found. Other studies did not indicate the participants' handicap (Hetu et al., 1998; Kras and Abendroth-Smith, 2001; Thompson, 2002; Thompson et al., 2007; Wells et al., 2009; Westcott et al., 1996). In addition, while some studies opted for young participants (Doan et al., 2006; Kras and Abendroth-Smith, 2001; Lennon, 1999; Seiler et al., 2006; Wu et al., 2007) or seniors only (Hetu et al., 1998; Thompson, 2002; Thompson et al., 2007; Thompson and Osness, 2004; Westcott et al., 1996), other investigations chose samples of varying (22-84 yr) age (Fletcher and Hartwell, 2004; Gordon et al., 2009; Keogh et al., 2009; Landford, 1976; Lephart et al., 2007; Reyes, 2002; Sell et al., 2007; Wells et al., 2009; Wiren, 1968; Yoon, 1998). There were even studies where neither age nor gender was indicated (Tsai et al., 2004) or where males and females were mixed (Wells et al., 2009). In the study of Wells et al. (2009) both males ($n = 15$) and females ($n = 9$) were included in the same analysis, thus artificially inflating the correlation between muscle strength and golf performance variables because although the two groups were high-level amateur golfers, they were heterogeneous in terms of absolute performance level. The wide age range sample (17-73 yr) and very different HCP (0-14) used in the study of Wiren (1968) facilitates finding correlation between variables but does not guarantee that within a highly competitive age range (approximately 18-35 yr) such a correlation exists. Studies in which driving distance was not actually measured but self-reported by the participants (Sell et al., 2007; Tsai et al., 2004) should not be worth considering. The accessibility of the participants is a factor that must also be taken into account. It is generally problematic to find a suitable group of elite players, regardless of age. The size of the sample is another important issue because a larger sample implies a narrower confidence interval which allows generalizing

the observed correlations to the target population (Hopkins, 2006). However, in the majority of the reviewed studies sample sizes were too small to draw sound conclusions about the importance of various expressions of muscle strength to improve golf swing performance.

Methodological designs have to be carefully considered when attempting to generalize research results. The sample profiles employed in these studies are too heterogeneous to allow extrapolation to different populations (e.g. amateurs vs. professionals, young vs. adults, men vs. women).

Training design: longitudinal studies

Regarding training methodology, all the investigations were of short duration, ranging from 4 to 11 weeks, except Lennon (1999), with a majority of 8-wk training programs, 2-4 sessions per week, 35-90 minutes per session. Even though the training programs significantly differed between studies, the strength protocols show some common traits: 2-3 sets x 10-12 repetitions and/or 2-3 sets x 6-8 repetitions. Some of these programs included plyometric exercises (Doan et al., 2006; Fletcher and Hartwell, 2004; Hetu et al., 1998) and only one used isometric training (Reyes, 2002). Although the results of these studies showed significant improvements in some or all of the strength exercises evaluated, some studies did not include a control group (Doan et al., 2006; Hetu et al., 1998; Jones, 1999; Wenzel, 1968), or in some cases the information was not disclosed (Lephart et al., 2007). Of the investigations that used a control group, only some of them assigned the participants randomly (Fletcher and Hartwell, 2004; Landford, 1976; Lennon, 1999; Sthromeyer, 1973; Thompson et al., 2007; Thompson and Osness, 2004). When a control group is not used, it is difficult to ascertain whether the observed improvements are actually due to training or to naturally occurring changes, learning effect between tests or biological maturation in the case of youngsters. An analysis of the relationship between changes of these variables could possibly help to overcome the aforementioned limitations.

Conclusions

Taken together, the results of the reviewed studies seem to indicate that: 1) a positive relationship exists between handicap and swing performance variables (even though few studies have investigated this issue); 2) there is a positive correlation between skill (handicap and/or score) and muscle strength; and 3) there is a relationship between driving distance, swing speed, ball speed and muscle strength.

Results suggest that training leg-hip, trunk power and grip strength are especially relevant for golf performance improvement, although more research is clearly needed to identify the major muscle groups and optimal assessment movement patterns for golf. Further studies should determine muscle strength needs in relation to final swing performance, using well designed experiments and strict isoinertial assessment protocols which adequately relate to specific golf motion, age and skill level.

The few longitudinal studies conducted so far seem to indicate a relationship between muscle strength and driving distance, swing speed and/or ball speed. Studies that analyzed variations in swing performance following a resistance-only training program are scarce, thus it is difficult to prove whether the observed improvements are actually attributable to changes in strength levels. On the other hand, improvements in strength, in conjunction with flexibility and balance led to an increase in CHS, ball speed, carry distance and total distance. An important drawback of these longitudinal studies was the lack of analysis of changes in strength levels and their results in swing performance. The most significant changes were observed in older golfers, while very few investigations included junior players in their samples. Many of the studies reviewed presented some methodological errors in their design and not all strength assessment protocols seemed appropriate. Finally, few are the studies which included women in their samples; thus, future investigations should address this deficiency. More studies with elite participants, either professional or amateur, would be especially desirable.

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Key points

- Positive correlations exist between: 1) handicap and swing performance variables; 2) muscle strength and skill (handicap and/or golf score); and 3) driving distance, swing speed, ball speed and muscle strength.
- Leg-hip, trunk power and grip strength seem especially relevant for golf performance improvement.
- Further research should determine muscle strength needs in relation to final swing performance, using well designed experiments and strict assessment protocols which adequately relate to specific golf motion, age and skill level.

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